Stellingen

behorende bij het proefschrift van B.J. Daams
'Human force exertion in user-product interaction'

1. *De* maximum spierkracht bestaat niet.

2. Het ontstaan van produkten die weinig kracht vragen is geen spontane ontwikkeling, maar het gevolg van bewuste keuzen door ontwerpers.

3. Een omgeving waar zelden kracht hoeft te worden uitgeoefend heeft een negatieve invloed op de gezondheid van de gebruikers. Dit geldt vooral voor gebruikers die relatief zwak zijn en weinig conditie hebben.

4. Mensen die streven naar fysiek gemak in het dagelijks leven (bijvoorbeeld door met de auto te gaan), maar aan de andere kant gaarne fysieke arbeid verrichten door te sporten (bijvoorbeeld fietsen) leven niet erg efficiënt, aangezien zij het nuttige niet met het aangename weten te verenigen.

5. Een Krachtenatlas zoals voorgesteld in dit proefschrift zal een nuttig hulpmiddel zijn voor ontwerpers, maar zal nooit antwoord op al hun vragen terzake kunnen geven.

6. Horatius' 'Vis consuli expers mole ruit sua' geldt ook in de zin dat tabellen met menselijke krachten, gebruikt zonder inzicht, niet zullen leiden tot een beter ontwerp.

7. Bij het meten van menselijke krachtuitoefening op produkten is het aan te bevelen de proefpersonen wat houding betreft dezelfde mate van vrijheid te geven als in de te verwachten gebruikssituatie.

8. De meetmethode en de definitie van maximale kracht hebben grote invloed op de maximale volhoudtijden van relatieve sub-maximale krachten.

9. Houdingsverandering van proefpersonen tijdens het volhouden van een kracht is voor ontwerpers van consumentenprodukten een bruikbare en praktische maat voor discomfortgevoelens van toekomstige gebruikers.

10. Een ontwerper is beter af met gezond verstand dan met het 'P5-P95-syndroom'.

11. In de idee-fase van het ontwerpproces zijn algemene inzichten en vuistregels het nuttigst voor de ontwerper. Bij de uitwerking van het produkt is er juist behoefte aan gedetailleerde gegevens. Met deze tweedeling in de informatiebehoefte zou in ergonomische handboeken meer rekening moeten worden gehouden.

12. In ergonomische en andere wetenschappelijke publicaties waar naar geslacht wordt verwezen in tekst en tabellen, worden ten onrechte mannen altijd eerder genoemd dan vrouwen.

13. Assistenten In Opleiding krijgen te weinig loon naar werken en te weinig opleiding naar loon.

14. Aan een pro-motor, die dus verondersteld wordt andermans wetenschappelijk werk te doen voortbewegen, dienen hoge eisen te worden gesteld wat betreft kundigheid, enthousiasme en tijdbesteding.

15. Het zwaartepunt van de aandacht voor ontwerpen voor recycling ligt tot nu toe ten onrechte bij de kunststoffen.

16. Ontwerpen voor recycling is nooit een excuus om niet éérst aandacht te schenken aan afval-preventie en hergebruik van produkten of onderdelen.
Ontwerpen voor preventie en hergebruik is aan de andere kant nooit een excuus om de recycleerbaarheid van het product te verwaarlozen.

17. De structuur van een organisatie doet over het algemeen minder terzake dan de mensen in die organisatie, die de praktische werkbaarheid ervan bepalen.

18. Wellevende mensen roken niet in gezelschap. Weldenkende mensen roken niet.

19. Als roken niet sociaal geaccepteerd zou zijn, was het verboden door de opium- en ARBO-wetten. Zolang er geen algeheel rookverbod geldt, wordt het bewezen gezondheidsrisico voor de hele bevolking gebagatelliseerd tot een individueel en subjectief probleem tussen de meest fanatieke rokers en enkele assertieve niet-rokers.

20. Een goede stelling is de beste verdediging.

Delft, 26 april 1994.

Human force exertion in user-product interaction

Backgrounds for design

Human force exertion in user-product interaction
Backgrounds for design

Proefschrift

ter verkrijging van de graad van doctor aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus, Prof. ir. K.F. Wakker,
in het openbaar te verdedigen ten overstaan van een commissie,
aangewezen door het College van Dekanen,
op dinsdag 26 april 1994 om 10.30 uur door

Brechtje Johanna DAAMS,

geboren te Amsterdam,
ingenieur industrieel ontwerpen.

Dit proefschrift is goedgekeurd door de promotor:

Prof. dr. J.M. Dirken

Acknowledgements:

ing. J.J. Houtkamp *(equipment),*
H. Lok *(equipment),*
H.J. Arisz *(statistical analyses),*
M. de Geus *(correction of English text),*
ir. P.A. Kraaijeveld *(cover design, lay-out),*
ir. M.P. Wilming *(cover design),*
D.W. Daams *(illustrations),*
dr. ir. B.G.J. Wichers Schreur *(cover illustration).*

Handelseditie verschenen bij Delftse Universitaire Pers, ISBN 90-6275-995-5

"Les forces humaines n'ont pas de limites, madame..."
(Jarry, 1902)

to Ben

Contents

1 Introduction

1.1 Problem definition

Ergonomics is the science and the art of adapting a product, machine or environment to its users. The product should be comfortable, safe and efficient to operate, handle or use. It should meet these requirements in a number of ways, one of these being the force required to use the product.

This project focuses on forces exerted on consumer products. Characteristic for consumer products is that they are used voluntarily, by a variety of non-specialist users with different backgrounds, different levels of education and of varying strength. Generally speaking, they are used less than 8 hours a day, five days a week, all the year round. The relative importance of consumer products for the user ranges from 'essential' to 'just for fun'. Usually the person buying a product is also one of its users. If the consumer is not satisfied with the product, it may be replaced or just remain unused, and it will certainly not be bought again.

Users, even the physically weakest, should be able to operate, use or handle a product that is designed for them. A designer should therefore take into account the physical capabilities of weaker users, like the elderly, women, children and handicapped people, if they are targeted as future users. This is especially important in view of the 'grey wave' of elderly people that is now flooding western Europe and will continue to do so for the next decades. Their ability to handle everyday products in and around the house determines how long they will remain able to live on their own. This ability depends not just on the people themselves, but also on the proper design of the products in their immediate surroundings. About half of the people in The Netherlands who move into a home for the elderly do so because they become unable to do their own housekeeping (De Klerk and Huijsman, 1993). Products designed for this special group would help them to remain self-sufficient longer if they so choose, from which both they and the community would benefit. Even if a product is not especially intended for the elderly, a designer should realize that physical strength varies widely among individuals and that products intended for the general public will be used by different people, varying from those who are almost incapable of exerting any force at all, as is the case with the ill and elderly, to those with more than three times the average strength, as with young, healthy and well-trained men. Many individuals belong to relatively weak categories, and the lack of information on the characteristics and abilities of these groups is conspicuous. At the Department of Product and Systems Ergonomics of the Faculty of Industrial Design Engineering of the Delft University of Technology, a number of projects are dedicated to research into the characteristics and abilities of children (Steenbekkers, 1993), elderly people (Molenbroek et al., 1987; Vorst et al., 1992; Freudenthal, to be published in this series in 1996) and disabled people (Marinissen and Oldenkamp 1989, Kanis, 1993; Schoorlemmer and Kanis, 1992).

On the other hand, very strong users should not be able to inadvertently damage or break a product. If this happens, the product may still be functioning, in which case the damage will be no more than a minor annoyance. However, it may happen that the product is broken and cannot be repaired. In the worst scenario, depending on the product and the situation, a breakdown will cause serious injury. This, of course, is something a designer must try to avoid. For some products, safety standards and regulations are defined, for others the designer has to find out for herself what the acceptable limits are.

It can be argued that in these modern times products are becoming increasingly mechanized, servo-assisted and equipped with electronics. Less and less force is required for interaction with a product. So if we just wait a bit longer, we will require hardly any force at all to use the products our modern world offers. Then why bother about the forces people can exert? Because this reduction of force needed to operate or use products does not come about spontaneously, but has to be brought on by the designers of new products. It is therefore necessary to know about the capabilities of future users. Furthermore, if a product is designed with a more sophisticated view to force exertion, servo-assistance may not always be needed, which consequently makes it less complicated, cheaper and possibly less damaging to the environment.

Although large mechanical resistance and the corresponding necessity of large force exertion should be avoided in products, some force will always be required. For most products, this is inevitable as some functions inherently require force. For some products, resistance is indispensable for proper positioning. Without resistance, positioning would be awkward and overshooting would easily occur. All continuously variable controls, e.g. those on electronic equipment, therefore require some built-in resistance. For other products, resistance is indispensable to provide feedback, as for example with rotating dimmer switches, where increased resistance indicates the point where moving the knob any further will switch off the lighting completely.

Anyway, in itself it is a good thing that products require some force to operate them, as it is very healthy to do some physical exercise in daily life. In a domestic environment in which everything can be controlled at the flick of a finger, the inhabitants through lack of exercise will run the risk of losing their physical condition due to atrophy of the muscles and the cardiovascular and respiratory systems. One example of this is the use of the increasingly popular power-assisted bicycle. For elderly people, the physical ability to open a can with a normal canopener can decrease through the use of an electric machine. This deterioration of health due to the use of products that require little or no force mainly applies to people who do not take regular exercise. This may eventually result in deterioration of health on a national or even international scale.

Examples. An interview with eight dutch elderly ladies who do their own housekeeping gives some insight in the kind of products they are unable to operate (Daams, 1987). Some of the ladies have problems turning water taps or radiator valves which are not fitted with knurled knobs, medicine jars, toothpaste tubes, and hand-operated can openers, because they require too much force. None of them can open jam jars or bottles of lemonade by hand. They must ask someone stronger than they are to open these products, or resort to a variety of tools and tricks (although the use of tools does not always guarantee success). With some corkscrews, extracting the cork from a bottle is very difficult, but the double-lever type of corkscrew will easily do the trick. Most of these ladies had electric watches and alarm clocks, but those with mechanical clocks had problems winding theirs. Winding a watch is mainly difficult due to the small size of the crown.

Jam jars that are almost impossible to open will be a familiar phenomenon to most people. It is the traditional example of a form of packaging that is difficult to open. It is referred to as such in newspapers and popular magazines, e.g. De Volkskrant (Van Kleef, 1987) and Margriet (B., 1993). A patient can even attempt to open a jar of peanut butter, and in the struggle strain the muscles of an arm, as experienced by Dorrestein (1993, pp. 128-129). Problems with opening jam jars also received attention in research (Berns, 1981; Daams, 1987; Imrhan and Loo, 1988) and design (Schoorlemmer, 1989).

The nutcracker is a popular though problematic product. Many different mechanisms have been tried, none of them perfect. Cracking a nut takes too much force, not only for weak persons and certain types of nut will resist any force applied to them. With several nutcracker systems, the result is often nut pulp mixed with pieces of shell (Blankesteijn, 1993).Some nutcrackers, however, require so much force to operate that even persons of average strength will not succeed in using them properly.

Door-closing devices are designed to keep doors shut against draughts or to comply with fire regulations. Some perform so well that it becomes extremely difficult to open the door. Kanis (1991) describes a door in a train passage that automatically closes with such force that old ladies are hurt and a bunch of flowers is mercilessly crushed.

The author's own experience and experiences of acquaintances include a large diversity of problem products, among which the nutcracker, the train door and the jam jar feature prominently. A few other examples are listed below.

In many cases, operating the push button to flush a lavatory requires not only a minimum force, but also a minimum speed to succeed. This severely increases the degree of difficulty of the operation. In one case, the only way a healthy young woman could get the thing to work was by applying a karate kick.

To protect the blades of ice skates during transport, storage and 'klunen' (walking over land to get around an obstacle and to the next stretch of ice), protective polymer sleeves can be fitted over them. These are adjustable in steps, but sometimes in one position will the protectors be too loose, while the next position will make them so tight that they become very hard to put on. Especially with cold hands, as is often the case in the situations concerned, the operation is difficult.

Opening the lid of some large copiers ought to be prohibited by law. The lid is very heavy and must be opened by pulling a handle which is positioned so that the wrist is supinated maximally and the hand is in near-maximal dorsal flexion. Pain in the wrist is the price to pay for a few good copies.

Handbrakes in cars are another interesting product of which the use is complicated by a lack of feedback. It is hard to tell whether the brake is pulled sufficiently. Weaker subjects are stuck with the fear that their efforts were not sufficient and they will find their vehicle several metres from where they parked it (and hopefully, undamaged). A stronger, but not exceptionally strong subject is known to have broken off a brake handle with a seemingly gentle pull.

Disabled people who require the temporary aid of crutches can, after some exercise, move around quite swiftly and can sometimes even continue business as usual. Only then do they find out how great a force is applied by most door-closing devices. It is hard to open automatically closing doors while standing on one leg, and it requires some dexterity to keep them open long enough to pass through. Doors with less powerful closing devices are much easier to cope with, and apparently perform equally well in all other respects.

Latchkeys can be a problem too. A grandmother had to make herself a tool for turning the key to her front door – something she was unable to do otherwise by hand.

Lighting a gas fire or a geyser can be quite tricky. To get the pilot flame going, a button must be pushed or turned and held for as long as five minutes or even more. This is certainly not an easy task with a spring-loaded button which requires much force.

Child-resistant closures are another category of products in which the required force is an important factor determining the rate of success. On the one hand, children up to a certain age should not be able to open the closure, while on the other hand elderly people must be able to open it without problems. A complicating factor is that the maximal grip force of most four-year olds exceeds that of many elderly persons. As the closures should be easy to open by the latter, the resistance to opening by children is often further improved by using a combination of two forces (like pushing and turning at the same time) to open the closure. Nevertheless, this still requires too much force of the weakest elderly, who must wrestle regularly to obtain their daily medicines or to open bottles of household detergents.

The examples of man struggling with various types of packaging, apart from the notorious jam jar, are many, notably with coffee-creamer cups (Kanis, 1989a), milk cartons (Van Putten, 1990), complimentary sachets of bath foam in hotels (Den Uyl, 1979) and slices of luncheon meat hermetically sealed in plastic. In those cases the packaging material is so smooth that the friction between packaging and hand is very small, and in addition the shape is often such that it is hard to get a good grip on it. Consequently, although a subject may be able to exert sufficient force, he or she is unable to transfer it to the packaging.

Some products are not as easy to handle or operate as they could be. A good design may require investments, and when the benefits are not directly visible, such improvements find little support. The cost aspect is especially important in packaging, and may explain why a relatively large number of complaints originate from that area.

For some products, the cause of the problems can be bad maintenance (like those with the latch key), or bad adjustment (like the toilet push button). This does not make the problem less serious for the user. Designers should allow for bad maintenance and bad adjustment in the design of their products.

Atlas of Human Force Exertion. So it is of vital importance for designers to take the physical capacity of the users into account when designing a product. Therefore they have to be able to find information on the physical strength of various groups of people, relevant to product design. As far as we know, such sources of information in literature are few and far between. In general, present ergonomic literature on force exertion is insufficiently suited to use by designers. Therefore a book or database, containing as much data on human strength as possible and in such a form that designers can apply the information contained therein, would be a very valuable tool for product design. This database will be called an 'Atlas of Human Force Exertion'.

Brief. The original brief of this project was to make such an atlas of human force exertion. After initial orientation, it was concluded that the actual compiling of the atlas was impossible without first finding answers to other questions. Although a book with assorted tables can easily be produced, that was not what we had in mind. In the first place, how should research on force exertion be conducted in order for the results to be of use for designers? Which (type of) information is useful? How should the results be presented, i.e. what would be the style of the atlas? And to what extent can such an atlas succeed anyway? Perhaps the aim of such an atlas is unachievable, and thus the result of any attempt to make one would be doomed to fail its purpose. These are closely related and important questions.

Some authors have published work on what they also call an atlas of strength (Ayoub et al., 1981; Ayoub et al., 1982; Hafez et al., 1982) or an atlas of force (Hennion et al., 1989). Their atlases were not explicitly set up for designers and consumer products. Ayoub's atlas is directed to dynamic military tasks, for example manual lifting. None of the authors discussed the feasibility of the atlas, and they did not indicate the scope or limits of their ambitions, either. It seems that until now those questions have not been asked.

Thus, the questions that should precede the development of an atlas of human force exertion for designers form the brief of this project.

1.2 Force exertion and consumer product design

Characteristics. To clarify the discussion on force exertion on consumer products, some characteristics of their relation are given.

The two main differences between consumer products and professional products are that consumer products are used voluntarily and by a broad group of users, with much variation in characteristics and background. Users of professional products are aged between 18 and 65, are generally healthy and for some occupations predominantly male. Consumers include children, the elderly, the physically disabled, and the world's largest minority group, women. They range from the mentally handicapped to the highly gifted. In regarding the force required to operate a product, the capacities of all groups must be taken into account. Anyone ought to be perfectly able to operate the product, or even better: enjoy operating it.

To the user, the relative importance of consumer products ranges, as said before, from 'essential' to 'just for fun'. Many products range somewhere in between those two extremes. For essential products, the most important thing is that the product can be operated, whereas for fun products enjoying their use is the main requirement. If the consumers do not like it, they will not buy the same product again. Usually a consumer who buys a product is one of the users, whereas in the professional world the decision to purchase, the actual purchase, payment and use are often handled by different individuals. It could well be that satisfaction of the user contributes more to the sales figure for consumer products than for professional ones, for which e.g. efficiency and safety may be more important to the decision makers. Therefore the subjective experience of the consumer is an important factor in the assessment of what is an acceptable force for operating a product. The information on the maximally exerted force is in this view less important than information on the experience of the user during exertion of submaximal forces. The time of exertion must also be taken into account. Forces on consumer products can be exerted for any period of time, but they are usually not operated with the intensity and frequency of a full working day (8 hours a day, 5 days a week, all year round). Therefore the necessity to prevent injury through excessive exertion during work is not the first priority in the research into force exertion on consumer product design.

Force can be exerted both statically and dynamically. It is estimated that, with products in general, dynamic force exertion occurs probably more often than static force exertion. Mostly, force is exerted to create a certain effect, like opening, turning on, fastening, propelling or adjusting. By moving a handle, a knob, or even the whole product, the desired effect may be obtained. Some forces are initially static, like those exerted on the lids of jam jars, but in the end the idea is that the lid should move.

Design process. In a nutshell, the process of incorporating force exertion in design is the following (a more extensive version can be found in chapter seven).

First the function of the product, the target user group, the situation and the behaviour of the users should be established or estimated. For design purposes, the weakest users are often more relevant than the strongest, and beginners more than experienced users.

Then the implications for the design should be considered. Some elementary knowledge of physics and human force exertion, and some logical thinking are indispensable. This may result in a schematic idea for the product with the most comfortable, efficient or maximal force exertion. Then it can be inferred which information on force exertion is needed, and this information must then be gathered from somewhere. A private investigation into force exertion with the right subjects and the desired postures is advised, but if there is not enough time, literature can sometimes give an indication of the range of forces involved. Now, knowing the limits within which the product should function, the programme of requirements can be extended with operational requirements concerning force exertion. Then the product can be designed and, if possible, the first prototypes tested and evaluated, and the product improved accordingly.

If the required information on force exertion cannot be found, the probable forces involved cannot be predicted, but only very roughly estimated, and the design can neither be adapted beforehand to the needs of the users, nor be adequately tested and evaluated on the basis of a prototype. In most design projects, neither time nor funds are available to conduct experiments, and sometimes experience and enthusiasm are also lacking (except perhaps in cases where force interaction is a key topic for the design). So in general, designers have to rely on existing literature, which is so scarce that it takes much time to find details on the required force, if such information is to be found at all.

1.3 Force exertion and ergonomic research

Research on physical strength and force exertion is to be found in several areas of ergonomics.

In the first place, industrial ergonomics. Emphasis in research is put on lifting and carrying, or 'manual materials handling' as it is called. The aim is to establish the maximum workload, so that labourers will survive an eight hour working day, five day working week, without physical problems. Research is geared to prevent injury and improve efficiency. Research on cyclic work is necessary. Subjects are aged between about 18 and 65.

In the second place, military ergonomics. Research for military purposes focuses mainly on the control and maintenance of vehicles and aircraft. Subjects are predominantly young and male.

In the third place, health care. Forces are measured to establish the progress of disabled people. Static grip force is a favourite in this area, and research is often done to establish standards for various groups of people, to which the patient's grip force can then be compared. The maximal force is the maximum score of a short, maximal exertion. Subjects are recruited from all age groups, varying states of health and both sexes.

Finally, sports. The aim of research in this field is to monitor the condition of athletes and establish the effect of training schemes. In this case, dynamic force and staying power are investigated rather than static force exertion. The measures used to determine these are the maximum oxygen uptake (aerobic capacity) and power output. Subjects are usually younger people, both athletes and others.

Every area has its own research purposes, methods and subject groups. Research of forces on products is scarce, and in general too specific, directed towards one product or a select group of products. Research on force exertion according to a more general product-oriented principle, with a large variety of subjects, could make the results more valuable for designers.

1.4 Product design and ergonomic research

Research and design. The relation between design and research is a controversial and tricky one. This applies not only to ergonomic aspects, but also to other areas of industrial design engineering. The cause is sometimes attributed to bad communication between researchers and designers, but at close inspection it is clear that there are many discrepancies between their activities. Researchers are often interested in the cause of a phenomenon, whereas designers need data and care little where these come from or what the reasoning behind them is. Researchers extract information from the world surrounding us. Designers analyze information in order to generate a new idea for a product. Thus, to researchers information is the goal of their efforts, whereas for designers it is the starting point. To designers, the gathering of information should be quick, easy and to the point, in order to get on as quickly as possible with the design work. They prefer not to indulge in statistical analyses, or to linger at the deeper causes of the results. To researchers, experiments carried out that way are considered 'quick and dirty'. Although researchers and designers may agree that research should be to the point, researchers are usually not familiar with the way a product is designed, or the problems that are encountered by the designer. Consequently, they are ill-equipped to judge the relevancy of their research to design practice.

If a way can be found to show researchers how to gear research for design purposes, and to show designers how to interpret data correctly and with the right degree of caution, it will greatly improve their ways of communication and mutual understanding, and consequently, the results of their work.

Design and research on force exertion. Research on force exertion is usually conducted in one specific situation, with only a few variables varied each time. The daily use of products, on the other hand, has the potential of an enormous variety of situations, of which only the most common can be anticipated by the designer. The number of possible combinations of postures and force directions is nearly unlimited, and the research that has been done in this area lacks system and is rather thin on the ground. Furthermore the usefulness to designers is not taken into consideration when the research is set up. A situation in which force exertion is investigated seldom corresponds with the situation in which a product is expected to be used, and even less with the real situation. Postures are standardized and mainly static, maximal forces are measured for about four seconds, whereas in practice only the position of a handle or control is known and subjects will exert static or dynamic submaximal force for any time and in any posture they feel like, and to some extent with different muscle groups. And even if the usefulness to designers is taken into consideration, usually only one (type of) product is investigated so the results are too specific to be of much use for other product areas.

Research should be geared to generate those results that are useful to designers. Designers know the product they are going to make, they can target certain user groups and they can estimate the situation in which the product is likely to be used. Armed with this information, they should be able to find out how much force can be exerted. However, generally speaking, research is not geared to this question, as is evidenced by publications on ergonomics.

2 Objective

2.1 General objective

The objective of this project is to suggest how an 'Atlas of Human Force Exertion' for use by designers should be set up, and to assess how far it can contribute to the design of consumer products. This depends on the extent to which it is able to guide the designer and the degree to which its data are useful and can be easily located.

To get a better grip on this subject, first the following questions and their answers will be discussed. According to which principles and methods should research for this purpose be set up? How is one to go about developing a design which is adapted to the strength of future users? How should the atlas itself be set up, with respect to the data that should be included, the way they can be looked up and the way they are presented in the atlas?

It is expected that a satisfactory Atlas of Human Force Exertion will show researchers how to set up research geared to design purposes, and show designers how to interpret research results and data, thereby enhancing the interaction between research and design (and thus, ultimately, improving the products).

In addition, the objective is also to investigate the relations between the forces measured, and between those forces and anthropometric variables. This interest stems from general scientific curiosity on one hand, and from the possibility of data reduction on the other hand. A consistent relationship between variables will enable forces to be predicted from existing data on other forces and/or anthropometric variables, which will reduce the measurements needed to obtain information for the atlas. Or, in other words, with the same number of measurements more information can be obtained.

Summarizing, the questions to be answered were:
- How should research for design be set up?
- How should designers go about designing for the strength of future users?
- How should an Atlas of Human Force Exertion be set up?
- Can forces be predicted from other forces and/or anthropometric variables?

2.2 Limitations

From the nature of the objectives, the emphasis in this research is on the relation between research, results and design, and not so much on the interpretation of the results. So the physiological causes of the exerted forces, the why and the wherefore, are not deeply pursued, and instead, thought is given to the application of the results. This approach is required to answer the questions and meet the objectives.

The objective of the Atlas of Human Force Exertion is to provide designers with some information to enable them to improve their products on the aspects of force interaction with the user. It must be emphasized that the objective is not to answer all questions, give all necessary information or suggest the best solution, because that would be impossible anyway. It is clear from the nature of things that there are limitations. The number of possible force interactions is practically infinite, so information on all these can never be completely included in an atlas, let alone be measured. The ambitions of this Atlas do not extend beyond the presentation of some information for the assistance of the designer, as far as it goes. This is the best we can expect.

Further assessment in how far the atlas can contribute to design is necessary to improve the definition of the ambitions, to adjust the expectations of the designers, and to find out whether it is worthwhile to invest time and money to make one.

3 Literature

3.1 Introduction

3.1.1 Acquisition of information

The literature discussed in this chapter was acquired through various channels.

The archive of the anthropometric laboratory of the department of product ergonomics was the source of some older literature. In the faculty library, relevant journals were screened (Ergonomics, Human Factors, International Journal of Industrial Ergonomics, Applied Ergonomics, Ergonomic Abstracts) as well as ergonomic handbooks and conference proceedings (especially those of the Ergonomics Society and the Human Factors and Ergonomics Society). A few interesting Ph.D. theses were discovered through the Dissertations Abstracts Index.

A number of articles was acquired via colleagues at the department, at conferences and elsewhere. Quite a large number of articles were discovered through the literature lists of other articles.

3.1.2 Ordering of information

The objective of this literature research was to make a survey of present knowledge on the relevant aspects of force exertion, directed to consumer products. First, a list was made of all variables that possibly influence the forces exerted by an individual. They were categorized into four groups: variables depending on the subject, the product, the environment or the interaction during force exertion. The resulting list is included as figure 3-1.

Figure 3-1. Most variables are self-explaining, like the subject and environment variables. Some variables summarize general influence of a certain type, like psychological and physical factors.

The product variables are divided in form, size, position and material of the contact area. The position of the contact area will, of course, influence the posture of the subject. Furthermore, movement during force exertion is either required (dynamic force) or not (static force). A dynamically exerted force can either be directed, the movement following a predetermined path, or not determined, so that the direction of the movement is up to the person who exerts force. An example of the first is the movement of pedals on a bicycle, an example of the second is the movement of a vacuum cleaner during cleaning. Handles and knobs on which dynamic forces can be exerted have a certain resistance, which also influences the maximal force that can be exerted. In the case of products that are lifted or moved around as a whole, the weight is an important variable for speed and endurance of dynamic force exertion.

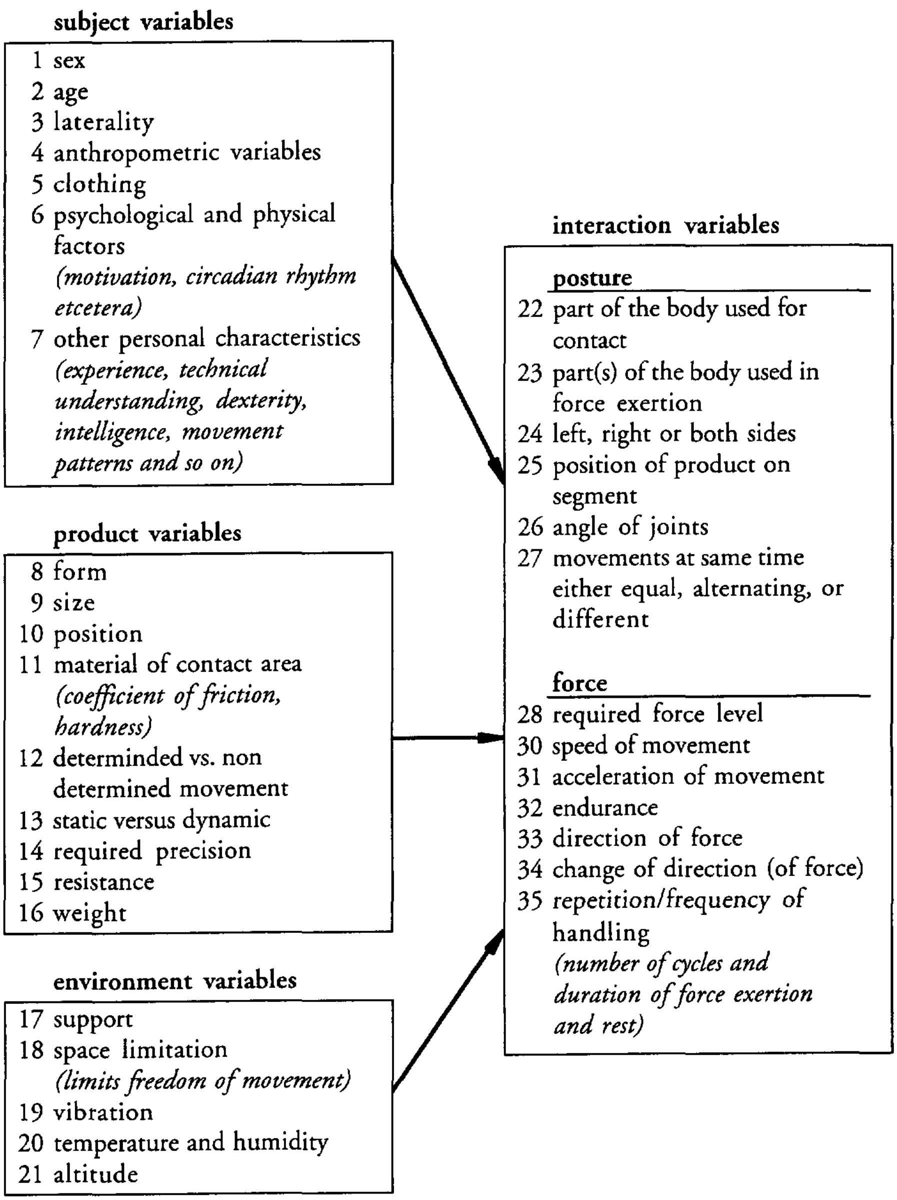


Figure 3-1: The 35 variables that influence force exertion. Subject, product and environmental variables also influence the interaction varables. This influence is indicated with an arrow.

The posture of subjects can be described by the part(s) of the body used for contact and for force exertion, the position (expressed in angles of the respective joints), the position of the contact surface on the segment concerned and the use of either the left or right arm or leg, or both. When exerting dynamic force with more than one limb at the same time, the movements can be exerted in unison, alternating or in completely different ways. An example of equal movements left and right is the symmetric carrying of a box. An example of simultaneously alternating left and right movements is the action of the left and right legs while riding a bicycle. An example of different movements at the same time is found in playing a musical instrument like the violin or the guitar.

An exerted force can be anything from minimal to maximal, with comfortable somewhere in between. How much force is required of the individual depends mostly on the product. The level of force required influences for instance the maximal endurance time and the speed of exertion. The maximal force that can be exerted also depends on the direction in which the force is exerted, relative to the person who exerts it, even if the posture remains the same, because different muscle groups are involved for e.g. flexion and extension. With dynamic force, it seems logical that the degree of acceleration of movement and changes in force direction should affect the force exerted, too, but no literature could be found on these subjects. With repeated force exertion, the work load, duration of work and rest periods, number or frequency of cycles and total working time are closely connected. These variables are not included in the literature survey, because most research on this subject is done with lifting and manual materials handling and incorporates measurements with which we are not concerned within the framework of this research.

This list, however, proved to be unpractical for ordering information from literature. Some variables are hard to separate from each other. The influence of posture, for example, has been investigated by the comparison of force exertion in standing, sitting and prone positions, which is different from the description of the posture variables given in figure 3.1. On other variables, no information was found, e.g. on vibration, nor on some personal characteristics like experience and character.

So, some variables are combined, and others left out in this literature survey. In the end, the categories were based on the most practical ordering of the available information found in literature, at the same time following the usual categorization in ergonomics for design. Thus, the following keywords are used to name the next sections:

- 3.2 Subject variables
  - 3.2.1 Sex
  - 3.2.2 Age
  - 3.2.3 Anthropometric variables
  - 3.2.4 Laterality
  - 3.2.5 Other personal characteristics
  - 3.2.6 Clothing
- 3.3 Product variables
- 3.4 Environment variables
- 3.5 Interaction variables
  - 3.5.1 Posture
  - 3.5.2 Velocity
  - 3.5.3 Endurance of static force
  - 3.5.4 (Dis)comfort

Within these sections, subdivisions are made. Data from handbooks are included, to see what is considered to be the right information on ergonomics for designers, and to find

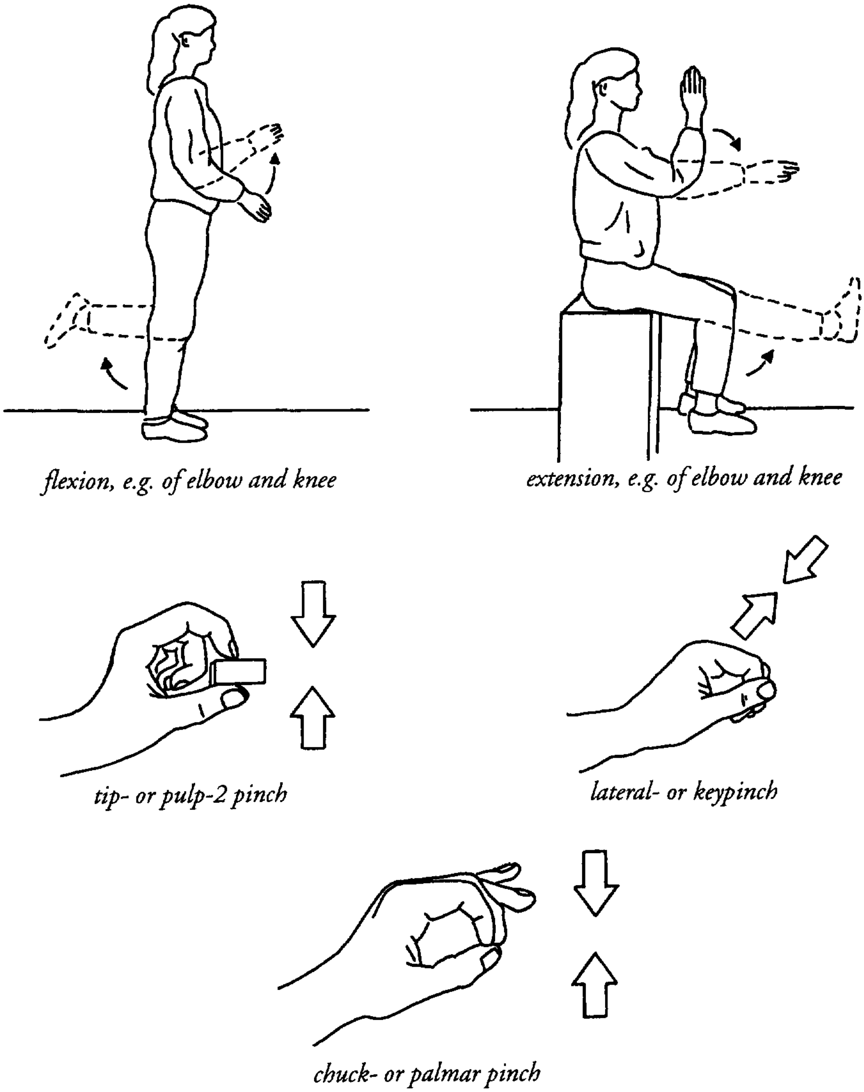


Figure 3-2: Illustration of some of the terms as defined in 3.1.3 'Definitions'

out what advice designers are supposed to receive from the handbooks. The handbook data are described in separate sections, to make a clear difference between data obtained through research and data from handbooks. Some handbooks often quote research sources, but some do not indicate the source of their information at all, which means that their statements cannot be checked. At the end of each numbered section, a conclusion summarizes the findings on the topic concerned.

The emphasis in the survey is on the relative change of exerted force, evoked by a change in one or more dependent variables. As far as possible, absolute values (Newton and Newton metre) are avoided in favour of relative values, which show the proportions more clearly.

It must be noted that in most cases, the exertion of force as discussed in this chapter concerns static, maximal force exertion. Only where the prefix 'sub', or the specification 'comfortable' is included can it be assumed that the force exertion involved is not maximal. Only where the addition of 'dynamic', 'isokinetic', 'isotone', 'eccentric' or 'concentric' is found can it be assumed that the force exertion involved is other than static.

In the following two sections, first some definitions and then the prevailing measuring methods are described.

3.1.3 Definitions

In general, agreement exists in literature on the definition of forces, postures and force directions. Some of the following descriptions are illustrated in figure 3-2.

Strength is the capacity to exert force (Caldwell et al., 1974). Usually, exerted force is used as an operational definition of strength. The exerted force, however, is subject to large variations as it is influenced by many variables (figure 3-1), and thus it is only a very indirect measure of strength. It may therefore be clearer to speak of exerted forces, rather than of strength (although in the following this latter term will be used, in order to conform to the other authors who use it).

Static force exertion (or *isometric force exertion*) is force exertion during which the length of the muscles does not change. Consequently, the speed of the movement during force exertion is zero. When the force exertion is maximal, some authors refer to this measured variable as 'Maximal Voluntary Contraction' or MVC.

Dynamic force exertion is force exertion during which the length of the muscles changes either concentrically or eccentrically, either isokinetically or isotonically. Consequently, the segments rotate relative to each other.

Concentric force exertion is dynamic force exertion during which the muscles shorten.

Eccentric force exertion is dynamic force exertion during which the muscles lengthen.

Isokinetic force exertion is dynamic force exertion during which the speed of the movement remains constant.

Isotonic force exertion is dynamic force exertion during which the tension in the muscles remains constant. In research, this situation is approached by using a constant resistance or weight.

Power is a measure of work. It is expressed in Watts, as the product of exerted force and velocity (Nm/s).

Flexion involves flexing body segments, decreasing the angle that adjacent participating segments make relative to each other.

Extension involves stretching body segments, increasing the angle that adjacent participating segments make relative to each other.

Dorsiflexion is flexion of the hand or foot in the direction of the back of the hand or foot.

Anteflexion is flexion of the hand in the direction of the palm, of the foot in the direction of the sole, or forward rotation of the arm from the shoulder in the sagittal plane.

Chuck pinch (or *palmar pinch*) involves pinching with the thumb pad opposing the pads of the index and middle fingers.

Three-point pinch involves pinching with the thumb tip opposing the tips of the index and middle fingers.

Lateral pinch (or *key pinch*) involves pinching with the thumb pad opposing the lateral aspect (the side) of the middle phalanx of the index finger.

Pulp pinch involves pinching with the thumb opposing the pad of one of the other fingers. Pulp pinch ranges from pulp-2, with the index finger, to pulp-4, with the ring finger.

Tip pinch involves pinching with the thumb opposing the pad of the index finger. It is identical to pulp-2 pinch.

Torque is the rotational moment during the gripping and turning of a knob, lid or handle.

Key pinch torque is the rotational force developed by turning the hand with the thumb pad opposing the lateral aspect (the side) of the middle phalanx of the index finger.

Push, pull, grip, press and *lift* are used in the same sense as in everyday life.

3.1.4 Methods of measurement

Since the famous and often referred to article of Caldwell et al. (1974) appeared, some standardization in measurement of static forces has developed. The less referred to articles of Kroemer (1970) and Chaffin (1975) give essentially the same information. They all recognize the influence of the instruction given to the subject, the duration of the measurement period, the posture of the subject and the amount of rest allowed between trials. They emphasize the importance of an extensive description of experimental method, which at the time was lacking in many articles. The following recommendations are all quoted from pages 201 and 202 from Caldwell et al., (1974):

- 'The subject should be informed about the test purpose and procedures. Instructions to the subject should be kept factual and not include emotional appeals. The subject should be instructed to 'increase to maximum exertion (without jerk) in about one second and maintain this effort during a four second count'.
- 'Rewards, goal setting, competition, spectators, fear, noise, etc. can affect the subjects' motivation and performance and, therefore, should be avoided'.
- 'Do not give instantaneous feedback during the exertion'.
- 'The strength datum is the mean score during the first three seconds of steady exertion'.
- 'During the sampling period strength variations within ± 10 % of the mean score should be tolerable'.
- 'The minimum rest period between related efforts should be two minutes'.

Furthermore, extensive description of subjects, test conditions, equipment and data is recommended.

With these recommendations, the instructions and the duration of measurement and rest period of maximal static force measurements are standardized to some extent. In publications, the duration of the measurement can vary a few seconds, but rest periods are nearly always two minutes and no feedback or encouragement is given. It is recommended to standardize posture, in the sense that it should be a well-documented body position. However, there are no guidelines on how to measure and describe different postures, so that at present there is a large variation in posture definitions, which makes it hard to compare the results of different investigations.

For dynamic force exertion, no general agreement on measuring methods could be discovered. Compared to static force exertion, the addition of speed, acceleration, starting point, trajectory and end point of movement to the dependent variables complicate the establishing of one measuring method. There are almost as many methods as there are experiments.

Berg et al. (1988) measured finger strength with various instructions on how to exert force, amongst which was one based on the Caldwell regimen. The different instructions yielded significantly different results. A sudden maximal peak force resulted in the highest force, whereas peak force and gradually built-up force which were both maintained for 5.5 s resulted in 93 and 85 % respectively of sudden peak force. They found that over half of the measurements did not meet the ± 10 % criterion for sustained maximal contraction for three seconds. They recommend that a ± 15 % criterion be used with a sustained maximal contraction of 2 s.

An impression of the variety of methods used to define a maximal force:

- the test procedure followed the Caldwell regimen, rest period 2 min. (Gallagher, 1989);
- grip force after 8 s was chosen arbitrarily as measurement of static grip force (Westling and Johansson, 1984);
- maximal force is the first and strongest effort (because fatigue appears to begin with the very first action) (Weiss and Flatt, 1971);
- maximal force is the highest value of two efforts (Schantz et al., 1983; Yamaji et al., 1983);
- maximal force is the average of three efforts (Molbech and Johansen, 1973; Brorson et al., 1989; Lee and Rim, 1991);
- maximal force is the highest value of three efforts (Bishop et al., 1987);
- maximal force is the average of four efforts (Hosler and Morrow, 1982);
- maximal force is the median of five efforts (De Groot, 1990);
- maximal force is the average of six efforts (Brooks et al., 1974);

Exertion time of static maximal force is for example:

- 1 minute (Tuttle et al., 1950);
- 20 s (Arnold, 1991);
- 8 s, without 'slamming' (Caldwell, 1964);

- 5 to 6 s, with instruction to apply force gradually and reach the maximum in about 2 s. measurements, with 1 min. rest in between (Caldwell and Grossman, 1973);
- steadily increasing force, attaining maximum after about 5 s. The peak was recorded (Roberts et al., 1959);
- 5 s, exertion as hard and fast as possible. Rest period 30 s (Peacock et al., 1981);
- 5 s (Pottier et al., 1969; Chaffin et al., 1983; Catovic et al., 1989; de Groot, 1990);
- 4 to 6 s, adequate rest was allowed (Chomcherngpat et al., 1989);
- 4 s (Hafez et al., 1982; Rohmert and Mainzer, 1987; Rohmert et al., 1987a, b and c);
- 3 s, instruction "to exert a slow maximum knee extension while making a conscious effort to breathe out at the same time to prevent Valsalva manoeuvre* effects". Two contractions were separated by 2 min. rest (Kroll and Clarkson, 1978);
- 2 s (Petrofsky and Lind, 1975b);
- 1 s, instruction to build up to the maximal force slowly, without jerking, over a 3 s period. Peak torque was measured (Mital, 1986);
- peak, instruction to "...get a firm grip and give it a single, hard twist, and then stop." (Swain et al., 1970);
- peak, instruction to "push with a single, forceful push" (Winters and Chapanis, 1986);

Sample size. The number of subjects who participate in experiments varies from 2 (Schutz, 1972; Rohmert et al., 1987b) to several hundred (Mathiowetz et al. (1985) 638 subjects; Kallman et al. (1990) 847 subjects; Steenbekkers (1993) 782 subjects). The modus of the sample sizes, as used in the surveyed literature, is estimated to be about fifteen subjects.

Distribution, variability, reproducibility, generality and specificity of measured forces are discussed in the following paragraphs.

Distribution. For dynamic lifting, strength is normally distributed up to the 70th percentile. Beyond this, the distribution is skewed. "The differences between actual percentile values and percentile values estimated from normal distribution, though practically insignificant, are statistically significant" (sic) (Mital and Genaidy, 1989, p. 634). Hafez et al. (1982) found, too, that the distribution of isokinetic and static torques appeared to be normal, or almost normal with skew to the high values. The skewness appears more pronounced for the data obtained from female subjects. Hettinger (1968) and Sanders and McCormick (1993) give graphs (reproduced in figures 3-3 and 3-4) which show the distribution of finger flexion force, ankle dorsiflexion force, leg strength and torso strength for women and men respectively.

* A.M. Valsalva, italian medical doctor who died in 1723. The Valsalva manoeuvre is an exhaling movement with mouth and nose closed, which in persons with intact tubae eustachii causes, amongst other things, an increase in pressure on the ear drums and a positive intrathoracal pressure. The manoeuvre offers various diagnostic and therapeutical possibilities.

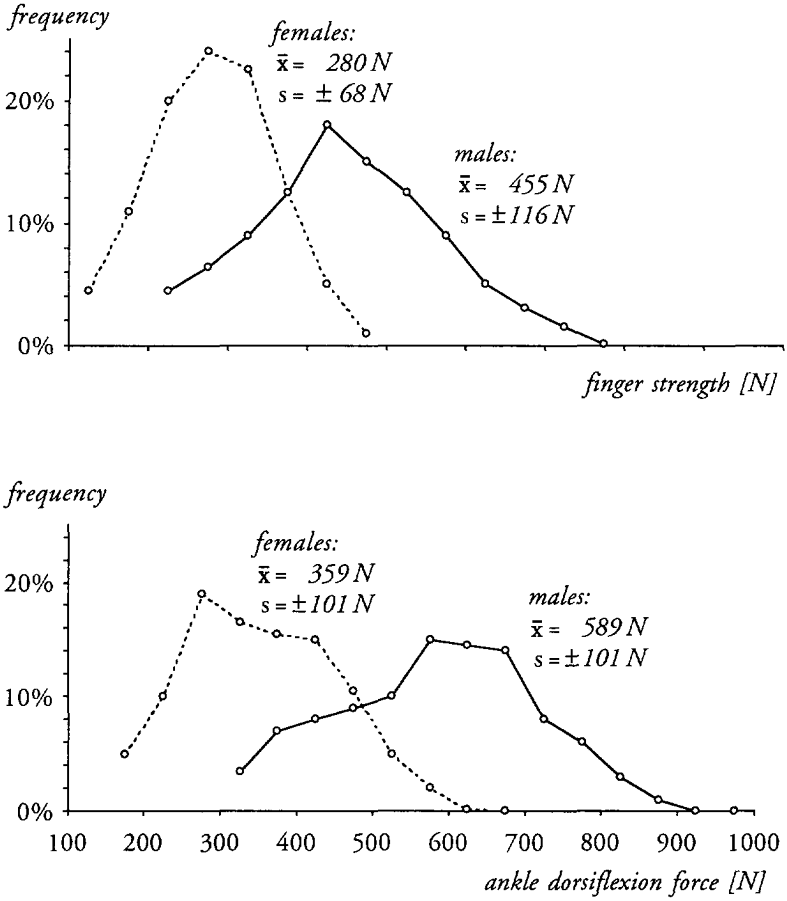


Figure 3-3: Distribution of finger flexion force and ankle dorsiflexion force for females and males (after Hettinger, 1968).

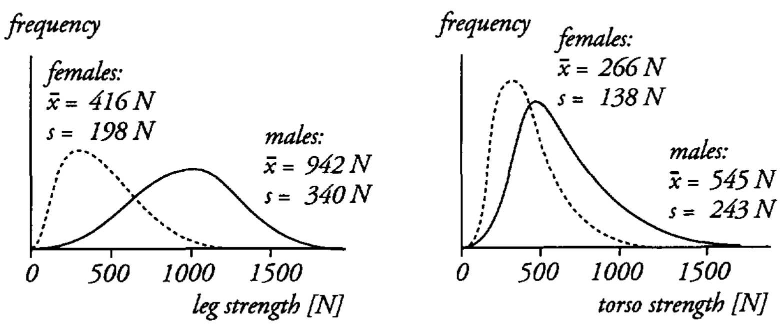


Figure 3-4: Distribution of leg strength and torso strength for females and males (after Sanders and McCormick, 1993).

Variability. Variability of forces is the extent to which the results of the various individuals in the sample differ from each other. In other words, it indicates the inter-individual variation of the measured variable. Variability is expressed in a variation coefficient as the ratio of the standard deviation to the mean of a measurement of the group. A sample from literature resulted in variation coefficients varying from 16% (Fothergill et al., 1992) to 78 % (Sanchez and Grieve, 1992), with an estimated average of about 40 % and with an exception for finger forces, the variation coefficient of which ranged from 4 to 5 % (Imrhan and Sundararajan, 1992). Mathiowetz et al. (1984) found that the variability decreases when the maximal force datum is the average of more efforts. The experience of Hennion et al. (1989) was that with visual feedback the variability decreases too. The same effect applies to a shorter exertion time. Sanders and McCormick (1993) found in literature that, even in an industrial population, the strength of the strongest person can be six to eight times that of the weakest person.

Reproducibility. Reproducibility is the extent to which the results of an experiment can be repeated with the same equipment and the same subjects, some time later. It indicates the intra-individual variation of the measured variable. Some authors call this the measurement error. With force exertion, however, there is always some fluctuation, even under exactly the same circumstances, no matter how it is measured. This is due to the influence of several continuously changing variables which are hard to control, like the subject's motivation, mood, physical condition, control of muscle contraction and tension, etcetera, and perhaps even chance. Thus the intra-individual variation of measured force exertion cannot be attributed completely to measurement errors, but is at least partially inherent to the nature of force exertion.

In general, the correlation coefficient between two series of repeated measurements is calculated as a measure of reproducibility. It can also be measured for non-repeated measurements if the number of subjects is sufficiently large. Then the group is randomly divided in two and the correlation between the results of those is the 'split-half reliability', also a measure for reproducibility.

Correlation, however, is not the ideal way to establish reproducibility, for it indicates intra-individual reproducibility relative to inter-individual reproducibility, and not the intra-individual in its own right. Comparing the differences between the group means or the mean differences between the two groups with a t-test is another possibility. An alternative would be to calculate both correlation coefficient and the mean differences between the groups, and compare the outcomes.

Even so, the method most authors use to assess reproducibility of their results is by correlation coefficient. That is, if they discuss reproducibility at all, for not many authors do so. A compilation of all values found in literature can be seen in table 3-1. Correlations are all significant and range between 0.52 and 0.99 for forces, for endurance (meaning the time a certain submaximal force can be exerted) a reliability coefficient of 0.68 and correlation coefficients ranging between 0.60 and 0.81 are noted. Some authors calculate a 'reliability coefficient', which need not be the same as reproducibility, and do not explain its meaning (Elbel, 1949; Hosler and Morrow, 1982).

body part	force		study	retest correlation	coefficient of reliability
arm	pull	maximal	Hazelton et al. (1975)	.69 to .99	
		maximal	Caldwell (1964b)	.93	
		endurance		.81	
		endurance	Caldwell (1963)	.79	
	push	maximal	Caldwell (1962)	.96 to .99*	
	elbow flexion	maximal	Start and Graham (1964)	.94	
		endurance		.83	
		endurance	Carlson (1969)	.60 to .68	
hand	grip	maximal	Mathiowetz et al. (1984)	.79 to .92	
	various pinches	maximal		.52 to .87	
	torque	maximal	Arnold (1991)	.98	
		comfortable		.97	
	various forces	maximal	Steenbekkers (1993)	.86 to .97	
leg	leg and hip extension	maximal	Elbel (1949)		.93 to .97
		endurance			.68
whole body	various arm and leg forces	maximal	Hosler and Morrow (1982)		all > .90
	pull	peak maximum	Fothergill et al. (1992)	.88	
		steady maximum		.91	

Table 3-1: Reproducibility of forces (maximal and comfortable) and endurance times of submaximal force, found by various researchers.
** Correlations per subject, 25 measurements with different elbow angles and different back support heights.*

Specificity and generality. Generality is defined by Laubach (1978) as the percentage of variance of data accounted for by variable X, and is determined by r^2 (the square of the coefficient of correlation between the data measured with various settings of variable X). Specificity is the percentage of variance accounted for by other variables than X and is determined by $1 - r^2$. A correlation coefficient of at least 0.71 is required to show more generality than specificity, so that the variance explained by variable X ($r^2 * 100$) is 50 % or more. Laubach remarks that forces, even when exerted by the same subjects, do not correlate well. He quotes Whitley and Allan (1971), who pointed out "... that individual differences in static strength ability demonstrate more specificity than generality". It is suggested that, because of the low correlations between forces in general and consequently the low generality and high specificity, information generally has to be gathered experimentally rather than computed from other force data.

body part	force		study	subjects' age	ratio female/male strength
arm	elbow flexion	eccentric	Singh and Karpovich (1968)	18 - 35 yrs.	41 - 51 %
		concentric	Singh and Karpovich (1968)	18 - 35 yrs.	35 - 46 %
		static	Singh and Karpovich (1968)	18 - 35 yrs.	39 - 47 %
			Kahn and Monod (1984)	19 - 35 yrs.	71 - 74 %
			Kroll et al. (1990)	17 - 28 yrs.	54 %
	elbow extension	eccentric	Singh and Karpovich (1968)	18 - 35 yrs.	41 - 51 %
		concentric	Singh and Karpovich (1968)	18 - 35 yrs.	42 - 53 %
		static	Singh and Karpovich (1968)	18 - 35 yrs.	39 - 52 %
			Kroll et al. (1990)	17 - 28 yrs.	58 %
	one-arm curl	isotonic	Bishop et al. (1987)	15 - 28 yrs.	37 - 57 %
	bench press	isotonic	Bishop et al. (1987)	15 - 28 yrs.	46 - 57 %
	pull (one hand)	static	Hallbeck et al. (1990)	20 - 30 yrs.	63 %
			Steenbekkers (1993)	4 - 12 yrs.	77 - 93 %
	push (one hand)	static	Steenbekkers (1993)	4 - 12 yrs.	79 - 89 %
hand	grip strength	static	Swanson et al. (1970)	17 - 60 yrs.	42 - 63 %
			Kellor et al. (1971)	20 yrs.	50 - 51 %
				70 yrs.	55 - 58 %
			Page (1981)	≤ 74 yrs.	42 %
				≥ 75 yrs.	19 %
			Mathiowetz et al. (1985)	20 - 74 yrs.	55 - 66 %
				≥ 75 yrs.	65 - 68 %
			Mathiowetz et al. (1986)	6 - 13 yrs.	88 - 97 %
				14 - 19 yrs.	66 - 77 %
			Bishop et al. (1987)	15 - 28 yrs.	62 - 67 %
			Fransson and Winkel (1991)	18 - 60 yrs.	66 - 75 %
			McMullin and Hallbeck (1991)	20 - 65 yrs.	76 %
			Steenbekkers (1993)	4 - 12 yrs.	81 - 95 %
	wrist flexion	static	Hallbeck (1990)	20 - 30 yrs.	76 %
	wrist extension	static	Hallbeck (1990)	20 - 30 yrs.	72 %
	torque	static	Berns (1981), comfortable	20 - ≥ 71 yrs.	53 - 68 %
			maximal		66 - 70 %
			Pheasant (1983)	students	58 - 93 %
			Mital and Sanghavi (1986)	mean 22 yrs.	66 %
			Imrhan and Loo (1988)	60 - 97 yrs.	77 %
			Steenbekkers (1993)	4 - 12 yrs.	75 - 94 %
fingers	chuck or palmar pinch	static	Swanson et al. (1970)	17 - 60 yrs.	50 - 74 %
			Kellor et al. (1971)	20 yrs.	67 - 69 %
				70 yrs.	51 - 57 %
			Mathiowetz et al. (1985)	20 - ≥ 75 yrs.	63 - 80 %
			Mathiowetz et al. (1986)	6 - 13 yrs.	90 - 99 %
				14 - 19 yrs.	78 - 85 %
			Brorson et al. (1989)	21 - 65 yrs.	71 - 72 %
			Berg et al. (1988)	20 - 42 yrs.	72 %
			Hallbeck and McMullin (1991)	20 - 65 yrs.	77 - 81 %
	three-point pinch	static	Kellor et al. (1971)	20 and 70 yrs.	60 - 63 %
	pulp pinch	static	Swanson et al. (1970)	17 - 60 yrs.	65 - 74 %
	tip pinch	static	Mathiowetz et al. (1985)	20 - ≥ 75 yrs.	62 - 76 %
			Mathiowetz et al. (1986)	6 - 13 yrs.	86 - 103 %
				14 - 19 yrs.	75 - 83 %
			Berg et al. (1988)	20 - 42 yrs.	72 %
			Brorson et al. (1989)	21 - 65 yrs.	71 - 72 %
			Steenbekkers (1993)	4 - 12 yrs.	76 - 94 %
	lateral or key pinch	static	Swanson et al. (1970)	17 - 60 yrs.	64 - 71 %
			Kellor et al. (1971)	20 and 70 yrs.	59 - 63 %
			Mathiowetz et al. (1985)	20 - ≥ 75 yrs.	60 - 75 %
			Mathiowetz et al. (1986)	6 - 13 yrs.	85 - 93 %
				14 - 19 yrs.	74 - 77 %
			Berg et al. (1988)	20 - 42 yrs.	68 %
	key pinch torque	static	Steenbekkers (1993)	4 - 12 yrs.	86 - 98 %
	push with forefinger	static	Steenbekkers (1993)	4 - 12 yrs.	80 - 96 %
	pull with thumb & foref.	static	Steenbekkers (1993)	4 - 12 yrs.	84 - 99 %
legs	leg press	isotonic	Bishop et al. (1987)	15 - 28 yrs.	63 - 73 %
	one-leg extension	isotonic	Bishop et al. (1987)	15 - 28 yrs.	66 - 76 %
whole body	lift	static	Lee and Bruckner (1991)	18 - 28 yrs.	49 - 55 %
			Sanchez and Grieve (1992)	?	av. 70 %
	pull-up	dynamic	Mital and Genaidy (1989)	20 - 31 yrs.	av. 46 %
	pull, push, lift and press	static	Fothergill et al. (1991)	mean 31 yrs.	50 - 83 %
	pull		Fothergill et al. (1992)	mean 30 yrs.	60 - 88 %

Table 3-2: Sex differences found in literature.

3.2 Subject variables

3.2.1 Sex

It is generally known and has often been shown that on average males are stronger than females. An overview of some ratios of mean female to mean male strength found in experiments is given in table 3-2. Figures 3-5 and 3-6 of Hettinger (1968) and Knook (1982) indicate the influence of both sex and age.

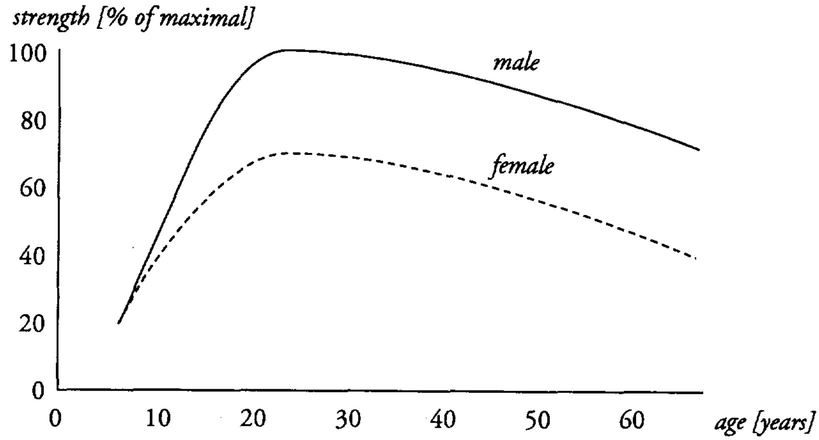


Figure 3-5: The influence of age and sex on maximal muscle force exertion (after Hettinger, 1968, after various researchers).

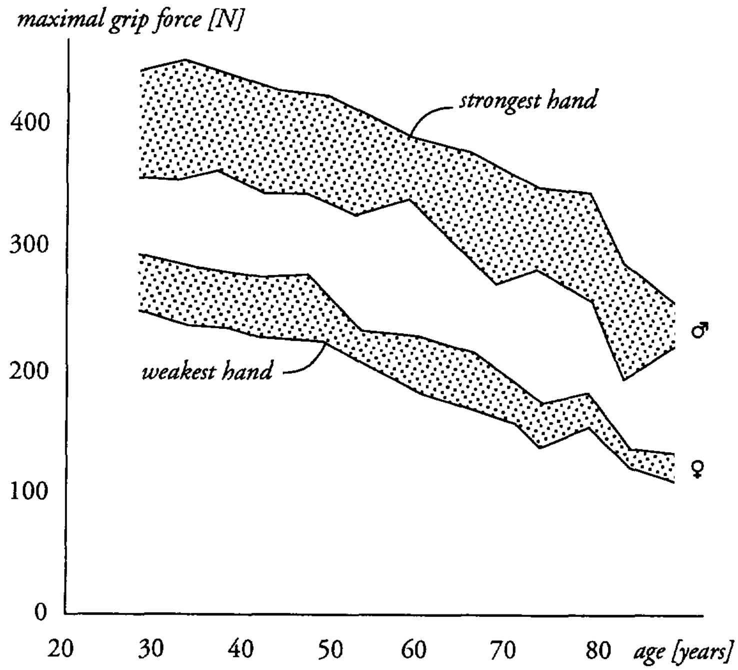


Figure 3-6: The influence of age and sex on maximal grip force (after Knook, 1982).

Imrhan and Loo (1988) found that sex explains 7 % of the variation in torque force in elderly people. Hosler and Morrow (1982), using regression analysis, found that sex accounts for 60 % of arm strength and 74 % of leg strength variance in isokinetic force. When body size and composition were added to the model, however, sex accounted only for an additional 2 % (arm) and 1 % (leg) of the variance. So although males and females differ significantly in strength, the effect of gender is small after allowing for body size and composition. Fransson and Winkel (1991) measured maximal grip force and found that about 35 % of the sex difference in hand strength was due to hand size differences. The findings of Bishop et al. (1987) suggest that the sex difference in muscular strength in equally trained men and women is almost entirely accounted for by the difference in muscle size. Fat Free Weight and limb Fat Free Cross Sectional Area are probably more valid criteria for the prediction of strength than sex. Lifting strength at different heights, reaches and angles was investigated by Sanchez and Grieve (1992). When strength was expressed as a fraction of body weight, and height and reach were expressed as fractions of stature, predictive equations were obtained which were 'gender free'.

Lee and Bruckner (1991) found that, although women exerted on average 49 to 55 % of the strength of men, lifting strength hardly correlated with sex, r being 0.38.

Dynamic force. Van Ingen Schenau and De Groot (1983) found that during 'supra-maximal' cycling female and male ice skaters generated equal power per kilogram body weight. Laubach (1976), cited by Bishop et al. (1987), reviewed nine articles and concluded that differences in exerted force due to sex are equal for static and dynamic force, female static force being 56 - 72 %, dynamic force being 69 % of male force. After assessment of isokinetic lifting force, Mital and Genaidy (1989) concluded, however, that sex difference may become more pronounced with dynamic exertions.

Muscle groups. Hafez et al. (1982) studied static and dynamic elbow flexion, shoulder flexion, shoulder abduction, lower back extension, hip extension and knee extension. Each was tested statically and isokinetically (making rotating movements at 5 and 25 rpm). Overall, female torque equals 52.6 % of male torque. Generally, differences are larger for the upper extremities and smaller for the trunk and lower extremities.

Endurance. There is no agreement on the influence of sex on the endurance of relative force. Caldwell (1963) found no significant difference. Both Petrofsky and Lind (1975a) and Byrd and Jeness (1982) found that women endure the same percentage of maximal force for longer periods than men. Kahn and Monod (1984) also found that women endured longer than men in all situations, though this was significant in only half of the cases. Caldwell found that the 'total output' (absolute force * maximal endurance time) was approximately twice as great for males as it was for females.

Handbooks. In some handbooks, rules of thumb are given for the ratio female/male maximal force, without a scientific justification. According to Rohmert and Hettinger (1963) the female/male force ratio is on average 0.67, but through physical training the difference between females and males can decrease. Hettinger (1968) gives the female/male force ratios for 18 different muscle groups, which vary from 55 % for elbow extensors to 80 % for chewing muscles. VanCott and Kinkade (1972) say that at 30 years a woman's strength is approximately 2/3 that of a man, it declines more rapidly with age and at 50 years a woman is about half as strong as a man. Burandt (1978) claims that young women can exert 60 % and older women 40 % of the force exerted by young men. Laubach (1978) gives an overview which is reproduced in figure 3-7. Woodson (1981) states that women in general have 2/3 the strength of men. Eastman Kodak (1986) gives a table with female/male ratios for various hand and arm forces. They range between 52 % and 78 %.

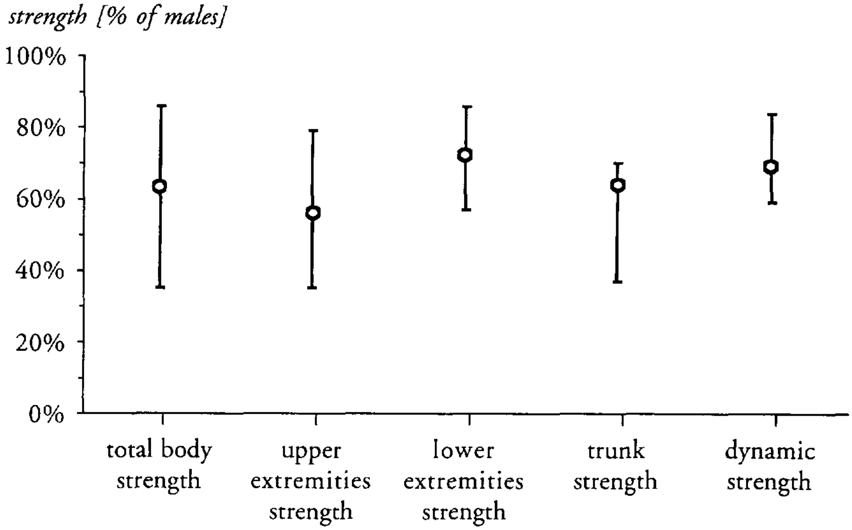


Figure 3-7: An overview of the range and average mean percentage differences in muscle strength between males and females (after Laubach, 1978).

Conclusion. Differences in exerted force due to sex seem to be roughly equal for static and dynamic force. There appears to be no sex difference in muscle performance, and strength can better be predicted by body size and composition than by sex. Still, there is a considerable difference in maximal force exerted on average by women and men. The ratio of mean female to mean male maximal force varies between 35 % and 88 % for various adult subject groups (with one exception of 107 % in table 3-2), between 19 % and 68 % for elderly people over 75 years of age, and between 74 % and 103 % for children. It is suggested that the female/male ratio for forces exerted with the upper extremities (arms and hands) is lower than that for forces exerted with the trunk and lower extremities. However, the diversity of the ratios and the scarcity of literature on lower extremities make a definite conclusion difficult. The ergonomic handbooks may be not too far off with their estimate that the physical strength of women is 1/2 to 2/3 of that of men.

3.2.2 Age

Human strength increases with age in children, and declines with age in elderly people. Most literature on strength and age covers force exertion of adults and elderly, few articles on the physical strength of children were found.

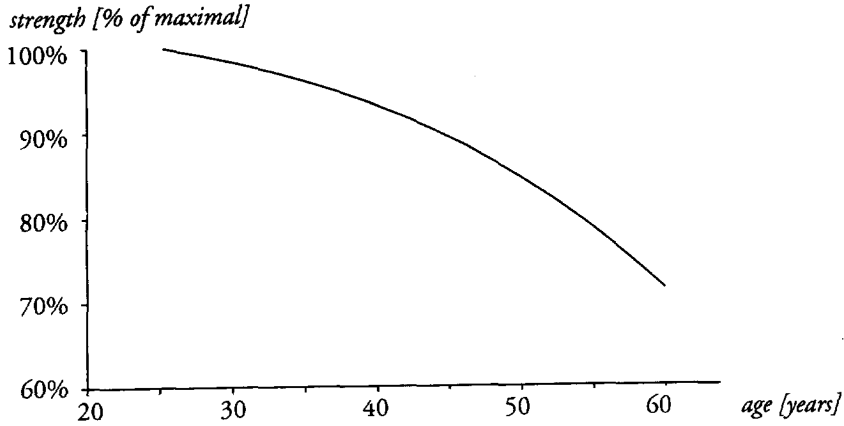


Figure 3-8 The influence of age on maximal muscle force exertion (after Rohmert and Hettinger, 1963, after various researchers).

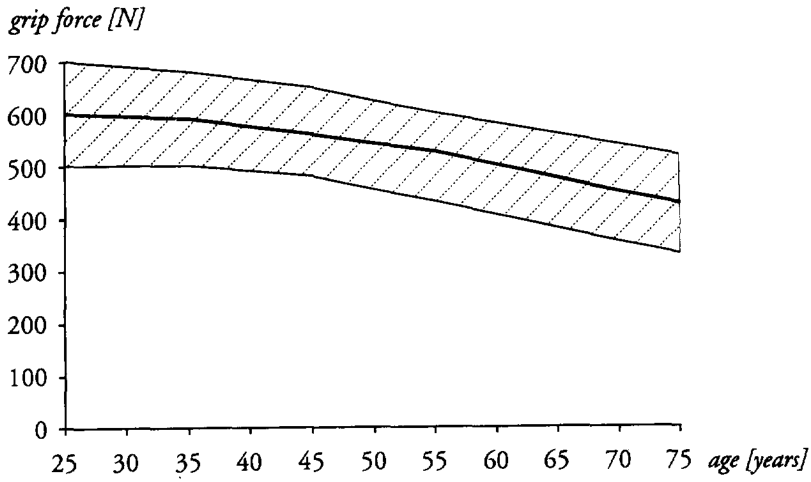


Figure 3-9: The influence of age on maximal grip force of males (after Dean, 1988, after Damon et al., 1972).

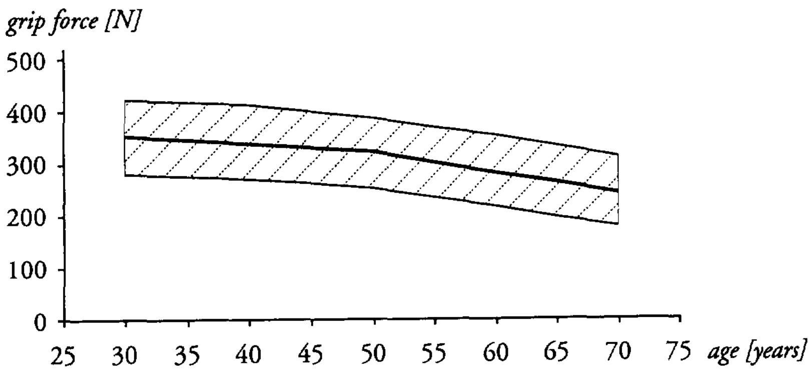


Figure 3-10: The influence of age on maximal grip force of females (after Dean, 1988).

The relation between age and strength found by Hettinger (1968) and Rohmert and Hettinger (1963) can be seen in figures 3-5 and 3-8, the relation between age and maximal grip force found by Knook (1982), Damon et al. (1972) and Dean (1988) can be seen in figures 3-6, 3-9 and 3-10 respectively. Coefficients of the correlation between exerted maximal force and age from different experiments are gathered in table 3-3. Most correlations are not significant. Imrhan and Loo (1988) measured subjects between 60 and 97 years and found that, although wrist twisting strength declines with age, age explained only 9 to 20% of the total variation, which is not enough to make a good single predictor for strength. Kellor et al. (1971), measuring hand forces of subjects aged 18 to 89, hypothesized that curvilinear relations exist between maximal strength and age. They found, however, that their data were represented quite adequately by linear equations, and deviations from linearity were determined to be of no statistical significance. Lusa et al. (1991) measured peak torques for back extension and knee extension of younger (32 years, s = 2) and older (47 years, s = 5) firemen. They were not significantly different for the two age groups.

body part	force	study	subject age	correlation force/age*
arm	elbow flexion	Deeb et al. (1992)	20 - 59 yrs.	n.s.
hand	grip strength	Dirken (1972)	male, 30 - 70 yrs.	0.49
		Petrofsky and Lind (1975a)	male, 20 - 59 yrs.	n.s.
			female, 20 - 59 yrs.	0.50
		Petrofsky and Lind (1975b)	22 - 62 yrs.	n.s.
		Churchill et al. (1978)	female, av. 23 yrs. (s = 6.5)	0.15
			av. 30 yrs. (s = 6.3)	-0.03
			male, av. 28 yrs. (s = 4.2)	0.16
		Mathiowetz et al. (1985)	20 - ≥ 75 yrs	-0.61 to -0.6
		Kallman et al. (1990)	20 - 89	partial $r^2 = 0.38$
		McMullin and Hallbeck (1991)	20 - 65 yrs.	n.s.
	pinch	Mathiowetz et al. (1985)	20 - ≥ 75 yrs	-.025 to -.05
	tip pinch	Brorson et al. (1989)	21 - 65 yrs.	-0.31 to -0.5
	chuck pinch	Hallbeck and McMullin (1991)	20 - 65 yrs.	n.s.
	various pinch forces	Imrhan and Sundararajan (1992)	22 - 39 yrs.	n.s.
	various forces	Steenbekkers (1993)	4 - 12 yrs.	0.51 to 0.87
leg	leg strength	Elbel (1949)	av. 22 yrs.	n.s.
	knee extension	Deeb et al (1992)	20 - 59 yrs.	n.s.
whole body	lift	Lee and Bruckner (1991)	18 - 28 yrs.	n.s.
	push and pull	Frank et al. (1985)	5.5 - 8.5 yrs.	0.35 to 0.56
			10 - 13 yrs.	n.s.

* *n.s. = not significant*

Table 3-3: Correlations between age and maximal force exertion.

The age span during which force is maximal and relatively stable is quite large. Swanson et al. (1970) found that the maximal grip strength of men remains constant between 20 and 50 years of age, while the strength of women is maximal between 30 and 40 years. Mathiowetz et al. (1985) measured the highest grip strength between 25 and 39 years, while pinch strength was relatively stable between 20 and 59 years and declined from 60 to 79 years. According to Kallman et al. (1990), grip strength increases into the thirties and declines at an accelerating rate after 40. Arnold (1991) found that women over 65 years of age exerted 63 to 67 % of maximal, and 64 to 82 % of comfortable, torque exerted by women aged between 18 and 65. Kroll and Clarkson (1978) studied isometric knee extension for two age groups. Subjects aged 55 to 79 years exerted on average 57 % of the maximal force exerted by subjects aged 18 to 28.

Sex. VanCott and Kinkade (1972) state that the strength of women declines more rapidly with age than that of males. The results of Kellor et al. (1971), on the other hand, indicated that men lose grip strength at a greater rate than women. Page (1981) measured grip strength and found that women of 75 years and older exerted on average 32 % of the force exerted by younger women, 65 to 75 years old. For males this percentage was 71 %.

Mathiowetz et al. (1986) found that for ages 6 to 19, males are stronger than females in all age groups. For ages 6 to 13, male and female scores increase at a parallel rate. However, the scores of 14 to 19 year old males increases rapidly, whereas the scores of females of the same age increased only slowly (see table 3-2). Bovend'eerdt (1980) found a similar effect with pulling strength of children aged 12 to 18. Malina and Bouchard (1991) quote from various sources. According to their information, grip strength, pulling strength of shoulders, biceps strength and quadriceps strength is slightly larger for boys than for girls. The maximal forces exerted increase equally with age for both groups until 12 or 13 years, after which boys' strength increases more rapidly. The results of Steenbekkers (1993) with various hand forces of children aged 4 to 12 years confirmed their findings.

Endurance. No change of maximal endurance with age was found by Elbel (1949), Petrofsky and Lind (1975a and 1975b) and Larsson (1978). It must be noted that the subjects of Elbel were military students, so probably they covered only a small age range. The subjects of Petrofsky and Lind were aged 20 to 59 and 22 to 62 years respectively, those of Larsson 10 to 65 years. However, in an experiment of Deeb et al. (1992) with subjects aged 20 to 59 years, older adults showed significant longer endurance than younger subjects at 40 and 60 % of maximal force.

Children. Brooks et al. (1974) measured hand twisting strength of twelve children. Their average maximal force increased from 1.5 Nm at 4 years to 4.27 Nm at 10 years of age.

Mathiowetz et al. (1986) measured grip and pinch strengths of children aged 6 to 19. Average maximal grip strength ranged from 122.9 N for the left hand of 6 - 7 year old girls, to 489.9 N for the right hand of boys at age 18 - 19. Average maximal tip pinch ranged from 27.7 to 77.1 N, key pinch ranged between 41.3 and 106.6 N and palmar pinch between 38.1 and 108.0 N.

Bovend'eerdt et al. (1980) investigated pulling strength with one arm, and found that maximal strength of boys increased rapidly from approximately 330 N at 12 to 670 N at 18 years, while girls' strength increased slowly from 305 to 425 N in the same period. The force that could be generated per kg body weight increased with age for boys, and was fairly constant for girls.

Frank et al. (1985) categorized children in two age groups: 5.5 to 8.5 years and 10 to 13 years. When pulling and pushing, sitting with support for the back and the feet, the group with older children exerted on average 1.5 to 1.7 as much maximal force as the group of younger children. Push force of the 5th percentiles are 96 and 163 N, pull force of the 95th percentile are 509 and 836 N respectively for the younger and the elder group.

Malina and Bouchard (1991) investigated the stability of strength over a longer period of time. 'Stability' here refers to the relative position of a child within his or her age and sex group over a period of time. They found that the correlations between measurements taken at 5 to 6 year intervals range from about 0 to 0.65. Correlations between forces at 7 and 12 years tend to be lower than those between 12 and 17 years. Stability of strength tends to be slightly better for the lower extremities than for the upper extremities.

Steenbekkers (1993) measured various maximal hand forces of children aged from 4 to 12 years. She found that boys are on average slightly stronger than girls (see table 3-2). This ratio has no specific tendency to increase or decrease with age within that period. From 4 to 12 years, average forces increase with a factor 2.3 to 4.6.

Handbooks. Morgan et al. (1963) found in literature that strength reaches a maximum by the middle to late 20's, remains at this level for 5 - 10 years, and thereafter declines slowly but continuously. By the age of 40, muscle strength is approximately 90 - 95 % of the maximum, by age 50 it is about 85 % and by 60 about 80 %. Not all muscle strength, however, declines with age at the same rate. Hand grip seems to be relatively stronger in later years than other types of muscular performance, and the strength of the back muscle drops faster with age than that of either the hands or the arms.

VanCott and Kinkade (1972) found in literature that strength reaches a maximum for men between 25 and 30 year, and will stay at that level for 5 to 10 years, after which it gradually declines. At 40 years, strength is 95% of the maximum, between 50 and 60 years it is 80 %. Women attain maximal strength between 20 and 25 years and stay at that level for about 10 years. Muscle-strength decrease does not proceed at the same rate in all parts of the body. Force capabilities of hand and arm are less affected by age than those of trunk and leg.

Burandt (1978) states that old men exert 80 % of the force of young men, old women 2/3 of that of young ones. Ages are not specified. Woodson (1981) says that individuals have maximum strength between the ages of 30 and 40. At 40, people begin to lose about 10 % of their strength, 15 percent by age 50, 20 % by age 60 and at least 25 % by age 65. Lange (1991) shows a graph of the influence of age on maximal force, based on the graph of Hettinger (1968) (see figure 3-5). According to Sanders and McCormick (1993), the decline of maximal force by age varies for various muscle groups (figure 3-11)

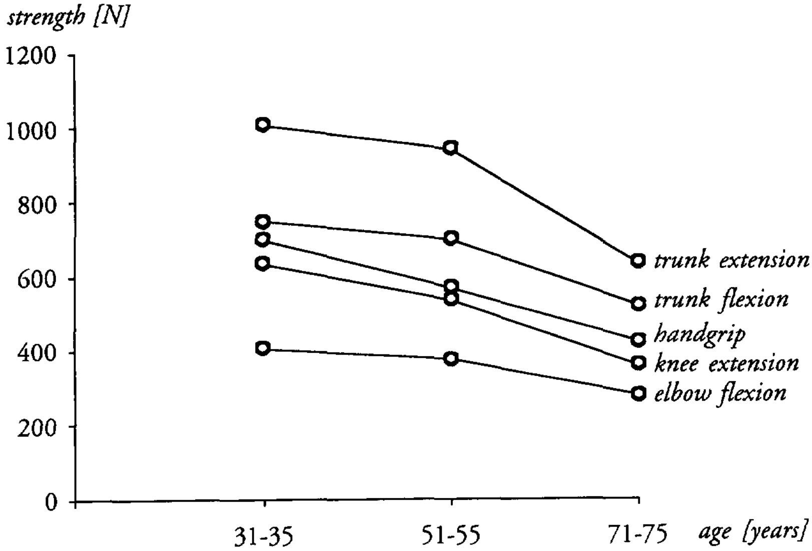


Figure 3-11: Maximal isometric strength for five muscle groups as a function of age (cross-sectional study) (after Sanders and McCormick, 1993, after Viitasalo, Era, Leskinen and Heikkinen, 1985).

Conclusion. The correlation between age and maximally exerted force is generally not very high. Consequently, age will not be a good single predictor of strength. Maximal strength may be attained between 20 and 30 years (which corresponds with the optimum of the biological age curve at mid-twenty), it may be relatively stable between 20 and 59 years and it may start to decline between approximately 35 and 60 years, but there is no close agreement on the exact ages. Neither is there agreement on how rapidly strength declines with age, whether the relation is linear or curved and whether the decline differs for men and women. It is agreed, however, that various muscle groups decline at different rates. No quantification of this last aspect is given.

3.2.3 Anthropometric variables

The results of research into the correlation between maximal force and body size, body weight and other forces is summarized in table 3-4. Elbel (1949) correlated maximal leg strength with, among other things, total leg length, lower leg length and sitting height, and found that r was sometimes significant but never exceeded 0.29.

force	study	subjects	correlation of force(s) with body height	body weight	each other
arm pull	Caldwell (1964a)	males, av. 20 yrs.	0.50 to 0.57	0.40 - 0.46	
elbow flexion and extension	Kroll et al. (1990)	females, 17 - 28 yrs.		0.35 - 0.59	0.82
		males, 17 - 28 yrs.		0.24 - 0.69	0.55
grip	Churchill et al. (1978)	females, av. 23 yrs.	0.3	0.36	
		av. 30 yrs.	0.32	0.37	
		males, av. 28 yrs.	0.33	0.43	
	Molenbroek et al. (1987)	females and males, 50 - 110 yrs.	0.58	0.42	
grip, elbow flexion and extension	Roberts et al. (1959)	young males	0.44 to 0.48	0.42 - 0.68	0.31 to 0.63
torque	Imrhan and Loo (1988)	females and males, 60 - 97 yrs.	up to 0.25	up to 0.28	
torque	Mital (1986)	females and males, 21 - 29 yrs.		0.17	
torque and shoulder strength					0.22
torque and arm strength					0.21
push, pull, grip and torque of hand and fingers	Steenbekkers (1993)	girls and boys, 4 - 12 yrs.			0.58 to 0.86
		corrected for age and sex			0.29 - 0.72
grip, tip- key- and palmar pinch	Mathiowetz et al. (1985)	females, 20 - >75 yrs.			0.58
		males, 20 - >75 yrs.			0.57
finger pinches, finger pulls and handgrip	Imrhan and Sundararajan (1992)	males, 22 - 39 yrs.	0.25 to 0.72	0.46 - 0.63	0.32 to 0.86
finger pinches			0.39 to 0.58	0.46 - 0.55	0.73 to 0.86
finger pulls			0.25 to 0.35	0.50 - 0.63	0.69 to 0.76
knee extension	Elbel (1949)	males, av. 22 yrs.	n.s. to 0.30	0.43 - 0.64	
	Maughan et al. (1982)	males, 20 - 36 yrs.		0.47	
knee extension, dynamic	Dibrezzo et al. (1991)	females, 18 - 36 yrs.		0.40 - 0.60	0.76 to 0.99
knee flexion, dynamic	Dibrezzo et al. (1991)	females, 18 - 36 yrs.		0.20 - 0.60	0.64 to 0.95
push/pull with whole body	Frank et al. (1985)	girls and boys, 5.5 - 8.5 yrs.	0.46 to 0.58	0.38 - 0.56	0.55 to 0.83
		girls and boys, 10 - 13 yrs.	0.44 to 0.66	n.s. - 0.49	0.56 to 0.83
lift while standing, sitting and lying	Chomcherngpat et al. (1989)	females and males, 18 - 28 yrs.	n.s.	n.s.	
	Lee and Bruckner (1991)	females and males, 18 - 28 yrs.			0.79 to 0.91
		genders separately			0.47 to 0.86
various forces	Malina and Bouchard (1991)	girls and boys to 12 yrs.			

Table 3-4: Correlations of maximal forces with each other and with body height and body weight. n.s. = not significant

Maximal grip force and elbow flexion and extension were correlated by Roberts et al. (1959) with, amongst others, upper arm length, forearm length, hand length, upper arm girth and forearm girth. Of the 15 correlation coefficients, 13 were significant at $p < 0.05$ (of which 12 also at $p < 0.01$) and ranged from 0.34 to 0.70.

Churchill et al. (1978) correlated grip strength and many anthropometric variables for various populations. All correlations they found demonstrated more specificity than generality For airforce women, the values of r ranged between -0.02 and 0.43, for flying personnel they ranged between 0.005 to 0.52, and for male basic trainees between 0.02 to 0.59.

Caldwell (1964a) correlated arm pull strength with upper arm length (not significant), forearm length ($r = 0.31$ to 0.38), upper arm girth (0.31 to 0.32) and forearm girth (0.37 to 0.43).

Correlations of pinch strength and finger length by Weiss and Flatt (1971) are found to be significant and positive and vary between 0.34 and 0.66.

Kroemer (1977), referring to Kroemer and Laubach (1972), states that the correlations between maximal forces and anthropometric variables are in general small, only 1 % of the correlation coefficients is greater than 0.7. For correlations of maximal forces with each other, this is 2 %. So most of those correlations demonstrate more specificity than generality.

Janda et al. (1987) measured grip strength and hand sizes, and found that persons with larger hands generated greater maximal forces.

Imrhan and Loo (1988) investigated wrist-twisting strength of the elderly. Their wrist-twisting strength correlated stronger with other forces that were measured than with other anthropometric measurements. Hand grip explained 41 - 67 % of variance, chuck pinch 31 - 48 % and lateral pinch 30 - 51 %.

Hallbeck (1990) found no significant correlations between maximal forces (wrist flexion and extension force) and the following anthropometric variables: forearm length, distal and proximal forearm circumferences, wrist breadth, wrist thickness, wrist circumference, hand breadth, hand length and active range of motion of the wrist.

Several lengths, girths and volumes of parts of the arm are correlated by Kroll et al. (1990) with maximal isometric elbow flexion and extension, for both sexes separately. The correlation coefficients are more often significant for females than for males, at $p < 0.05$ 20 out of 26 r values are significant (of which 16 even at $p < 0.01$) for females, and only five for men. The correlations with lengths range between -0.38 and 0.60, those with girths between 0.01 and 0.80 and those with volumes between -0.07 and 0.78.

Body composition. Petrofsky and Lind (1975a) investigated the relation between grip strength and a weight factor. The weight factor had been demonstrated to be a satisfactory index of body fat content. The relation was positive, which would mean that people with overweight are stronger. Hosler and Morrow (1982) added body size and body composition to an analysis of variance in order to explain arm and leg strength. Those variables explained 63 % of arm and 78 % of leg strength variance. A comparison by Dibrezzo et al. (1991) of dynamic knee flexor and extensor strength with body fat percentage (calculated from skinfold measurements) yielded no significant correlations.

Larsson (1978) found significant correlations (r = 0.44 to 0.54) between strength and fast twitch fibre area. Strength of the arm flexor was found by Ikai and Fukunaga (1968) to be fairly proportional to the cross-sectional area of the upper arm flexor, regardless of age and sex. According to Maughan et al. (1982), strength correlated with lean body mass r = 0.53 and with muscle cross-sectional area also r = 0.53. Kallman (1990) found that grip strength correlated with muscle mass as r = 0.60. Muscle cross-sectional area, investigated by Häkkinen and Häkkinen (1991), correlated with maximal leg extension with r = 0.82. Bishop et al. (1987) also assessed the correlation between muscle cross-sectional area, with arm and leg strengths. The r values they found varied between 0.74 and 0.89 for swimmers, and between 0.82 and 0.91 for non-athletes. Correlation of the same strengths with fat free weight resulted in r values of between 0.77 and 0.85 for swimmers, and between 0.86 and 0.93 for non-athletes.

Force exerted per cm^2 muscle. The maximal force that could be exerted by muscles varied for individuals between 40 to 80 N/cm^2, according to Ikai and Fukunaga (1968). There was no difference between ordinary and trained subjects. Häkkinen and Häkkinen (1991) found mean values ranging from 45.4 to 47.6 N/cm^2, with standard deviations up to 7.0 N/cm^2. There were no significant differences between various age groups.

Endurance. The correlation between maximal force exertion and endurance of a submaximal force was found by Caldwell (1964b) to be 0.76. Elbel (1949) calculated the same correlation for leg strength and found that r was significant and varied between 0.26 and 0.40. Dibrezzo et al. (1991) calculated the correlations between body weight and a dynamic endurance ratio (the last four of 20 repetitive exertions divided by peak torque of the first four) and found that they were very low, ranging from r = 0.20 to r = 0.20 (sic!).

Aerobic capacity. The correlation found by Dirken (1972) between static grip strength and maximum aerobic capacity measured on a bicycle ergometer was 0.48.

Handbooks. Woodson (1981) states that, as a rule, people with larger body builds have more strength. Morgan et al. (1963) remarked that body build is markedly related to strength. Fisher and Birren (1945) are quoted, who found that strength correlated significantly with height and weight, but at low levels (r = 0.2 to 0.5). According to Rohmert and Hettinger (1963; p. 9 and 10), the highest forces are exerted by people of the athletic type ("*Kräftig, sehnig, breite Schultern, muskulär, massiv, starker Knochenbau*[1]",), and the lowest forces by the leptosome type ("*Schlank, hoch afgeschossen, grazil, scharf-profiliert, dichtes Kopfhaar*[2]"). The forces exerted by the pyknic type ("*weiches, breites Gesicht auf kurzem, dickem Hals, starker Fettansatz, Mächtige Umfangentwicklung, geringe Schulterbreite, spärlicher Haarwuchs auf schön gerundetem Schädel*[3]") range between those exerted by the other types. VanCott and Kinkade (1972) also state that body build is

---

1 Strong, sinewy, broad-shouldered, muscular, strong-boned.
2 Slim, tall, gracious, sharp-featured, with a thick head of hair.
3 Soft, broad face on a short thick neck, strong fat deposition, impressive girth, narrow shoulders, sparse hair on a round skull.

related to strength and significant but often low correlations have been found between strength and body weight, circumferences and lengths. Schmidtke (1981) too, recognizes the influence of body weight and height on muscle performance, which is all the information they give.

Conclusion. The linear relation between maximal force exertion and body height and weight is in general significant but not very high, except for children. Correlations between different maximal forces vary enormously. Correlations can be enhanced by the combination of male and female data. Correlation may also depend on the comparison of actions of the same muscle group (pinch forces, or lifting strengths) or of slightly different ones (e.g. torque compared with shoulder strength). The correlations between exerted force and various data on body composition vary between 0.44 and 0.93. The best correlations are those with muscle cross-sectional area, with values of r ranging from 0.53 to 0.93.

3.2.4 Laterality

Arm. Singh and Karpovich (1968) measured eccentric, isometric and concentric force exertion of elbow flexors and extensors between 50° and 140° elbow flexion. There was no difference in strength between the preferred and the non-preferred arm, except for isometric contraction of flexors at 50° and concentric contraction of extensors at 90°, where the preferred arm was stronger.

Hand. The effect of laterality for grip and pinch strength was investigated by various researchers. Their results are summarized in table 3-5. All subjects were adults. Steenbekkers (1993) measured children aged 4 to 12. She investigated push, pull, grip and torque of both fingers and the whole hand. The only systematic and significant differences for preferred and non-preferred hand occurred during pushing with the forefinger and grip of fingers and of the whole hand. These differences were not very large, though.

Foot. Graham and Garbutt (1993) investigated isokinetic plantar and dorsal flexion, and inversion and eversion of the foot. They found no significant differences ($p < 0.05$) between the forces exerted by the foot on the side of the preferred hand and those exerted by the other foot. Only for plantar flexion and eversion at the end of the range of motion (-15° and -20° respectively), the foot on the non-preferred side exerted significantly more force. This corresponds with the common phenomenom of cross-dominance of upper and lower extremities.

Handbooks. According to Rohmert and Hettinger (1963), the differences between forces exerted by left and right side are within the normal variation of the data. Therefore it is not necessary to discriminate between the left and the right side. Morgan et al. (1963) quote several studies and conclude that in general, the preferred side is the stronger. VanCott and Kinkade (1972) say that handedness has relatively little effect on strength and working capacity. For practical purposes, the slight differences of the two sides of the body can be neglected. According to Schmidtke (1981), the left hand can exert on average only 96 % of the force exerted by the right hand.

Conclusion. The difference in strength between the preferred and the non-preferred side of the body ranges between 'not significant' and the non-preferred side exerting 87 % of the strength of the preferred side.

body part	force	study	subjects	ratio non-preferred/ preferred
arm	elbow flexion and extension	Singh and Karpovich (1968)		n.d.*
hand	grip	Swanson et al. (1970)	females	0.91
			males	0.95
		Mathiowetz et al. (1985)	females	0.87
			males	0.93
		McMullin and Hallbeck (1991)		0.94
	pinch (various)	Swanson et al. (1970)	females	0.94
			males	0.96
		Mathiowetz et al. (1985)	females	0.96
			males	0.96
		Brorson et al. (1989)	females	0.89
			males	0.89
		Hallbeck and McMullin (1991)		0.94
		Weiss and Flatt (1971)	children	n.d.*
	finger pull	Imrhan and Sundararajan (1992)		n.d.*
foot	flexion, inversion and eversion	Graham and Garbutt (1993)		n.d.*

** = no difference. See text for a few exceptions.*

Table 3-5: The influence of laterality on maximal force exertion.

3.2.5 Other personal characteristics

Many physical and psychological characteristics influence force exertion of the individual. The topics on which information is given here are found in literature. There may be more characteristics that influence force exertion, on which no information was found, e.g. experience, skill, dexterity, intelligence, social conditioning and character. The information is not summarized in a conclusion, given the many variables and the few articles found per variable.

Activity level, training and condition. Kroll and Clarkson (1978) investigated the difference in force exertion caused by a physically active and exercising lifestyle, compared to an inactive, more sedentary life. Isometric knee extension of active and inactive groups of subjects showed that the inactive groups exerted 80 to 95 % of the average force of the active groups, and the variation within the active groups was larger than in the inactive groups. Grip force of an active group of subjects and an inactive group was compared by Atkinson et al. (1993) at different times of the day. Only in one of the six times the groups differed significantly ($p < 0.05$), the inactive group being stronger than the active, contrary to expectations. Maximal isometric forces of five muscle groups were measured for three age groups by Era et al. (1992). Good self-rated health and the intensity of physical exercise during leisure were positively associated with muscle strength in the youngest and middle-aged groups, whereas in the oldest group the most important variable was home gymnastics.

Di Prampero et al. (1970) found no significant difference in aerobic and anaerobic power (measured by having subjects running up stairs and stepping up and down from a bench) relative to fat-free body weight, between Olympic athletes and ordinary people. The fat content of the athletes was significantly lower, though.

Handbooks: activity level, training and condition. The amount of training should be taken into account by multiplying maximal force with a factor 1 for the well-trained to 0.75 for the badly trained (Burandt, 1978). VanCott and Kinkade (1972) say that training or exercise can improve force and working capabilities significantly within the innate physical potential, which is obvious. Schmidtke (1981) also recognizes the influence of training, health and degree of fatigue on muscle performance, although no indication is given on the order of their effects. Hettinger (1968) states that various muscle groups differ in the extent to which the maximal force they can exert can be increased by training, varying from 1 % weekly improvement for finger flexors to more than 5 % weekly improvement for foot extensors. This 'trainability' varies for individuals, too.

Circadian rhythm. The influence of the circadian rhythm on maximal static force exertion is investigated by Swanson et al. (1970), Reilly and Hales (1988) and Atkinson et al. (1993). Swanson et al. reported no obvious differences between measurements in the morning and the afternoon, although this statement was not statistically analysed. Reilly and Hales found that grip strength was significantly better in the evening than in the morning ($p < 0.01$). The physically active group of Atkinson et al. showed 1.5 to 2.5 times greater rhythm amplitudes for, amongst others, grip strength than the inactive group ($p < 0.05$). Significant rhythms ($p < 0.05$) were found for left hand grip strength in both groups and for right hand grip strength of the active group, but not for the inactive group.

Drugs. Although the influence of drugs is not a personal characteristic, it is added here because it affects body functions, and thus the performance, of individuals. Grip strength was significantly higher under treatment of D-amphetamine than under treatment with chlordiazepoxide, with placebo or without drug. Estimated strength, obtained by having the subjects exert 70 % of their maximal strength and guess how much force they could exert maximally. did not differ significantly for the different treatments (Hurst et al., 1968). Caffeine has no effect on maximal dynamic force exertion and endurance, according to Jacobson and Edwards (1991). Three groups of subjects were pretested for strength, administered 600 mg caffeine, 300 mg or a placebo, and tested again after an hour. No significant effect on dynamic force or endurance was found.

Ethnicity. Di Prampero et al. (1970) measured aerobic and anaerobic power and found no difference between Negroid and Caucasoid athletes, except for a higher fat content in the latter. The maximal aerobic power output of African natives, investigated by Di Prampero and Cerretelli (1969), is not different from that of other ethnic groups per kg of fat-free body weight. The body fat percentage, however, is significantly lower in African natives, particularly in children. The maximal anaerobic power is lower in African natives, possibly because of a slightly different anatomy and geometry of the lower limb muscles.

Dean (1988) quotes Furukawa et al. (1975) and Borkan and Norris, who give a grip strength conversion scale for Caucasoid and Asian subjects, based on comparative age-adjusted data (see figure 3-12).

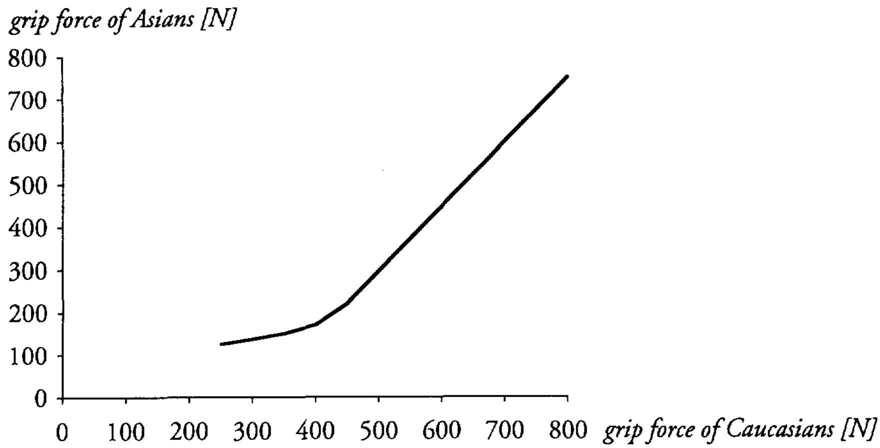


Figure 3-12: Maximal grip force conversion scale for caucasians and asians, based on comparative age-adjusted data (after Dean, 1988, after Furukawa et al. and Borkan and Norris).

Handbooks: hypnosis. Hettinger (1963) quotes Ikai and Steinhaus, who found that under hypnosis maximal elbow flexion force increased with as much as 30 % for 'normal' (not specially trained) individuals. For athletes, however, the force increased by only 10 %. According to Woodson (1981), strength may increase as much as 26 % under hypnosis

Menstrual cycle. Dibrezzo et al. (1991) found little or no effect of three different menstrual phases upon the relationships among body weight, percent body fat, dynamic knee extension and flexion force or endurance. The dynamic forces measured did not seem to differ for the different phases. Birch et al. (1993) found no significant effect of menstrual cycle phase on maximal isometric lifting strength, isometric endurance capacity, maximal dynamic lifting, self-chosen lifting capacity or the ratings of perceived exertion to any of these tasks.

Motivation. The motivation of subjects can be influenced by, amongst others, the amount of feedback (of the exerted force) that the subject receives. Peacock et al. (1981) studied isometric extension of the leg, with four conditions of feedback: no feedback, auditory feedback (with encouragement), visual feedback (the dial of the dynamometer being visible) and both visual and auditory feedback. The effects of feedback conditions were significant. The maximal forces exerted were least without any feedback; auditory and visual feedback at the same time showed an increase of about 10 % in maximal force. In between ranged force exerted with either auditory or visual feedback.

Handbooks: motivation. Hettinger (1963) quotes an experiment on the influence of motivation, in which the 'normal' maximal force exerted by male subjects was measured. A day later, the subjects were again asked to exerted maximal force after they had been told that others did better in the test. This time, their score was far better than the day before. The third day, an attractive female watched the proceedings. Again, the subjects scored better than on the first day. Woodson (1981) states that strength may increase under stress (i.e. fear, panic, rage, or even excitement), with the subject shouting, or when force exertion is preceded by a pistol shot.

Occupation. Male and female subjects were classified according to occupation by Swanson et al. (1970) in skilled, sedentary and manual. There were differences in exerted maximal grip and pinch force between the groups, skilled and sedentary workers exerted respectively 78 to 95 % and 68 to 99 % of manual workers' average maximal force. Statistical significance, though, was not calculated and the influence of possible, but not mentioned, body size variations between the groups was not discussed. Era et al. (1992) classified male subjects in manual workers and lower and higher white collar workers, and in three age groups as well. The subjects exerted maximal grip strength, trunk flexion and extension, elbow flexion and knee extension. Trunk extension, elbow flexion and knee extension were for an unreported reason combined to one score. Of all the group scores, occupation had only significant influence on trunk flexion of middle aged men.

Handbooks: occupation. Morgan et al. (1963) assure that white-collar workers are significantly weaker in muscle strength by some 10 - 20 % than manual workers, quoting research carried out between 1934 and 1952. Rohmert and Hettinger (1963) remark that training at work influences muscle force development, and that differences in strength are possibly caused by selection, too. Woodson (1981) states, too, that white-collar workers are generally about 10 - 20 % weaker than manual or blue-collar workers.

Pregnancy. The effects of pregnancy, resulting in change of body weight and body size, on manual handling and lifting were studied by Sinnerton et al. (1993). No significant changes in performance were found for an isometric endurance lift and a vertical and asymmetric dynamic lift, performed at 12 - 14 and at 18 - 20 weeks of gestation.

Sleep deprivation. For three nights, a group of subjects slept only 2.5 hours per night. Another group was used as a control. There was no effect of sleep deprivation on grip strength until the third evening of the experiment. However, the decline was not apparent on the final morning of testing. This observation would suggest a fall in motivation for muscular efforts, rather than a reduction in the ability to generate maximal muscular tension (Reilly and Hales, 1988).

Traversal of multiple time zones ('jet lag'). A literature review on the effects of rapid traversal of multiple time zones on performance is put together by O'Connor and

Morgan (1990). Evidence suggests that distance running and sprint running, as well as dynamic muscular strength and endurance of the elbow flexors is impaired in untrained individuals following west-east travel across 6 time zones.

3.2.6 Clothing

The transmission of force from a person to the outside world, e.g. a floor or a handle, depends on friction. Both shoes and gloves influence this friction between a person and his surroundings. Some research has been done into the effect of gloves on force exertion. Other clothes may restrict movement or breathing, thereby influencing force exertion. One article was found on the influence of respirators on maximal force. No literature on the influence of either shoes or other clothing could be found.

Grip strength. Three-fingered neoprene gloves reduce grip force significantly to 84-86 % of bare-handed force (Vincent and Tipton, 1988). Grip strength is reduced by cotton thermal gloves to 89 %, by knit mesh gloves to 85 %, by knit reinforced gloves to 84 % and by combinations of those gloves to 79 % of bare-handed grip strength. The factor 'glove' explains 5 % of the total variance in an analysis of variance (McMullin and Hallbeck, 1991). Leather, asbestos, rubber and cotton gloves reduce maximal grip strength significantly to 82 %, 82.9 %, 87.9 and 89.6 % respectively. Grip force with open-finger gloves and surgical gloves did not differ significantly from the strength without gloves (Wang, 1991).

Torque. Standard Air Force gloves (thin leather shells with separate woollen inserts) consistently reduce torque on small knobs (diameters 92 to 184 mm) to 79 - 97 % of bare-handed force, with one exception of 102 %. The factor 'glove' explains only 4 % of the total variance in an analysis of variance (Swain et al. 1970). The results of Chen et al. (1989) are slightly different: torque exerted with smooth leather gloves and suede leather gloves was not significantly different from torque exerted with bare hands. Torque with cotton gloves, however, was about half that value. The factor 'glove' explained 36 % of the variance in an analysis of variance. Adams and Peterson (1988) compared torque exerted with work gloves (an inner layer of wool, an outer layer of sewn leather), chemical defense gloves (a cotton inner liner, a smooth rubber intermediate layer and a leather covering) and without gloves. No significant differences occurred for loosening. For tightening only torque exerted with work gloves was significantly different, in this case higher, than without gloves. The gloves offer added advantage, though, by reducing the discomfort caused by tightly grasping an object.

Chuck pinch. Hallbeck and McMullin (1991) measured maximal three-jaw chuck pinch. The effect of glove type was significant, but it explained only 2.4 % of the total variance in an analysis of variance. With cotton thermal gloves, on average a force of 104 % was exerted compared to force exerted with the bare hand. With knit mesh and knit reinforced gloves, as well as with combinations of these, there was no significant difference with the bare hand.

Glove size. According to Chen et al. (1989), glove size does not influence torque. McMullin and Hallbeck (1991), however, found that the bulkier and less form-fitting the glove, the less force can be generated. They add that single layer gloves are preferable to multi-layer ones. Wang (1991) compared six different types of gloves and found that the extent of reduction in grip strength correlated significantly with glove thickness, with $r = 0.88$ and $p < 0.01$.

Respirators. The effect of wearing a respirator on maximal static grip force was investigated by Zimmerman et al. (1991). The experiment included a dust mask, a half-face mask, a full-face mask and no mask as a control. The differences in maximal grip strength between the respiratory conditions were not significant.

Handbooks. Items of clothing and personal equipment decrease maximum push and 1 minute push endurance by 12 - 14 % for one harness simulating restrictive clothing, says Fox (1957), quoted by Morgan et al. (1963). Heavy items increase body weight, and tight or bulky items restrict the range of movement and, possibly, preclude getting into the positions for exerting maximal strength. VanCott and Kinkade (1972) found that, when wearing standard heavy flying gloves (wool liner inside a leather shell), all subjects experienced a considerable reduction of their maximal barehanded grip force, averaging about 20 %. Schmidtke (1981) advises to take the use of gloves and heavy gear into account, but does not say how. Sanders and McCormick (1993) conclude that reduction of grip strength when gloves are worn is a rather consistent finding in the literature. They give an example, in which rubber, cotton and insulated gloves reduce grip force to respectively about 80, 75 and 60 % of bare-handed grip strength.

Conclusion. Gloves certainly do not enhance, and in general reduce, grip strength and torque. For pinch strength, however, the influence of gloves seems to be slightly enhancing. Furthermore gloves may reduce pain when exerting force. Wearing a respirator does not seem to influence maximal static grip force.

3.3 Product variables

Apart from weight or mass, which obviously influences force exertion, the only product variables on which information could be found were characteristics of the product interface with the hand. No information on the characteristics of pedals was found, except in handbooks. No research at all was found on the influence of resistance.

Knob size. Although torque on small knobs is significantly influenced by many variables and interactions, only differences in knob size has a marked effect on the 5th percentile values normally used as design maxima (sic!), according to Swain et al. (1970). The objectionable habit of some designers to automatically design for the 5th and the 95th percentiles of the population (the 'P5-P95 syndrome') is commented on in 7.2.2 'A design process for force exertion'. Swain et al. found that the standard maximum torque limits for knobs of 92 and 123 mm diameter should be 49 and 62 % respectively of the torque limit for a knob with diameter 184 mm. Hand grip torque on electrical connectors with diameters of 23, 38 and 51 mm was investigated by Adams and Peterson (1988). The greatest torque in tightening and loosening was obtained with the largest connector. Maximal torque exerted on the others was 15 - 20 % of the larger one for the

23 mm connector, and 53 - 60 % for the 38 mm connector. Thus strength was found to be directly related to connector diameter.

Lid diameter. For jars, the average maximal torque, exerted by elderly people, increases with lid diameter for 31, 55 and 74 mm lids. For the 113 mm lid maximal torque increased for a lid with rough surface and decreased for a lid with smooth surface. For the latter, 83 mm may be the optimal diameter for elderly people (Imrhan and Loo, 1988).

Handle diameter. Drury (1980) compared literature sources and concluded that a handle for manual materials handling should be at least 115 mm long, be 25 to 38 mm in diameter and have a hand clearance of 30 to 50 mm. Handles with diameters of 10, 30, 50 and 70 mm were tested by Pheasant (1983) for torque differences in a gripping and turning action. The optimal handle size was found to be 50 mm for both female and male subjects. Handle diameters in the range 30 - 50 mm were found by Hsia and Drury (1986) to be better than 'too small or too large ones'. For grip force, Lee and Rim (1991) investigated handles with diameters ranging from 25 to 51 mm and found that a cylinder with a diameter of 32 mm enables the largest force exertion. Fähnrig et al. (1983) found results comparable to these investigations. For gripping and turning screwdrivers and other tools, Pheasant and O'Neill (1975) studied maximal force exerted on cylinders with diameters between 10 and 70 mm. Maximal torque increased with increasing diameter. They advise to maximize hand/handle contact in hand tool design, as this will minimize shear stress on the skin and hence reduce abrasion.

Grip span. The highest resultant force between the jaws of a pair of multiple slip joint pliers ('*waterpomptang*'), obtained by grip strength, was generated at a handle separation of 50 - 60 mm for females and 55 - 65 mm for males. For wider handle separations, the resultant force between the jaws was reduced by 10 % per cm increase up to 100 mm. Force-producing ability was influenced by the grip type ('traditional' and 'reversed', where the little finger was closest to the head of the tool), and the highest force between the jaws was obtained with the traditional grip (Fransson and Winkel, 1991). Radwin and Oh (1991) measured grip strength with handle spans of 40, 50, 60 and 70 mm. The handle span resulting in maximal grip strength increased as hand size increased. Subjective preference of handle size also was directly related to operator hand length.

Handle shape. Highly concentrated loads on the skin should be prevented by eliminating sharp corners, edges, ridges or finger grooves (Drury, 1980). Handles with sharp curvatures performed worse than straight handles, according to Hsia and Drury (1986). Handles with various cross-sectional shapes are compared by Cochran and Riley (1986) for their effect on forces in six directions. The results show that the shape of the handle on which most force can be exerted depends on the direction in which force is exerted. For wrist extension and flexion, rectangular handles with large (up to 1:2) width-to-height ratios should be used. For thrust push and pull forces, handles with a triangular cross-section are recommended. For tasks which involve both orthogonal push and pull forces, rectangular handles with a width-to-height ratio of about 1 to 1.25 appear to be the best compromise. For any task involving more than one sort of force exertion, the handle selection is a trade-off. Bordett et al. (1988) investigated torque exerted on faucet handles by elderly women, and recommended to round the edges so that a painful hard edge is avoided. The handle on which the largest moment was exerted, though, was a paddle-type handle (a long arm with a large, flat end).

On the other hand, Pheasant and O'Neill (1975) found that maximal torque exerted on screwdriver-like cylinders was significantly larger ($p < 0.001$) for knurled than for smooth handles. They conclude, however, that differences in the precise shape of handles must be seen as an irrelevance, since the cylinder diameter and the strength of grip are the main factors determining torque.

Bandera et al. (1985) found that maximal force exerted on knobs and transferred through friction (so that the maximal transferrable force is limited by the maximum amount of friction) is less than force exerted on knobs with such shape that friction does not influence the transferred force.

Handle material. The surface material of a handle influences friction, and therefore the amount of force that can be transferred. Bordett et al. (1988) advise to use a non-slip surface for handles. Bullinger and Kern (1979) found that a smooth surface generally has a larger friction coefficient in combination with a hand, and therefore provides better purchase, than a rough surface. This is explained by the contact between the participating surfaces, which is less with the rough than with the smooth surface. However, the results of Imrhan and Loo (1988) show that on lids with diameter 113 mm and a rough surface about 1.5 times more maximal force was exerted than on those with smooth surface. For lids ranging from 31 to 74 mm in diameter, no effects due to surface finish were manifested.

Push and pull forces exerted on a slippery handle (treated with engine oil additive) were on average 86 % of those exerted on a dry handle (Hallbeck et al., 1990). A foam grip was preferred over a plain wooden handle while using a common gardening lopping shear ('*snoeischaar*'), with significantly lower ratings of hand tenderness and hand fatigue (Fellows and Freivalds, 1989).

While screwing in lamp bulbs, different maximal torque is exerted on various types of bulbs, according to research of Putto (1988). It is likely that the tactile characteristics, as well as shape and size of the bulb determine the maximal torque.

Handle orientation. The best orientation of a handle for carrying a box is at an ulnar deviation of 5.7°. This was deducted by Hsia and Drury (1986) from their comparison of handles with four different orientations by subjective ratings. Hallbeck et al. (1990) studied four orientations of opposition forces relative to the hand, in a power grasp: pushing and pulling, both resisting a force either at the top or at the bottom of the handle. Figure 3.13 illustrates these four situations. The orientation found to be superior to the other three was the pull resisting a force at the bottom of the hand (illustrated by the fourth drawing of figure 3-13).

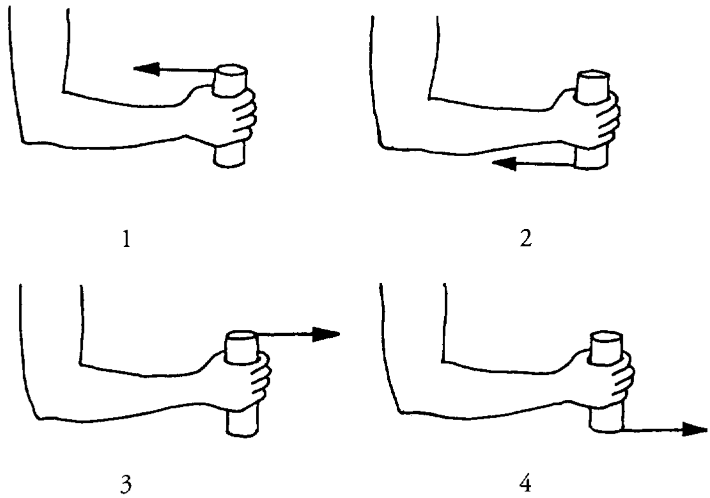


Figure 3-13: Handle oriantations: resisting a force either from the top or the bottom of the handle, a force that is acting either to push the handle proximally or to pull it distally (after Hallbeck et al., 1990).

Handle position. One-handed pulling strength is significantly affected by both handle type and height (1 and 1.75 m above the ground), although the placement of handles with poor hand-handle interfaces had little effect on pulling strength (Fothergill et al., 1992). Investigating hand grip torque on electrical connectors, Adams and Peterson (1988) found the connector height and direction of rotation to be of no effect. Higher torque was exerted when the connectors were on the subject's preferred side.

Carrying a box with two asymmetrically placed handles, combining handles in position 8 and 6 as shown in figure 3.14, is perceived by the subjects as least exerting compared to other positions. This handle position also seemed to enable the longest endurance (Bishu et al., 1990).

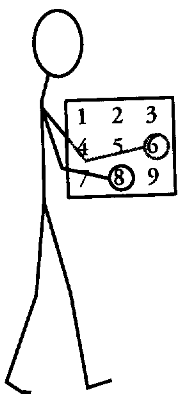


Figure 3-14: Asymmetrically placed handles in position 8 and 6 are perceived as least exerting and enable longest endurance when carrying a box (after Bishu et al., 1990).

Precision. If precision is required, the exerted force should be taken into account. Hammarskjöld et al. (1989) quote Heide and Molbech (1979) who found that maintained isometric muscle work may alter the precision of manual performance.

Zinchenko and Munipov (1989) state that, to increase control precision, the resistance of handles to the operator's force should be between 7 and 12 N. During switch-over, the operator should feel the handle's transition, but the additional force required should not exceed 10 % of the recommended value.

Handbooks. Burandt (1978) shows a graph with the influence of grip size and pedal height and angle on grip strength and maximal leg force respectively. Morgan et al. (1963) give extensive design recommendations for hand and foot controls. VanCott and Kinkade (1972) recommend that at the beginning of hand movement, the resistance should be low.

For continuously variable controls, Zinchenko and Munipov (1989) advise a handle diameter of 75 mm for forces of 13 to 19 N, and a diameter of 100 mm for forces of 19 to 25 N. The diameter should not exceed 140 mm, and not be less than 12 mm. They also give a table with optimal forces, lengths and diameters of toggle switches for 'easy' (2 to 7 N) and 'heavy' (10 to 25 N) types. Above 25 N, lever-type switches should be used.

Lange (1991) suggests handles with various curvatures ('*Griffkrümmungen*', probably referring to diameter), of which the minimal radius depends on the weight to be carried or lifted. Their advice ranges from 3 mm for force up to 50 N, to 13 mm for forces over 200 N. Sanders and McCormick (1993) notice that the optimal grip diameter (about 41 mm) is smaller than the optimal grip span (about 80 mm).

Eastman Kodak (1986) gives a number of design guidelines for contact areas. They recommend that handles be designed to make use of the maximum strength capability of the hand by featuring a power or oblique grip involving the palm, and to obviate the need for pinch gripping. They suggest that handle diameters be kept as close as possible to 3.75 cm and that the span on double-handled tools be from 5 to 6.25 cm. A graph is given to show the effect of grip span on grip strength (see figure 3-15). The handle should be made long enough, about 10 cm. The handle should be oriented so it can be used without unduly deviating the wrist. Cold and hard surfaces and vibration are to be avoided.

Conclusion. Maximal torque, but not maximal force, increases with increasing diameter of knobs and lids. The optimal diameter, however, is limited by the hand size of the subjects. A good handle for lifting and carrying should be about 25 to 50 mm in diameter. Grip force appears to be maximal with a handle separation of about 55 to 60 mm, although it seems to be related to hand size. Sharp corners, edges, ridges, finger grooves and curvatures should be avoided. For various force directions, various cross-sectional shapes of handle are recommended. Soft, non-slip surfaces are preferred. Depending on the task, handle height can influence force exertion.

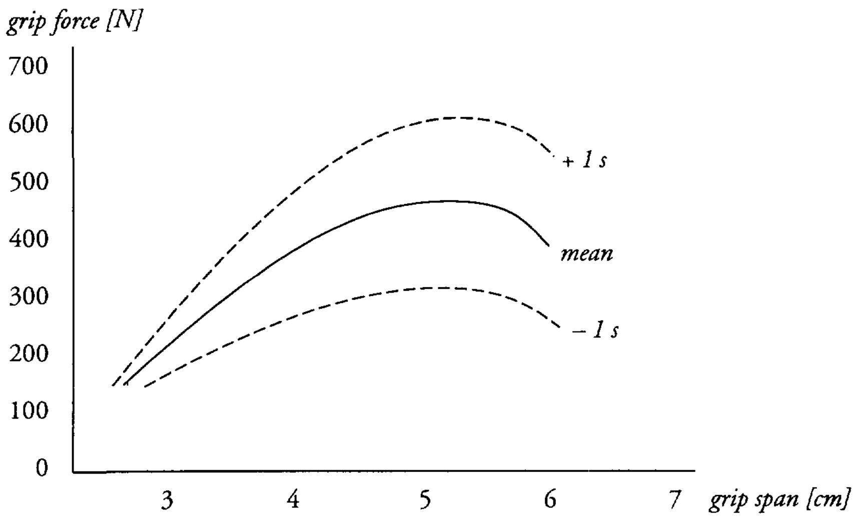


Figure 3-15: The effect of grip span on maximal isometric grip strength, mean and standard deviation on both sides, n = 14 (after Eastman Kodak, 1986).

3.4 Environment variables

Support. Pinch forces are 0.3 to 6.3 N higher when the arm is supported (Catovic et al., 1989). Swanson et al. (1970), however, found that with the arm supported, only 90 to 94 % of the maximal grip force with an unsupported arm was exerted. And Genaidy et al. (1992) found no effect of wrist support on grip and pinch strength. For some situations, it is clear from a physical point of view that a support enables larger force exertion. For example, back and frontal support given by a harness enable exertion of much more push and pull force (Rohmert et al., 1987a). Caldwell (1962) measured maximal arm extension with various back support heights (see figure 3-16). The effect of back rest condition was significant, and there was an interaction with the elbow angle. Without back support, the elbow angle had little effect on the maximal force. At elbow angles of 135° and 160°, the height of the back support affected the maximal force. Although elbow angle and height of back support (of which the last affects the position of the reaction force) are the independent variables in Caldwell's experiment, the change in the maximal force exerted may also be limited by the strength of the chain of muscles and limbs of the whole upper body, which guides the exerted forces.

Handbooks: support. Burandt (1978) advises to multiply leg forces with a factor of 1.4 to 2.5 when the body has a support it can push against. He gives a table showing the effect of back support height on leg force. Woodson (1981) also states that it is important to provide appropriate support and anchoring conditions. VanCott and Kinkade (1972) recommend a lumbar support for exerting foot forces, which is essential if large forces must be exerted. Frankel et al. (1984) show that for subjects who are standing and reaching far forward, a support at the level of the pelvis can reduce the moment at the lower back with 30 %. This results in a more comfortable posture.

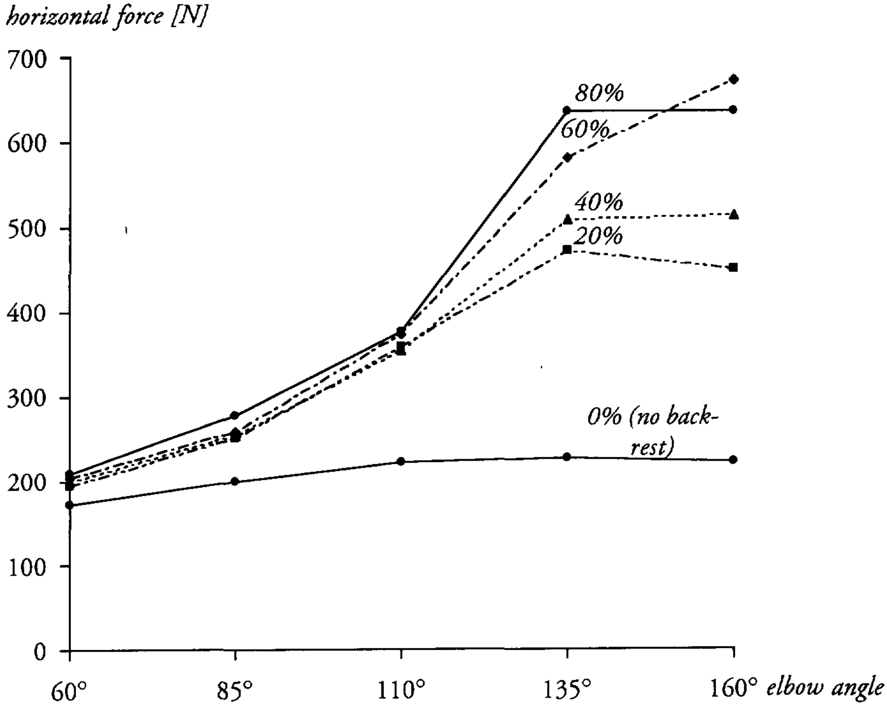


Figure 3-16: The effect of back support heights and reach distance on maximally exerted force (after Caldwell, 1962).

Temperature. In general, to investigate the effect of temperature on maximal strength, arm and/or hand are immersed in water for a certain period, after which grip strength is measured. Vincent and Tipton (1988) found that intermittent immersion in water of 5° C of either hand or forearm reduced grip force by 13 to 18 %. Only the changes which occurred during the measurement after the first two minutes of immersion were significant, after which the average grip force did not change significantly any more.

Endurance of 33 % of maximal grip force was measured by Clarke et al. (1958) during immersion in water with temperatures ranging from 2 to 42 °C. The optimum water temperature for sustained contractions appeared to be 18 °C, which corresponded with a muscle temperature of 25 to 29 °C (6 to 10° lower than in a normal resting condition). With other temperatures, endurance is shorter.

An increase of muscle temperature is accompanied by an increase in magnitude of maximal muscle velocity and maximal power, but not of maximal force (Binkhorst et al., 1977).

Handbooks: temperature. According to Woodson (1981), heat affects strength adversely when temperatures exceed 29 °C, especially under conditions of high humidity. In general people regain strength when acclimatized. Low temperature, on the other hand, has little effect on strength. VanCott and Kinkade (1972) state that at temperatures over 29 °C endurance is reduced, but short outbursts of energy are not greatly affected.

Furthermore, unacclimatized males tolerate heat better than unacclimatized women. Adaptation and acclimatization to low temperatures help to overcome the adverse effects.

Handbooks: acceleration. Accelerations up to 5 g affect endurance, but do not affect strength. Arm movements are effective up to 6 g, wrist and finger movements up to 12 g (Morgan et al., 1963; Woodson, 1981).

Handbooks: altitude. Woodson (1981) states that altitude does not influence grip strength up to 3600 m, endurance declines progressively above about 2500 m, to about one-half at 6100 m, without extra oxygen. Partial grip paralysis begins at around 7300 m. Acclimatization requires several weeks or months. Morgan et al. (1963) and VanCott and Kinkade (1972) give similar information. The former adds that brief muscular exertions are affected less than muscular endurance is.

3.5 Interaction variables

3.5.1 Posture

Posture is an influential variable in force exertion. Seemingly small changes in the experimental condition, e.g. a change of knee angle, may bring about substantial differences in strength scores (VanCott and Kinkade, 1972). And even small constraints in posture are found to have a considerable effect on the strength which could be exerted (Haslegrave, 1992). The posture of the subject influences the force that can be exerted in various ways.

In the first place, static maximal force in some postures is limited by static laws. The sum of all forces should be zero, as should be the sum of all moments. When the sum of forces and moments is not zero, this will result in movement, and the posture will change so force exertion will be dynamic instead of static. From the height of the handle, the position of the centre of mass, the pivot around which rotation would start and sometimes the coefficient of friction with the environment, the maximal force that can be exerted can be calculated. If this force exceeds the force that physiologically can be exerted by the muscles of the subject, his or her maximal force is not limited by the posture. If, however, the calculated maximal force is less than the physiologically exertable force, it is clear that the posture will limit the force that the subject can maximally exert.

It is evident that with nearly all postures the mass of the limbs affects the forces that can be exerted. To move or keep the limbs in place against gravity (to maintain posture), 'internal forces' must be exerted, depending on the postures of limbs and body. These are exerted by the same muscles that generate the forces that are exerted on purpose on the environment ('external forces'). So, the combination of mass/posture/gravity influences external force exertion. This phenomenon mainly affects the endurance times of sub-maximal forces.

Furthermore, in certain postures maximal force can be limited by active insufficiency, when the muscles reach maximum contraction before the joint rotation reaches its limit. Maximal force can also be limited in extreme joint angles, where the joint does not allow further movement, or by the configuration of limb segments. Different joint angles correspond with different muscle lengths and at the same time with different moment arms within the body. The moment arm is the distance between the point of attachment of the muscle and the pivot around which the segment will rotate. Both muscle length and moment arm affect the maximal force that can be exerted.

All these influences of posture on the force exerted are recognized. They undoubtedly are the cause for many differences found in exerted force in literature. However, they are not further discussed because this chapter is concerned with the influence of posture on exerted force as it is found in ergonomic literature. This generated the following information.

Sitting, standing and lying. The difference in force exertion caused by the posture of the whole body, while the task stays the same, is investigated by a number of researchers. Mital and Sanghavi (1986) measured static torque exerted with various hand tools, in sitting and standing posture. More torque is exerted in the standing posture ($p < 0.01$), although this pattern is not uniform for all hand tools investigated. Only with wrenches is more torque exerted while standing, and with screwdrivers greater torque is exerted in a seated position. Mital (1986) measured torque exerted with various hand tools while standing, kneeling, squatting or lying face up, down or on one side. Though the posture effect is statistically very significant, torque values do not change substantially unless the body assumes extreme postures.

Catovic et al. (1989) measured various static pinch forces in standing and sitting positions. Forces were slightly higher when standing, although no statistics were used to prove it.

Static lifting strength in various postures was measured by Gallagher (1989), Chomcherngpat et al. (1989) and Lee and Bruckner (1991). Gallagher found that lifting forces were not affected by standing, kneeling on one knee or kneeling on two knees. Chomcherngpat et al., however, found a significant influence of posture on the maximally exerted static force. Lying on the stomach without elbow support, on average only 15 to 16 % of the mean force exerted when standing could be produced. There was no significant difference between maximal forces exerted when sitting and lying on the stomach with elbow support, which was 35 to 38 % of the average force produced when standing. Lee and Bruckner found exactly the same, which after closer inspection can be attributed to the fact that they probably describe one and the same research.

One-arm isokinetic pulling while sitting and standing was investigated by Mital and Faard (1990). The results indicated that, when sitting, approximately 73 % can be produced of the maximal force exerted while standing. Gallagher (1989) measured two-handed maximal pushing and pulling strength and found they were significantly affected by posture. Maximal push force exerted while kneeling on one knee and while kneeling on two knees generates 116 % and 130 % of the maximal force while standing.

For pulling, force exerted while kneeling on one knee generates 169 % of force while standing, and kneeling on two knees has no significant effect compared to standing.

Dynamic force. Imrhan and Ayoub (1990) studied the effects of starting position of dynamic pull on the configuration of the arm at which peak pull strength is achieved. They found that pull strength depends strongly on the starting position of the arm. The angular configuration of the arm at peak strength was unaffected by the starting position of the arm. This suggests that there may be an optimal arm configuration for dynamic (or even static) pull strength. For each of the three tested velocities, a different optimal configuration was found.

Garg and Beller (1990) also investigated dynamic pull strength. When the pulling height was increased from 40 to 70 % of shoulder height, there was a decrease in strengths by 25 N for peak strength and by 15 N for mean strength per 10 % shoulder height. Overall, the mean and peak pulling strengths decreased by approximately 16 %. Speed ranged between 0.7 and 1.1 m/s and pulling angle between 15° and 35° with the horizontal plane. The height effect was more pronounced at a lower speed (0.7 m/s) and at a high pulling angle (35°). On the average, maximum strengths occurred at a pull angle of 25° and minimum strengths at a pull angle of 35°, with a decrease in mean strength of 22 % and a decrease in peak strength of 19 %.

Mital and Genaidy (1989) measured dynamic pull-up strength in 15 different postures, ranging from kneeling to standing. The posture effect was significant at $p < 0.01$. Maximum force was exerted with two hands in stooped posture. The least force was exerted in a sitting posture with one (the preferred) hand fully extended in the sagittal plane. Similar postures result in about the same magnitude of strength. Therefore, minor variations in posture do not seem to have a pronounced influence on maximal isokinetic force exertion. However, if posture differences are substantial, force exertion capability changes drastically.

Choice of posture. Haslegrave (1991 and 1992, and Haslegrave and Corlett, 1988) investigated postures of subjects during single-handed static force exertion in different directions and locations. Otherwise, the posture was free. Most of the resulting postures were highly asymmetric, quite different from general 'standard postures'. She found that the choice of posture was influenced by a number of biomechanical and psychophysical factors. It is apparent that muscle strength, joint stability and bracing of the skeletal framework are all important factors in deciding on a postural strategy. With factor analysis, ten factors which characterize a posture were identified. Groups of variables are adjusted together in choosing a posture to maximize the force exerted. There was a large degree of inter-individual variability in the postures, adopted by the subjects. This did not necessarily affect strength but did cause differences in the resulting biomechanical stresses. In free posture, two elbow angles predominated, corresponding to the arm being nearly fully extended and to the arm being tightly bent with the hand close to the shoulder. The subjects were not choosing elbow posture in order to maximize the force exerted by the muscles of the arm.

Postural Stability Diagrams. A number of researchers systematically investigated the maximal static forces that can be exerted in all directions of one plane. Usually those are pushing, pulling, lifting, pressing and combinations of those in the sagittal plane, exerted in standing position. Maximal force exertion in standing position is partly limited by a number of variables which can be calculated using the physical laws of equilibrium of forces and moments. Only static forces can be predicted in that way. The maximal forces are visualized in figures, like figure 3.17, which are called either Postural Stability Diagrams or Vectograms. Grieve (1979a) states that if the position of the centre of gravity of the subject, of the contact with the earth and the contact with the handle are known, the theoretical limits for pushing and pulling can be calculated. In a subsequent article (Grieve, 1979b) the influence of environmental factors, such as friction, task demands and safety requirements are included in the model.

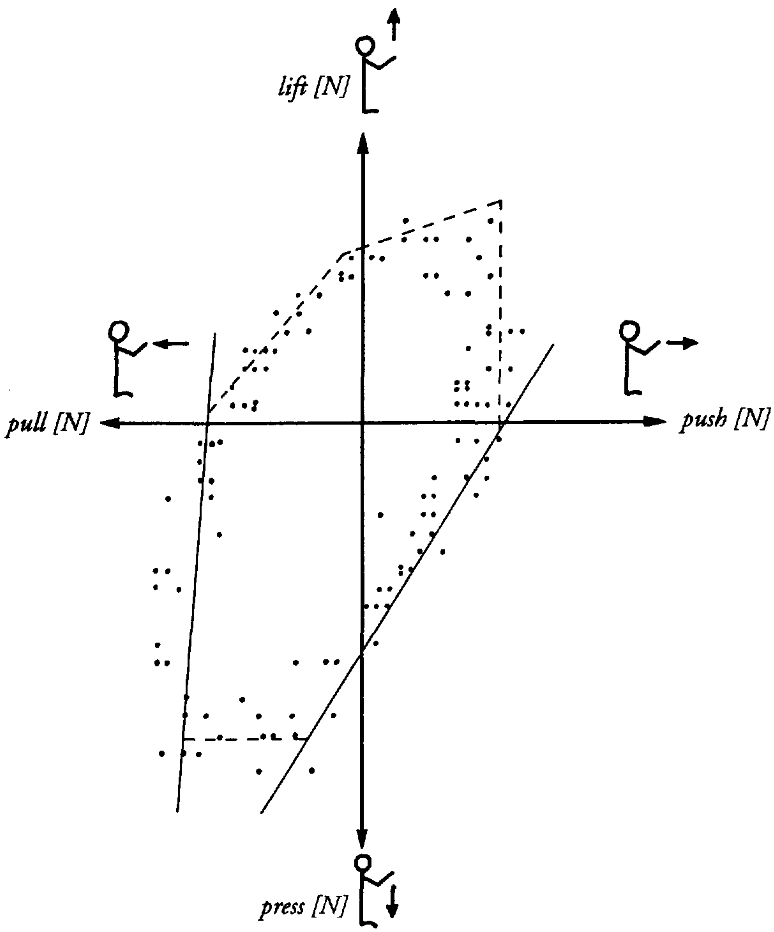


Figure 3-17: Vectogram or Postural Stability Diagram (after Rohmert et al., 1987a), representing forces exerted in the sagittal plane. On the horizontal axis, the size of horizontal maximal push and pull forces are plotted. On the vertical axis, the size of vertical lift and press forces are plotted. In between, the size of maximal forces in corresponding directions are plotted.

Rohmert and Mainzer (1987) state that in the fore and aft direction, or pushing and pulling, maximal force is limited by mechanical stability. Upward and downward, or lifting and pressing, maximal force is limited by the muscle force the subject can generate. Force exertion with the trunk fixated indeed resulted in a deviating vectogram: more force was exerted than without support when pushing and pulling (Rohmert et al., 1987a). The height of the handle, and thus the posture of the subject, influences the shape of the vectogram (Rohmert et al., 1987b). If the posture is free, however, the resulting vectogram differs from that of a prescribed posture, where the position of feet are set. In all directions within the sagittal plane, more force is exerted (Rohmert et al., 1987c). The geometry of the vectograms is not determined by inter-individual differences (Rohmert et al., 1988).

One- versus two-hands. The ratio of one- versus two-handed force exertion in the sagittal plane (pushing, pulling, lifting, pressing, and all their combinations), as measured by Fothergill et al. (1991), ranges from 0.64 to 1.04. Two-handed strength commonly exceeded one-handed strength at a handle height of 1.0 m, but showed fewer significant strength differences ($p < 0.05$) according to direction at 1.75 m. Sanchez and Grieve (1992) measured static lifting strength at various heights, in the sagittal plane and at different angles to it. The ratio of one versus two-handed lifting ranges from 0.61 to 1.01.

Asymmetric postures. Kumar (1990) investigated static (isometric) and isokinetic (0.5 m/s) maximal lifting strengths in a stooping posture, in the sagittal, 30° and 60° lateral planes and with different reach distances. With increasing asymmetry, the exerted force decreased significantly.

Reach distance. Isometric and isokinetic maximal lifting strengths, in various planes and from half to full reach distance, were measured by Kumar (1990). The strength was inversely related to reach distance. The greatest declines in strength were at distances of between half and three-quarters of full reach (45 to 50 %). From three-quarters to full reach, the drop was between 10 - 30 %. For pulling, it seems to be the reverse: Mital and Faard (1990) measured one-armed isokinetic pull strength and found that strength increases with the reach distance. At 40 and 25 cm, 90 % and 71 % of maximal strength at 50 cm is exerted.

Arm position. Pinch forces are highest in standing position with the forearm 60° towards frontal position, and in sitting position with the forearm perpendicular to the frontal position (Catovic et al., 1989). Kahn and Monod (1984) measured static elbow flexion forces with the upper arm horizontal and the forearm flexed, and with the upper arm vertical and the forearm horizontal. Maximal force was not significantly different for the two positions. With the performance of repetitive arm movements while standing, measured by Wiker et al. (1990), substantial complaints were soon reported if the arms were above shoulder level, in spite of low-level force exertions and generous rest intervals. They state that strength capacity is significantly influenced by changes in arm posture. Mital and Faard (1990), for one-armed isokinetic pull strength find that, with movement of the arm from the frontal in the direction of the sagittal plane, maximal exertion is attained at 90° of the frontal plane (i.e. with the arm in the sagittal plane) and weakens beyond that angle. In the frontal plane, maximal force of the arm is 83 %

of that exerted in the sagittal plane. The results of Hennion et al. (1990) show that, with the arm stretched and the hand at the height of the acromion, maximal pulling force is highest with the arm in the sagittal plane, and declines when the angle of the arm changes in the transversal plane. They also found that force exerted in a 'preferential' direction (in the direction of the arm) declines less than force exerted in another, imposed, direction.

Wrist position. Wrist position has a significant effect on grip force (McMullin and Hallbeck 1991) and on three-jaw chuck pinch force (Hallbeck and McMullin, 1991). Both are maximal (100 %) with the wrist in neutral position. Grip force is reduced to 82 % when the wrist is dorsally extended 45° and to 56 % when flexed 65°. Pinch strength is reduced to 92 % when the wrist is extended 45° and to 75 % when flexed 65°. Fernandez et al. (1991) found, too, that maximal pinches (pulp, chuck and lateral) are highest with the wrist in neutral position. With maximal deviation, pinch force was reduced to 66 %. In pulling, however, Hazelton et al. (1975) found no variation of the maximal force with wrist positions of 21° ulnar deviation, 14° radial deviation and flexion varying between two-thirds of the active range of motion, but not more than 45° anteflexion or 60° dorsiflexion. From a biomechanical point of view, Frankel et al. (1984) recommend that force be exerted with the fingers while holding the wrist in a neutral position.

Gast (1991) did an extensive literature research into the relation between flexion of finger, wrist and elbow joints and maximal grip force. It is very likely that flexion of those joints affects grip force, but the relations are not unambiguous. Possibly for the wrist 0° flexion (or neutral position) is the optimal position.

Finger position. Pinch grip performed with the remaining fingers flexed resulted in forces from 42 % to 92 % higher than when the remaining fingers were extended, according to Hook and Stanley (1986). Pinch with all fingers results in 50 % more force than forefinger or middle finger pinch separately (Catovic et al., 1989). Fransson and Winkel (1991) found with grip force an interaction between the postures of the fingers. The maximal force of one finger depended not only on its own grip span, but also on the grip spans of other fingers. Bandera et al. (1985) found that maximal push and slide forces of the thumb are larger than those of the other fingers, and all types of force exerted with the pad of the fingertip are larger than those exerted with the tip of the finger. Maximal forces exerted with the flat of the hand exceed all finger forces. They also formulated a number of rules on the influence of the direction of push and slide forces exerted on knobs.

Leg position. With increased thigh angle, the pulling force exerted with the arm in sitting position increases. Also, with increased thigh, knee and elbow angle, endurance of pulling increases (Caldwell, 1964b).

Ankle position. Molbech and Johansen (1973) found that plantar flexion force is 2 to 3 times greater than dorsal flexion force. Graham and Garbutt (1993) measured isokinetic plantar and dorsal flexion force between -10° and 30° ankle flexion. Their subjects were professional soccer players, but their results were similar to those of Molbech and Johansen, who used male and female subjects from 18 to 56 years. Plantar flexion force is

1.3 to 3.2 times greater than dorsal flexion force, increasing nearly linearly with ankle angle. They also measured inversion and eversion force between -15° and 15° ankle flexion. The ratio inversion/eversion strength increased almost linearly from 0.60 to 1.19 with ankle angle.

Handbooks. All handbooks recognize the influence of posture on exerted force. Rohmert and Hettinger (1963) present a large collection of data on arm and leg forces exerted in various postures, originating from various sources. Burandt (1978) states that the exerted force can be increased through better body posture, suitable work height and more advantageous direction of movement. Graphs are given in which hip and knee angle are related to exerted leg force. Laubach (1978) gives data of an investigation into the effect of seat back angle and arm position on the size of maximal static push with the arm. The average forces range from 170 N to 752 N.

Woodson (1981) states that when individuals are not restricted in terms of body position and are provided with the appropriate support, they generally will assume a position from which they can apply their maximum force. However, this may not necessarily be the best posture for endurance of lower force levels. General rules for assessing the right limb position for force exertion are the following:

- Hand grip forces generally are greater if the gripping task is close to the individual's body rather than at arm's length.
- Arm strength is greater if the individual can push against a backrest or footrest.
- Maximum leg force occurs when the individual's knee is slightly bent.
- Maximum arm force occurs when the force can be applied approximately at shoulder level.
- With the subject seated, pull force is greatest when the object is positioned close to maximum arm length; push force is greatest when the object is positioned at about half the full arm extension.

VanCott and Kinkade (1972) quote Lehmann (1958), who found that the largest operating forces on a pedal are exerted in or very near the line connecting the hip-joint with the centre of the pedal directly in front of the operator; as the direction of force moves laterally, or downward below the level of the hip, the amount of force that can be exerted becomes less. For rotary motions and repetitive motions, a number of rules on posture is given.

The Materials Handling Research Unit (1980) made a booklet with information on how much force can be exerted lifting, pushing and pulling in different postures. When pushing with one hand and lifting with one or both hands, the closer to the body, the more force can be exerted.

Schmidtke (1981) demonstrates the importance of body posture with a graph. Size and direction of maximal leg forces depend on the angle between upper and lower leg.

Conclusion. All changes in posture have an effect on the maximal force that can be exerted. The postures, and thus the effects, are so numerous and diverse that a good summary of the above information would become too extensive for the goal of this chapter. Therefore, no summary of results is presented.

3.5.2 Dynamic force

Dynamic force exertion is force exertion during which the length of the muscles changes. Consequently, the segments that are connected by these muscles rotate relatively to each other. In literature, dynamic force exertion is less frequently investigated than static force exertion. It is more complicated to research, in the first place because more sophisticated equipment is required, in the second place because more variables influence maximal force and endurance time. These are velocity, resistance, starting point, trajectory and end point of the movement. Force exertion with constant velocity is called isokinetic, and force exertion with constant muscle tension is called isotonic.

Starting position. Ayoub et al. (1981 and 1982) and Hafez et al. (1982) measured static and isokinetic force of elbow, shoulder, back, hip and knee with angular velocities of 0, 5 and 25 rpm, with varying starting positions and a constant stopping position. Torques were observed to decrease as the starting position was moved closer to the stopping position, and thus the range of motion decreased. Imrhan and Ayoub (1990) found, too, that pull strength depends strongly on the starting position of the arm. The elbow was kept at 90° flexion and the movement of the upper arm started at 170, 130, 90, 50 and 10 degrees shoulder flexion. The peak pull forces were greatest when the shoulder started at 90° flexion.

Configuration at maximum force. Hoes et al. (1968) investigated force exertion during cycling at 60 rpm, and Sargeant et al. (1981) measured force exerted on a bicycle ergometer worked for 20 s at constant velocity (23 to 171 rpm). They both found that peak force was exerted at 90° past the top dead centre in each revolution. In the experiment of Sargeant et al., peak force declined during the 20 s from the maximum, attained near the start of exercise, the rate of decline being velocity dependent. On the other hand, Ayoub et al. (1981 and 1982) found that various angles of rotation for elbow, shoulder, back and knee produced no substantial differences in maximum torque. Only the hip showed any effect with the maximum torque decreasing as the hip was abducted from the sagittal plane.

Imrhan and Ayoub (1990) found that pull strength depends strongly on the starting position of the arm and velocity of pull. However, the angular configuration of the arm at peak strength was unaffected by the starting position of the arm. This suggests that there may be an optimal arm configuration for dynamic pull strength. For each tested linear hand velocity (15, 30 and 46 cm/s), a different optimal configuration was found.

Velocity. Thorstensson et al. (1976), Larsson (1978) and Ingemann - Hanssen and Halkjær - Kristensen (1979) investigated knee extension force in relation to velocity of knee angle rotation. The former found that dynamic force decreased with increasing speed from 0 to 180°/s. The second found correlation coefficients between dynamic strengths at different speeds of contraction, ranging from 0.86 to 0.95. The third found that peak torque decreased linearly with increasing angular velocity in a semilogarithmic scale.

The peak force measured by Sargeant et al. (1981) on a bicycle ergometer was inversely and linearly related to crank velocity. Maximal power was generated at a velocity of 110 rpm. Ayoub et al. (1981 and 1982), for elbow, shoulder, back, hip and knee found that strength across a joint decreases as the speed of movement increases. According to the results of Garg and Beller (1990), the rate of perceived exertion of one-handed pulling decreased significantly ($p < 0.01$) with an increase in speed of the hand from 0.7 to 1.1 m/s. Imrhan and Ayoub (1990) found that pull strength depends strongly on the velocity of pull. The maximal force exerted at a linear hand velocity of 46 cm/s was roughly half of the force exerted at 15 cm/s. Figure 3-18 shows the theoretical relation between the exerted force and velocity of contraction for a separate muscle (Hof, 1987).

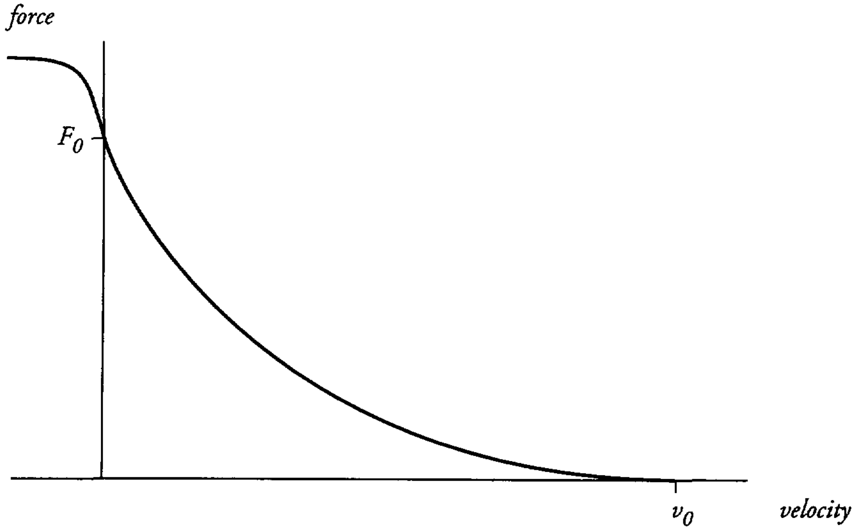


Figure 3-18: Force-velocity characteristics of skeletal muscle, showing a decrease of maximal tension (maximal force) as the muscle shortens and an increase as it lengthens (after Hof, 1987)

Relation static-dynamic force. Larsson (1978) found high correlations between isometric and dynamic knee extension strengths, $r = 0.86$ to 0.89. Ayoub et al. (1981 and 1982) and Hafez et al. (1982), however, studied the correlation coefficients between static and isokinetic elbow, shoulder, back, hip and knee forces and found them to be 'relatively poor'. At an angular velocity of 5 rpm, the average r is 0.53; at 25 rpm, the average r is 0.29. The value of r ranges from -0.18 to 0.67.

Eccentric and concentric force. According to the results of Singh and Karpovich (1968) maximal static and eccentric force are nearly equal for both elbow flexors and extensors for elbow angles between 50° and 140°. Concentric forces range between 64 and 95 % of eccentric forces. Speed or resistance were not indicated in the article. The results of Schaefer and Schmidtke (1989) agree with this, maximal eccentric forces approach the maximal isometric forces over the whole flexion range of the elbow, measured between 21° and 158°. Maximal concentric forces are only about 63 % of the highest isometric values. This is measured at the speed of 6 s per period of one concentric and one eccentric contraction. According to the investigations of Schaefer and Brödler (1991), who studied arm flexors, subjects were able to exert, at the speed of 0.16 Hz per flexion-extension cycle, 85 % of static force during concentric contraction and 145 % during eccentric contraction.

Teamwork. During isometric lifting in teamwork, a two-man team exerts 94 % of the sum of the individual strengths and a three-man team 90 %. For isokinetic lifting these values are only 68 % and 58 % for a two-man and three-man team respectively. Thus, especially for dynamic force, the efficiency of multi-member teams seems to decrease as the number of the participants increases (Karwowski and Mital, 1986).

Handbooks. Relatively little information on dynamic force exertion was found in the handbooks, although there was some information on lifting which is not discussed here. VanCott and Kinkade (1972) give recommendations for the design of rotary pedal cranks. Normally, the pedal crank arm should have a radius of about 19 cm, and be operated at 40 to 90 rpm, depending on the power output desired, and the body dimensions of the operator. A hand crank should have an arm length of about 30 cm

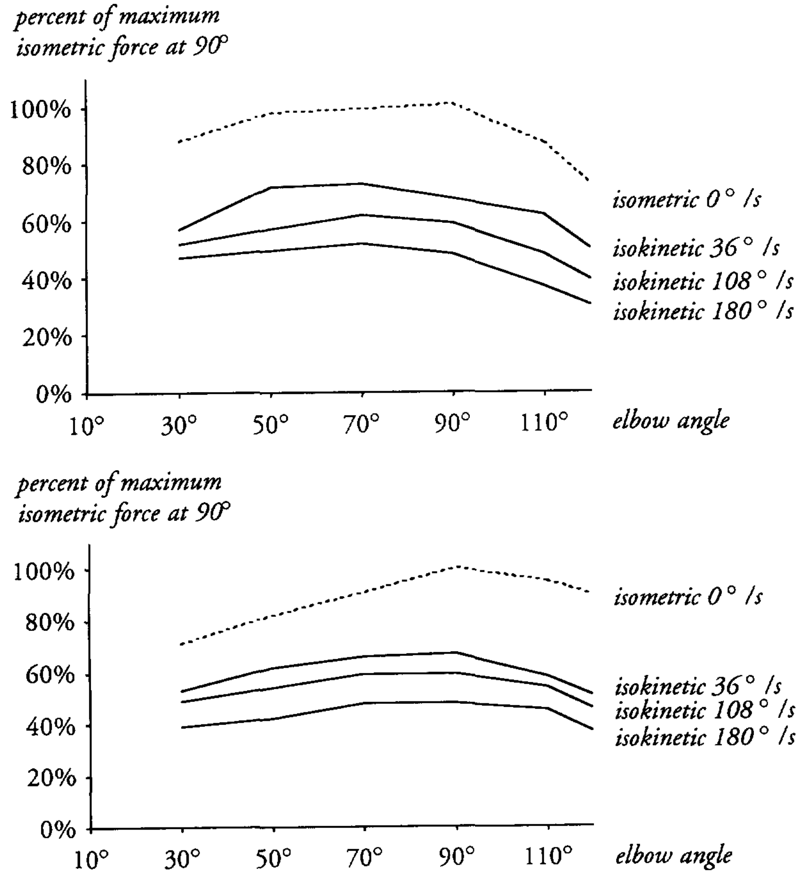


Figure 3-19: The effect of velocity and elbow angle on maximal elbow ***flexion*** *forces of women and men (after Eastman Kodak, 1991).*

and be operated at approximately 30 rpm. Laubach (1978) concludes that comparisons between static and dynamic forces have resulted in conflicting opinions about their relationship. A large number of researchers found a high degree of correlation, and an equally large number reported that the mathematical relationship is not high. Static maximal force is usually larger than dynamic maximal force, and eccentric contractions yield higher values than concentric ones. Eastman Kodak (1986) shows the influence of velocity and elbow angle on maximal elbow flexion and extension force of women and men, see figures 3-19 and 3-20.

Conclusion. Dynamic force exertion is influenced by the starting position, the range of motion, the configuration of the limbs and the velocity. The closer the starting position to the stopping position, and thus the smaller the range of motion, the smaller the exerted force. On velocity, all authors agree that with increasing speed, dynamic force exertion decreases. With cycling, peak force is exerted at 90° past the top dead centre in each revolution. The correlation between static and dynamic force is not yet unanimously established. It is agreed, however, that static and eccentric force in general exceed concentric force. For teamwork, the efficiency of lifting decreases with the increase of the size of the team.

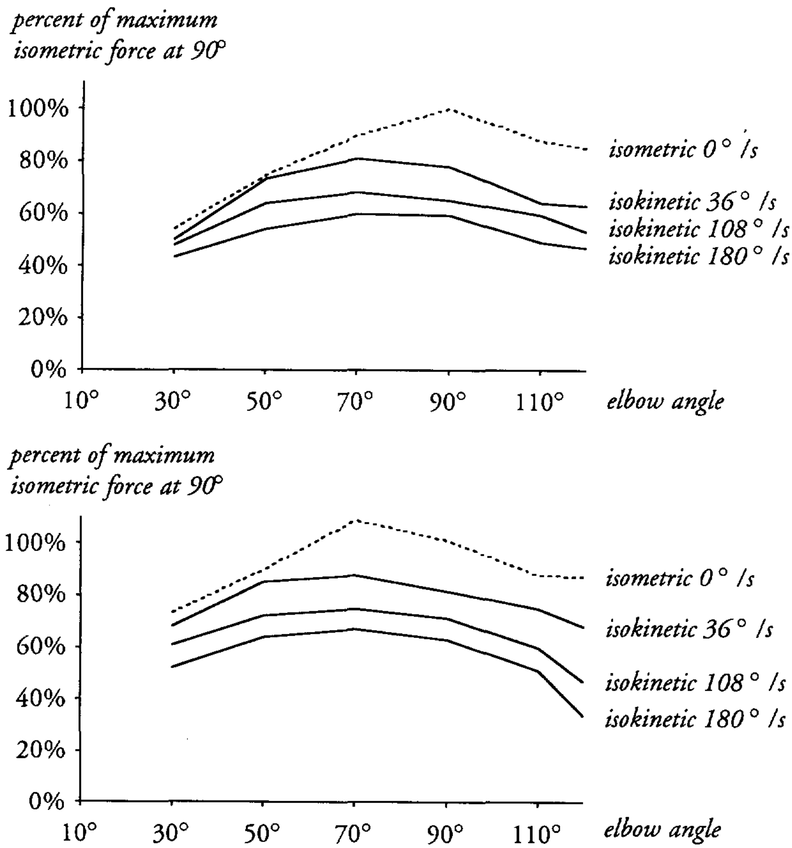


Figure 3-20: The effect of velocity and elbow angle on maximal elbow ***extension*** *forces of women and men (after Eastman Kodak, 1991).*

3.5.3 Endurance (of static force)

There is no standardized way to measure endurance of static force. In general, though, it is measured as function of a percentage of maximal force, with straingauge-like techniques. Mostly arm muscles (biceps) are measured (Björksten and Jonsson, 1977; Caldwell, 1963, 1964a and 1964b; Carlson, 1969; Deeb and Drury, 1992; Rohmert, 1960; Rose et al., 1992; Schutz, 1972; Schutz and Chaffin, 1972; Start and Graham, 1964; Start and Holmes, 1963), sometimes leg muscles (Deeb and Drury, 1992; Elbel, 1949; Hultén et al., 1975; Rohmert, 1960; Larsson, 1978; Sjøgaard, 1986), grip force (Byrd and Jeness, 1982; Clarke et al., 1958; Humphreys and Lind, 1963) or whole body forces maintaining a posture and holding a weight (Bishu et al., 1990; Rohmert et al., 1988; Rose et al., 1992).

Methods are not always sufficiently described. In only a few publications, the definition of the point at which the measurement ends is given. This also applies to the limitations of the movement subjects were allowed to make. The way maximal force is determined is not always mentioned, either.

Some research into endurance is done as preliminary research into work cycles and/or rest determination (Rohmert, 1960; Monod and Scherrer, 1965; Pottier et al., 1969; Schutz, 1972; Björksten and Jonsson; 1977).

Endurance in this review is measured as a function of a percentage of maximal force, unless otherwise stated.

Sex. Caldwell (1963) found no difference in endurance between women and men. Byrd and Jeness (1982) found, to the contrary, that women endure the same percentage of their own maximal force for a longer time than men: on average 73.9 s for women against 63.1 s (85 %) for men, which is a significant difference. It should be noted that, according to the measuring method of Byrd and Jeness, endurance time is the time during which a force is exerted until it falls below 50 % of the maximal force.

Age. Elbel (1949) looked into the correlation between age and endurance for three groups of young male subjects, which yielded r values of -0.04, -0.05 and -0.09. A significant effect on the endurance was found between two age groups of 20 - 29 and 50 - 59 years old by Deeb et al. (1992). In this case, the group of older subjects showed longer endurance. There was also an interaction effect with force level: the endurance difference between the groups increased with decreasing force level. Furthermore, the older age group reported significantly higher perceived exertion at higher levels of force and across time (Deeb and Drury, 1992).

Subject. Rohmert (1960) stated that endurance does not depend on the subject. Both Caldwell (1964a) and Bishu et al. (1990), however, found a difference between endurance of subjects, significant at $p < 0.01$. Caldwell also compared the endurance of the weakest and strongest subjects (maximal force < -1 s or > 1 s from the average) and found no difference. Therefore, the influence of the subject could not be explained by differences in maximal force.

Force level. Rohmert (1960) stated that endurance does not depend on the absolute force. Caldwell (1964a, p. 78) measured endurance from 50 % to 80 % of the maximal force, and found an "essentially linear relationship between relative load and endurance". Caldwell (1964a), Bishu et al. (1990) and Deeb and Drury (1992) found with analysis of variance that force level is a significant factor influencing endurance. Force level usually is defined as a percentage of maximal static force, because it is argued that in that case effects of subject, muscle group and postural differences on endurance are either non-significant or very small, and thus can be neglected (amongst others Schutz and Chaffin, 1972).

Posture. Caldwell (1964a) found that endurance scores showed significant ($p < 0.05$) but little difference (on average 39.5 s against 42.8 s) for two arm positions yielding different maximum force. Thus, relative loading tended to equalize endurance, despite large differences in the actual force of the sustained response. Caldwell (1964b) also found that increased knee-, thigh- and elbow angles result in an increased endurance of manual pull. It is concluded that most favourable characteristics for maximal force are also the most favourable characteristics for long endurance. Rohmert et al. (1988) compared endurance in two postures with the endurance according to his own model (Rohmert, 1965). One posture agreed with the model, the other yielded a much longer endurance. Bishu et al. (1990) found a significant effect on endurance of the way handles are positioned on a box (inducing various postures of the subjects holding it).

Muscle group. Rohmert (1960) stated that endurance does not depend on muscle group. Sato et al. (1984), however, found different regression lines to fit their experimental data from endurance of elbow flexion, shoulder abduction and knee extension force. The ratio of slow twitch and fast twitch fibers varies for different muscle groups. According to Hultén et al. (1975), the relation between endurance and slow twitch/fast twitch fiber ratio is linear. The results of Viitasalo and Komi (1978) confirm the findings of Hultén et al..

Deeb and colleagues investigated endurance of biceps and quadriceps, which have a different slow twitch/fast twitch ration, and published two articles on this subject. Deeb et al. (1992) measured knee extension and elbow flexion. However, contrary to expectation they did not find a significant effect of type of muscle group on endurance time. They suggested this might be attributed to small sample size and/or large variability of data. On the other hand, Deeb and Drury (1992) did find a significant effect of type of muscle group on the rate of perceived exertion in a similar experiment.

Temperature and blood flow. Clarke et al. (1958) found that the optimum environmental temperature for sustained contraction is 18°C. Humphreys and Lind (1963) did research into the blood flow during muscle contraction. They found that changes were the same for environmental temperatures varying from 18°C to 42°C. These changes comprised increase of blood flow with time during contraction, and decrease with increasing tension (or force level). With artificially occluded blood flow, the endurance decreased. The results suggest that intramuscular pressure during contraction can not occlude the blood supply until the tension exerted is above some value greater than 70 % of the maximal force. Start and Holmes (1963) found no significant difference between endurance with occluded and open blood circulation at exertion of 66 % of the maximal force. At 33 %, endurance time with open circulation was longer than that with occluded circulation (12.9 against 4.7 min.).

Reproducibility. There is a large interindividual variation in endurance. Mathiassen and Winkel (1992) quote the finding of a variation coefficient of 0.50, and a range that is about twice the value of the median. Individuals, however, reproduce endurance to some extent. Some retest correlation coefficients for endurance are collected in table 3-6. Byrd and Jeness (1982), who measured endurance as the time force is exerted until it falls below 50 % of the maximal force, found correlation coefficients between endurance times at different force levels in the same situation of 0.45, 0.65 and 0.72. The last two are significant.

Correlation with maximal force. A number of coefficients of the correlations between maximal force and endurance in the same situation based on relative force can be seen in table 3-6. The cause of the discrepancy between the findings of Caldwell (1964b) and the others is not clear. Although even Caldwell himself finds contradicting values for r in different experiments (1963, 1964a, 1964b), he does not refer to the discrepancy in his articles.

study	retest correlation endurance	correlation max. force - endurance	remarks
Elbel (1949) 1st exp.		0.26 to 0.40	
Elbel (1949) 2nd exp.		0.19 to 0.56	
Caldwell (1963)	0.79	0.13	at 50 % of maximal force
Caldwell (1964a)		- 0.09 to - 0.03	
Caldwell (1964b)	0.81	0.76	
Start and Graham (1964)		-0.36	endurance of relative force
	0.83	0.75	endurance of absolute force
Carlson (1969)	0.60 - 0.68		
Byrd and Jeness (1982)		- 0.27 to - 0.43	endurance is the time until the force falls below 50% of maximal

Table 3-6: Reproducibility of endurance time experiments, and correlation between exerted maximal force and endurance time in the same situation, based on relative force (unless otherwise stated).

Carlson (1969) assessed the relation between maximal force and endurance in another way. He divided subjects in three groups, ranging from low to high strength. The low strength group showed a longer endurance time than the high strength group at 50 %, 60 % and 70 % of the maximal force. At 80 % there was no difference.

Elbel (1949) correlated maximal grip strength with endurance of absolute force by the legs. The correlation coefficients varied from 0.13 to 0.43.

Correlation with anthropometric variables. Correlation between anthropometric variables and endurance is found by Caldwell (1963 and 1964a) to vary between -0.07 and 0.13.

He measured stature, weight, upper- and forearm length and upper- and forearm girth. Elbel (1949) measured the endurance with absolute weights instead of relative loads. He also found non-significant correlations (r varied from -0.09 to +0.17) between the endurance time of 1360 N leg extension and age, height, weight, total leg length and lower leg length for three groups of subjects. In a second experiment, described in the same article, the endured leg extension force varied from 900 N to the maximal force exerted by the subject (the maximum force exerted by any of the subjects being 3175 N). The correlation coefficient between endurance and weight, calf girth and thigh girth for both right and left leg varied from 0.01 to 0.56.

Infinite endurance limit. In some literature, it is suggested that, at a certain force level, force can be maintained indefinitely. Rohmert (1960) and Monod and Scherrer (1965) estimated this limit at 15 % of the maximal force. The estimate of Björksten and Jonsson (1977) is 7.9 % of the maximal force for continuous contraction, and 14 % for intermittent static contraction. Sjøgaard (1986, p. 142), however, states that "human skeletal muscles are not adapted for continuous long-lasting isometric activity. Indeed, no matter how low the energy turnover is within the muscle, resting periods are needed for the muscle to recover". The results of experiments described by Ulmer et al. (1989) indicate too that 15 % of maximal force can not be maintained forever. Even after an hour's endurance of only 2.9 % of maximal force, the electromyograph of some subjects indicated fatigue.

Models. Some authors generated a model for the force level-endurance relationship, based either on their own data or on data from literature. An overview of these models is given. All models can be seen in figures 3-21 and 3-22.

General legend to the formulas:

- t = maximal endurance time in seconds;
- T = maximal endurance time in minutes;
- f = force exerted divided by the maximal force;
- F = force exerted as % of maximal force.

Rohmert (1960 and 1965) generated the following model, based on measurement of arms and legs, 26 % to 63 % of maximal force:

$$T = -1.5 + \frac{2.1}{f} - \frac{0.6}{f^2} + \frac{0.1}{f^3}$$

Start and Holmes (1963) measured endurance at 33.3 % and 66.7 % of the maximal strength, and assumed that endurance at 0 % is unlimited, and at 100 % is zero. On this information, they based a number of equations of best fit. The three closest were:

$$T = 9.7 \log \frac{1}{f}$$

$$T = 10.5\left(\log \frac{1}{f}\right)^{1.08}$$

$$T = 8.73 \log \frac{1}{f} + 2.52\left(\log \frac{1}{f}\right)^2$$

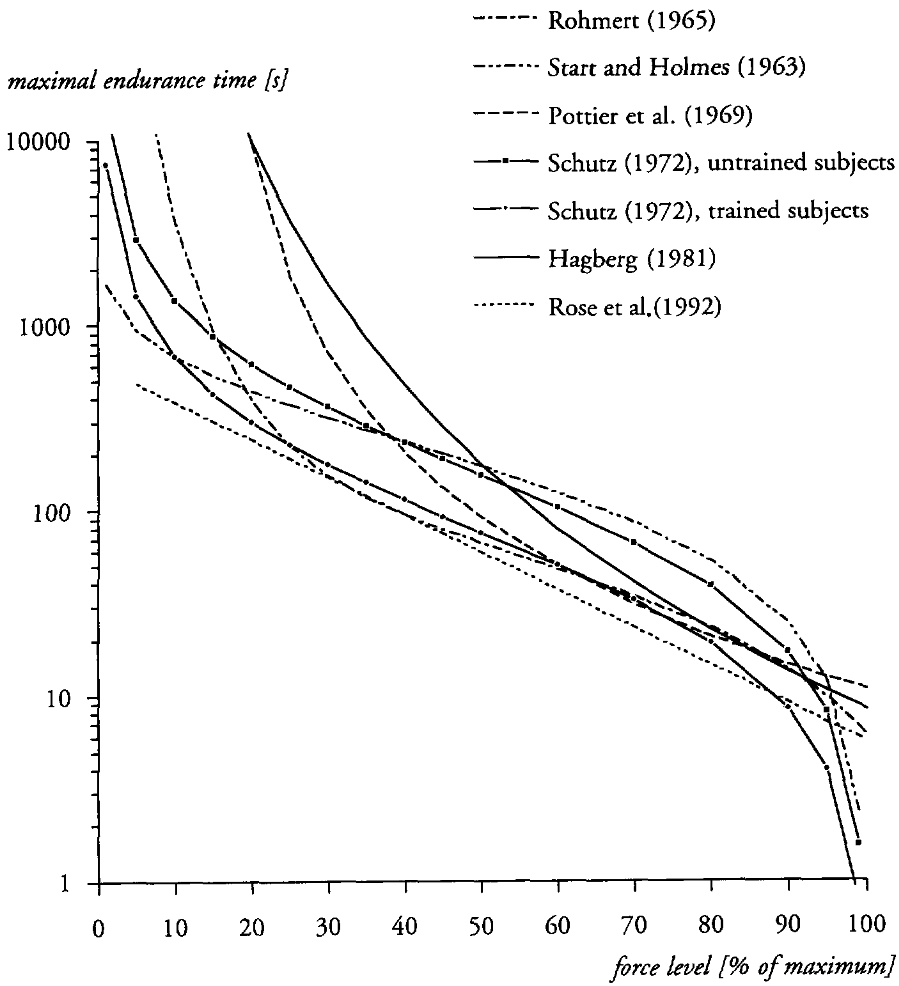


Figure 3-21: Various models describing the relationship between force level and maximal endurance time.

Monod and Scherrer (1965) deduced a model from force-endurance data of biceps, triceps, quadriceps and middle finger flexor. The formula extends to the prediction of endurance of cyclic work. Pottier et al. (1969) changed a coefficient, which results in the following formula:

$$t = \frac{7.3}{\left(f - \mathit{f}\right)^{2.4p}}$$

in which p is the time during which force is exerted, divided by the recovery time in cyclic work and f is the percentage of maximal force at which the endurance limit is supposed to be infinite. For endurance of static force, p = 1 and f = 15 %.

Schutz (1972) (also published by Schutz and Chaffin in 1972) measured the endurance of the biceps, with the elbow flexed at 45° and supported, and wrist loaded with 68 to

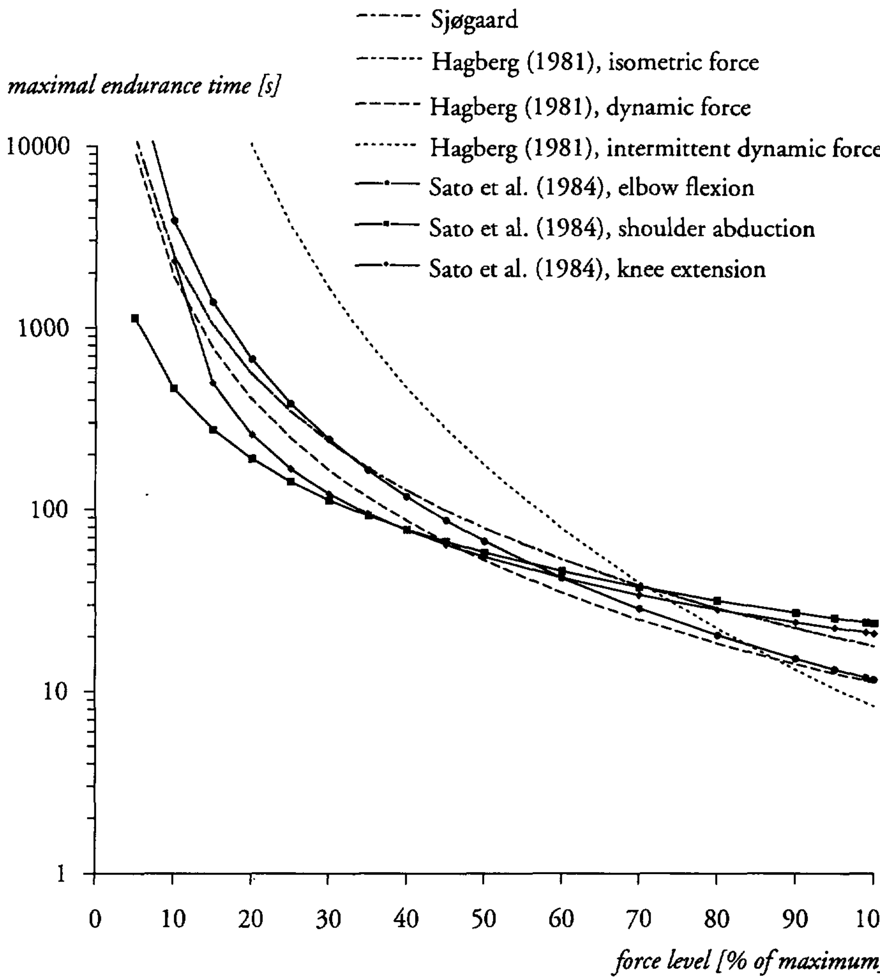


Figure 3-22: Various models describing the relationship between force level and maximal endurance time (continued).

204 N. It should be noted that only one subject was measured, before and after extensive training. With the resulting data, one formula for trained subjects and one for untrained subjects was made:

$$T = -2.54 + \frac{2.54}{F} \qquad \text{(untrained subjects)}$$

$$T = -1.25 + \frac{1.25}{F} \qquad \text{(trained subjects)}$$

Hagberg (1981) investigated endurance of elbow flexion during static, intermittent static and dynamic contractions. The dynamic contractions were eccentric and concentric at an angular velocity of 30°/s. The intermittent static contractions lasted for 2 s, with 2 s rest, resulting in a 4 s duty cycle. Surprisingly, the endurance of dynamic and isometric contractions proved to be similar at corresponding force levels. The following regression equations were made based on the results:

$\ln t = 12.74 - 2.14 \ln F$	(isometric contractions)
$\ln t = 12.69 - 2.23 \ln F$	(dynamic contractions)
$\ln t = 22.34 - 4.39 \ln F$	(intermittent isometric contractions)

Sato et al. (1984) fitted different regression lines to their data on endurance of elbow flexion, shoulder abduction and knee extension force. The r^2 varied between 0.92 and 0.95. The results were the following:

$\log T = 4.33 - 2.52 \log F$	(elbow flexion)
$\log T = 2.18 - 1.29 \log F$	(shoulder abduction)
$\log T = 1.96 - 1.23 \log (F - 8)$	(knee extension)

Sjøgaard (1986) shows with data from various research that 15 % of the maximal force can be maintained on average for about an hour, extrapolates the curve and suggests another formula to describe the relation between relative load and endurance, tailored to lower relative loads:

$$\ln T = 8.65 - 2.14 \ln F$$

Bishu et al. (1990) investigated the endurance while holding a box, with handles in various positions. They found a significant difference and consequently formulated four different formulas. They can, however, not be compared with the other models, because the weight of the limbs and the strain to maintain a posture are not included in the 100 % force. Therefore they are not included here.

Rose et al. (1992) made the following model, based on measurements of the arm, held horizontally, upper arm supported and wrist loaded with about 3 % to 100 % of the maximal force:

$$T = 10.23^{-4.69 f}$$

Handbooks. Both Hettinger (1963) and Lange (1991) quote the graph of the relation between relative force and endurance time as found by Rohmert. Grandjean (1967) quotes the graph of Monod and Scherrer, and states that static force exertion of less than 20 % of maximal force enables long endurance. Sanders and McCormick (1993) state that it is obvious that people can maintain their maximal force only briefly, whereas a lower force can be maintained for a rather more extended period. The evidence seems to indicate that strength and endurance are substantially correlated. As an example, they quote a study by Jackson et al. (1984) who found that strength tests predicted quite well the performance of work which involved an 'absolute endurance component'.

Conclusion. Static endurance is strongly influenced by the exerted force. It is generally accepted that, when the force is defined as a percentage of maximal force, the endurance is mainly determined by the force level, and seems to be less influenced by subject, sex, age, posture and muscle group. The literature does not agree on the effect of these factors. Whether subject, sex and age play an essential role, otherwise than influencing the maximum force, is not yet unequivocally determined. When significant differences are found, they are small. Various postures have a significant effect on endurance, but there is no agreement in literature as to the size of it. For different muscle groups, no significant differences were found, though they were expected on theoretical grounds.

The test-retest correlations of endurance found in literature are acceptable, with coefficients ranging from 0.68 to 0.83. There is not much correlation, though, between maximal force and endurance in the same situation, and hardly any between various anthropometric variables and endurance.

Although it is suggested that a certain force level (15 % or 7.9 %, according to different sources) can be maintained infinitely, not everybody agrees on this. The formulas to model force level-endurance relationship do not agree closely, which is best illustrated at very low or very high force levels (figure 3-21 and 3-22).

Any of the differences between results of various research may be caused by differences in experimental methods. No investigations were found into the influence of motivation and feedback on endurance, although it is noted by some authors that these are important factors.

3.5.4 (Dis)comfort

In ergonomics, comfort is generally defined as 'absence of discomfort'. If there is no discomfort at all, comfort is optimal by definition. Discomfort in ergonomics is mainly known in relation to reach zones, where the area close to the body is called 'comfort zone'. Controls put in this zone are easy to reach and therefore presumed to be comfortable to operate. For comfort during force exertion, no analogous reasoning can be given.

Comfortable force exertion. Exertion of 'comfortable force' is measured by Berns (1981), Bordett et al. (1988), Arnold (1991), Kanis (1989b and 1993) and Schoorlemmer and Kanis (1992). They all measured torque: Berns and Arnold did so on cylinders of various sizes (simulating packaging), Bordett et al. on several types of faucet handles. Kanis and Schoorlemmer measured torque, push as well as pinch forces on controls. All asked their subjects to exert a force that was comfortable to them for 4 s (Berns and Arnold for 20 s). All except Bordett et al. also measured the maximum force in the same situation.

Bordett et al. measured comfortable torque and grip strength of elderly females. The correlation coefficients they found between torque and grip strength varied between 0.44 and 0.79 per handle. The lower a correlation, the larger torques were exerted on the handle.

Arnold measured torque of adults, elderly and arthritic people and Berns of adults and elderly. Arnold used 20 s measurements and blocks of different sizes. The results were as follows. The retest correlation coefficient for five of the subjects was 0.97 for comfortable exertion. Packaging size had a significant influence on exerted comfortable torque for adults, but not for elderly and arthritic people. There was significant difference in comfortable exerted forces between the subjects groups. The ratios between the average comfortable and maximal forces can be seen in table 3-7. The comfortable force was in general slightly less than half the maximal force for Arnold, and slightly more for Berns. The variation coefficients of Arnold were of the same order for both comfortable and maximal forces, between 0.3 and 0.6 for adults and elderly people. For arthritic people, the variation coefficient for comfortable force in all three cases was about 1.

			ratio mean comfortable/mean maximal force				
subjects	study	*n*	push with thumb	push with index	lateral pinch	key pinch torque	torque
healthy	Berns (1981)	198					.71
	Kanis (1989)	34		.46	.56	.51	
	Arnold (1991)	36					.41 - .46
	Schoorlemmer and Kanis (1992)	19	.43		.61	.57	
elderly	Arnold (1991)	12					.45 - .53
arthritic	Arnold (1991)	12					.38 - .50
spastics	Schoorlemmer and Kanis (1992)	5	.35		.73	.37	
parkinson	Schoorlemmer and Kanis (1992)	3	.71		.80	.84	
rheumatics	Kanis (1989)	28		.45	.54	.46	
	Schoorlemmer and Kanis (1992)	28			.51		
muscle	Kanis (1989)	6		.48	.67	.72	
diseases	Schoorlemmer and Kanis (1992)	6			.64	.88	

Table 3-7: Ratio of mean comfortable and mean maximal forces exerted by women and men.

The publications of Kanis and Schoorlemmer concern various finger force measurements with different subject groups. Their subjects included both women and men. Kanis measured healthy and rheumatic subjects, and Schoorlemmer and Kanis measured spastic subjects, and persons suffering from Parkinson's Disease or a muscular disease. The ratios between the average comfortable and maximal forces varies between 0.35 and 0.88, as can be seen in table 3-7. The variation coefficients of the comfortable forces measured by Schoorlemmer and Kanis varied between 0.3 and 0.7 (with one exception of 0.98), and those of maximal force between 0.2 and 0.8. The group of healthy adults had the smallest variation coefficients. For the measurements of Kanis, the variation coefficients of the comfortable forces varied between 0.5 and 1.0, and those of maximal force between 0.6 and 1.1. The variations coefficients of comfortable forces seem to be only slightly larger than those of maximal forces.

Discomfort of dynamic force. Garg and Beller (1990) assessed the perception of dynamic force during one-handed maximal dynamic pulling. The subjects were asked to rate the level of perceived exertion on the Borg scale as published by Borg in 1962, and also the overall comfort on a scale from 'extremely comfortable' (0) to 'extremely uncomfortable' (7), for elbow, shoulder and back. The rating of perceived exertion decreased with an increase in speed of pulling. The high speed pulls were perceived as being more comfortable than the low speed pulls. The effect of speed on measured peak and dynamic strength was the reverse: higher forces were exerted at lower speeds. Thus, it appears that when people have to exert maximal force they prefer high-speed pulls, enabling less force to be exerted, over low-speed pulls enabling greater force to be exerted.

Discomfort of repetitive force exertion and endurance. Wiker (1991) assessed discomfort during repetitious pinch grasps. Series of 15 s isometric forces ranging between 5 and 25 % of the maximal force were exerted, with rest periods of 7.5 or 15 s in between, for a period of 104 min. At regular intervals, the subjects estimated the magnitude of discomfort sensed by adjusting the length of a line, anchored between 'no sensations' and 'maximum tolerable discomfort'. The results showed a rapid onset of significant discomfort and changes in the perception of forces produced. Effects generally increased as magnitude of required force, work/rest ratio and task duration were increased.

Schutz (1972) investigated discomfort during measurement of work-rest cycles of elbow flexion force. Four different types of pain were observed, all confined to the muscles of the upper arm. Unfortunately, it was not possible to quantitatively analyze the ratings, as the subjects could not quantify the level of intensity of discomfort.

According to Dul et al. (in press), discomfort of static postures can be based on endurance data. Their work-rest model estimates at population level the mean remaining endurance capacity of a static posture. Discomfort can be predicted from the remaining endurance capacity, because of a known relationship of the latter with discomfort as measured with the Borg rating scale.

Sato et al. (1984) measured the onset of subjective fatigue and pain at the same time with the endurance of elbow flexion, shoulder abduction and knee extension force. They fitted different regression lines to their data, see figure 3-23. The equations are:

$\log T = 3.14 - 2.21 \log F$ (tiredness, elbow flexion)
$\log T = 3.33 - 1.99 \log F$ (pain, elbow flexion)
$\log T = 1.20 - 0.96 \log F$ (tiredness, shoulder abduction)
$\log T = 1.69 - 1.10 \log F$ (pain, shoulder abduction)
$\log T = 1.58 - 1.33 \log (F - 3)$ (tiredness, knee extension)
$\log T = 1.35 - 0.96 \log (F - 8)$ (pain, knee extension)

The r^2 varies between 0.74 and 0.95.

Discomfort of posture. Discomfort during maintaining of different postures was investigated by Bonney et al. (1990), Wiker et al. (1990), Van der Grinten (1990 and 1991) and Serratoz-Perez and Haslegrave (1992). The former two asked their subjects to indicate their discomfort on a visual analogue scale, the last two used Borg's scale and an indication of the body regions where discomfort was experienced. Van der Grinten (1990) found that, during two–minute measurements of static postures, the effects of slight posture variations could be assessed with this last method in most cases. In research published in 1991, he assessed the test-retest reproducibility and found that with low relative loads it was reproducible for comparative purposes. However, when long intervals (some weeks) elapse between successive experimental conditions, one should be aware of shifts in average scores.

The postures of Wiker et al. were dynamic, subjects moved a stylus cyclically for 30 s, with 30 s rest. Subjects completed five sets of 12 trials within 75 min. After completion of each set of 12 movement trials, discomfort was rated. Bonney et al. had the discomfort rated every 2 min., Van der Grinten and Serratoz-Perez and Haslegrave every minute.

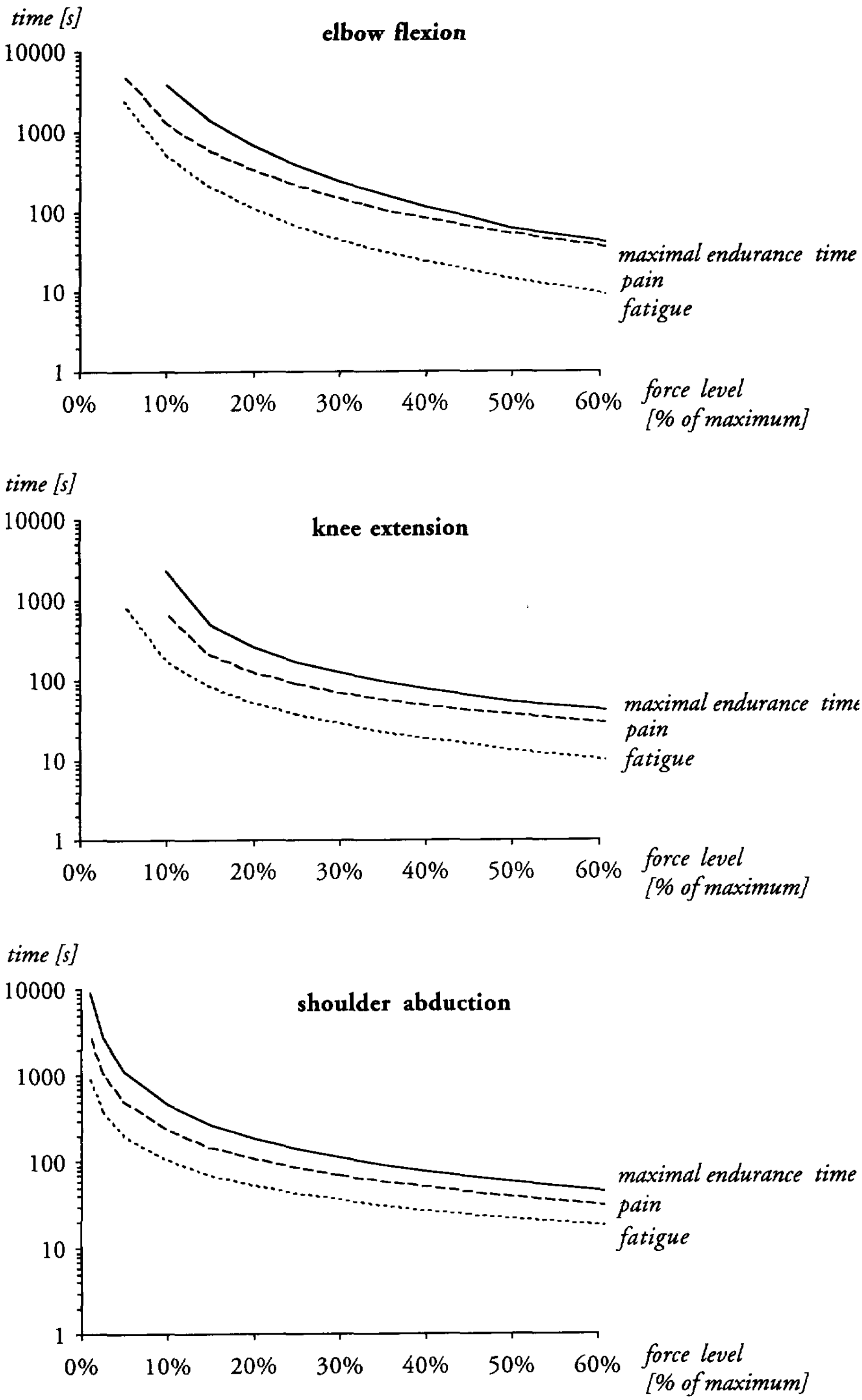


Figure 3-23: Onset of fatigue and pain measured during maximal endurance measurements of elbow flexion, shoulder abduction and knee extension force (after Sato et al., 1984).

Wiker et al. found that awkward arm postures produced substantial and rapid onset of postural fatigue and discomfort during a manual task where strength demands are low. Other arm postures, however, that appeared to be awkward, or which decreased strength capacity, did not necessarily increase discomfort or fatigue. Variations in strength capability found among arm postures within an individual subject, or among subjects assuming the same posture, did not affect onset of fatigue or discomfort when hands are postured near or above shoulder level. Therefore Wiker et al. suggest caution against sole reliance upon strength capabilities as predictors of fatigue and discomfort.

Related subjects. Some literature was found on related subjects within the field of the subjective experience of submaximal and sub-endurance force exertion. Topics found in literature include the perception of load (Stevens and Mack, 1959; Dirken, 1964), the perception of exertion (Garg and Beller, 1990; Deeb and Drury, 1992; Ulin et al., 1993), the perception of joint discomfort (Genaidy and Karwowski, 1993), the comparison of several methods of subjective scaling of force (Eisler, 1962), the comparison of different weights as a degree of exertion (Borg, 1990), and the discomfort during use of a wrist support (Genaidy et al., 1992).

Stevens and Mack found that the apparent magnitude of handgrip force increases as an exponential function of the force exerted on a hand dynamometer, the exponent being approximately 1.7. Eisler found that the subjective force was related to the physical force with an exponent of 1.6, and this exponent is the same for force of foot pressure and force of hand grip.

Dirken found that the rating of load on a scale from 1 (no load) to 7 (200 W load) during cycling at different loads is reproducible.

Genaidy et al. found that a wrist support which limits flexion resulted in significantly low discomfort scores compared to those without wearing the wrist support.

Conclusion. There is no standard method for measuring discomfort, and even less so for measuring discomfort during submaximal force exerted over a longer time. There are two main ways to investigate (dis)comfort. With the first, subjects are told to exert force on a 'comfortable' level, so the dependent variable is the exerted force (presumably comfortable). With the second, the force level is predetermined and the dependent variable is the subjectively reported amount of discomfort at a certain time. In all experiments, however, there is one common factor: the subjects are asked in advance to think about and indicate their feelings of (dis)comfort. The experiments that are repeated (Dirken, 1964; Arnold, 1991; van der Grinten, 1991) all generate reproducible results. Variation coefficients of comfortable forces are of the same order as variation coefficients of maximal forces.

Discomfort seems to increase with increasing force, work/rest ratio and task duration (Wiker, 1991). For dynamic one-handed pulling, it is suggested that exertion of maximal force at high speed is more comfortable than at low speed (0.7 vs. 1.1 m/s, Garg and Beller, 1990). Wiker et al. (1990) suggest caution against reliance upon strength capabilities as the sole predictors of fatigue and discomfort.

3.6 Conclusion

Much literature can be found on some aspects of force exertion, like the difference between the sexes. Other aspects, like (dis)comfort, seem to be little investigated. The influence of most variables on force exertion is investigated to some extent, leaving many new areas to be explored, and older areas to be investigated more thoroughly.

Measuring methods are not very standardized and often not described extensively enough. This is even more the case for measurements of endurance, discomfort and dynamic force exertion. In general, research tends to be unsystematic and often dictated by the need to gain information for a specific project or situation. The aim of most investigations is to gather specific data, not to provide a model or explain or generalize the results.

On the basis of the literature reviewed in this chapter, it can be determined in which areas research is most needed to contribute to the development of an atlas of human forces. This determination is described in the following chapter.

4 Approach

4.1 General approach

The previous chapters reflect the information on the characteristics of consumer product design and force exertion that was gathered and analyzed. The backgrounds and methods of research to date on the subject were indicated in chapter 1 and more extensively discussed in chapter 3. A basic incompatibility between information needed for consumer product design and research methods was noted in 1.4, Product design and ergonomic research. This observation led to the formulation of the objectives of this project as discussed in chapter 2.

The aim of the present chapter is to outline the proposed way of meeting these objectives. First, uncharted areas of force exertion in relation to consumer product design and relevant experiments are identified (4.2) and demarcated (4.3). The choice of the four topics which are elaborated on in subsequent chapters, is motivated in 4.4. These topics are not explicitly related to each other, but must be seen within the framework of the project to explore various unknown or underdeveloped areas of research on force exertion.

The selected experiments and their results are described in chapter 5, 'Experiments'. The relations between the results of the different experiments and the relations between these results and anthropometric variables are investigated in chapter 6, 'Overall analysis'. It is examined whether strength profiles of users exist and in how far force and endurance can be predicted from their relations. The newly attained insights are incorporated into answers to the questions stated in the objectives.

In chapter 7, 'Towards an Atlas', generalized conclusions on the set-up of research for product design are drawn from the experiments performed. An attempt is made to sketch an outline of an atlas of human force and to assess the extent to which such an atlas can contribute to the design of consumer products.

4.2 Possible areas for experimenting

Various unknown or underdeveloped areas of research on force exertion in relation to consumer product design exist, and these could be explored in view of the aim of this project. In this paragraph, these areas will be identified.

Subjects. There is certainly not enough knowledge about the force exerted by subjects from different population groups, nor about the variance within such a group, from weaker percentiles to stronger percentiles. In particular children, elderly and disabled persons should be investigated, but ethnicity may also make a difference (something which is recognized in anthropometry).

Dynamic force. Force exerted on products is estimated to be more often dynamic than static. Some research on dynamic force exertion has been done, but little compared to static force. For designers, it is difficult or impossible (depending on the force needed) to find relevant information. Therefore more research into dynamic force is necessary.

Postures. In nearly all experiments, postures are standardized in various ways. It is known that posture has a significant influence on the exerted force, and it is believed implicitly that if the posture is not defined in advance, it may vary to a large extent, so the exerted force will vary accordingly. This would render an experiment irreproducible. However, a verification of this thought by an experiment could not be found in literature. An investigation into the reproducibility of forces exerted in a non-standardized posture would be very welcome, because designers generally are not dealing with people and products in standardized postures, but with unpredictable users handling products within a range of positions which vary within known limits. Users in real life are not instructed to exert force with one or two fingers, as subjects are in the laboratory, but they use their thumb, fist or elbow according to their own whims. Forces will be predicted more true to nature, and the experiment will therefore be more valid, if they are measured in a realistic situation. Nevertheless, the results should always be reproducible.

Force around one or more joint(s). A sadly neglected area is the relationship between forces exerted around one or more joints. In biomechanics, it is implicitly supposed that the maximal moment that can be exerted around a joint at a certain angle is always the same, independent of the number of other joints (or really: muscles) that participate. Again, no literature could be found to confirm this assumption.

Combined types of forces. Neglected, too, are combinations of two or more different forces exerted at the same time. For example, pushing and turning or pinching and turning, as with child-resistant bottle caps, or pulling and turning, or pinching and pulling. Do these different forces influence each other when they are exerted at the same time? With a bit of luck, the single force that can be exerted may be found in literature. But then, how to cope with the combination? Do both forces increase because of co-contractions? Do they decrease because there are opposing forces at work? Or do they perhaps remain the same? No ergonomics literature was found on this topic, either.

Correlations. If correlations between different forces of the body are high, prediction of one force from another may be possible. Such correlations are published in some publications, although mostly as a by-product of research with a different purpose. However, not many correlations could be found (see table 3-4). No literature at all could be found on the hypothesis that correlations between forces exerted with the same muscle(s) may be better than between those exerted with different muscles.

Endurance. If comfort is investigated, the relation with endurance of submaximal force is an important feature to include in the investigations. Comfort measurement of a four-second force exertion only is not sufficient, and if a range of force exertions is examined, some pattern or relation with endurance may be discovered. Concerning endurance, much research has already been done, although the outcomes on the influence of variables often contradict each other, see 3.7.2, 'Endurance' (of static force). Additional research may help to find the reason for these contradictions, and get them straightened out.

Comfort. A very important, but controversial, area of research is 'comfort'. Comfort is controversial because there is no standardized method of measurement, and also a good operational definition is lacking (which does not make measuring it any easier). Various attempts to measure comfort or discomfort are summarized in 3.7.3, '(Dis)comfort'. Comfort is important to the success of consumer products as these are often bought by one of the future users. If not satisfied, the user will not buy the same product again, and so uncomfortable products will not sell in the long run. When the news is spread from mouth to mouth, or by publications of consumer organisations, it will not sell in the short run either.

4.3 Demarcation

Not all experiments are feasible or advisable within the limiting conditions of the project. The following topics, for example, will not be investigated for various reasons.

Manual materials handling. In the few experiments that will be conducted, manual materials handling, like lifting and carrying, will not be included. There is no direct need to investigate manual materials handling within the framework of this project, because a fair amount of research has already been collected on that subject, e.g. by Ayoub and Mital (1989), and for consumer product design the priorities are different at this moment.

Static or dynamic force. Furthermore, only static force is investigated. This is in the first place because the PhD-program leaves little time to dabble in research which needs the more complicated equipment and more elaborate experiments that dynamic force exertion requires. In the second place, not yet every secret about static force exertion has been revealed, so there is still enough to investigate in that area. This does not mean, though, that dynamic force is considered to be unimportant. On the contrary, it is recognized to be very valuable, and there certainly is a need for more information, too. But one cannot investigate everything at the same time.

Subjects. The only subject variable included in the experiments is gender. The experiments do not include subjects from different population groups (children, elderly, disabled and persons of various nationalities). The main reason is that, in order to measure different groups to gather information for force prediction, one must know what one wants to predict and thus how one has to measure. We need to find out what ought to be measured in the first place, and how, in order to be able to measure force the right way with the right subjects and larger populations. Alas, no time was left within the project to do this extended population investigation to establish frequency distributions, standards and percentiles. Therefore limited numbers of subjects participated, and representativity was not stressed.

Physiological measurements. The question how much force can be sustained for eight hours, five days a week, optimizing efficiency but without ill effect to the user, is not as critical to consumer product design as it is to industrial ergonomics. This research will thus not explicitly focus on the problems of preventing injury and improving efficiency, or obtaining maximal power output. Consequently, physiological measurements like oxygen intake, blood pressure, heart rate or electromyograms will not be included as they are less relevant within the framework of this project.

Conclusion. We are only interested in the amounts of force exerted on consumer products in different situations. The experiments are restricted to the measurement of static force exerted by a group of female and male adults in a variety of conditions.

4.4 Choice of experiments

Four experiments have been selected for this research. They include five of the areas identified above as interesting. These are: the postures, the forces round one or more joint(s), correlations between forces, (dis)comfort, and endurance.

The standardized postures problem is one of the most pressing, and one of the most easy to experiment on at the same time. If less standardized, i.e. more or less free, postures can be used, research becomes much easier and at the same time more effective for designers. It is therefore the first area selected to investigate in more detail.

Next, the forces exerted around one or more joints are investigated, to find out whether the number of participating joints influences the maximal force that can be exerted, whether there is a difference between moments exerted round a joint in single and in multi-joint force exertions, and how different forces exerted with the same group of muscles correlate.

An acceptable method for researching discomfort experienced during force exertion would be of great value to designers, especially if researched in combination with endurance and submaximal force exertion. These topics are the subjects of the third and fourth experiments.

5 Experiments

5.1 Static force exertion in postures with different degrees of freedom

Summary

In assessing human force exertion, the use of standardized postures can lead to inaccurate prediction of the forces and postures which occur in everyday life. Therefore force data obtained using postures freely chosen by the subjects themselves may be considered more relevant. A standardized posture, however, is generally considered to yield more reliable data. The question arose whether it would be possible to combine the two in some way, calling the result a 'functional posture'. Research was necessary to determine a way of operationalizing these functional postures, and to test their reproducibility.

First, a method is proposed to describe functional postures through explorative research. This includes the fixation of members that transfer force to the outside world, while the rest of the body is allowed to move freely. The results of further research show that the exerted force is reproducible in free, functional and standardized postures. The difference in average force, though, is considerable and significant. The conclusion is that force exertion in free posture is most suitable for design research. An article on this subject, which contains most of the information of the first two experiments in this chapter, has been published (Daams, 1993).

5.1.1 Introduction

When studying the possibility of creating an Atlas of human force exertion for designers, the question arises as to what information and which data are relevant. Until now, most research on force exertion was done using standard postures. One of the problems encountered by the designer is that in most cases the posture of the user during force exertion cannot be adequately anticipated.

The force that can be exerted is influenced to a high degree by the subject's posture. According to Caldwell et al. (1974, p. 203), "a model of the body must be carefully conveyed to the reader so that he can understand the experimental conditions and use the data." Standardized postures are generally used, though the methods of description tend to vary considerably. Information on, for instance, pushing and pulling in standing positions can be found in the literature (e.g. Rohmert and Hettinger, 1963; Burandt, 1978; The Materials Handling Research Unit, 1980; Gallagher, 1989; VanCott and Kinkade, 1972; Eastman Kodak, 1986), each with a different description of the posture (see appendix C). Even so, force data acquired from measurements in standardized postures may not have predictive validity; they may be unsuitable to predict forces in practice if these are exerted without constraints on posture.

Research on force exertion in free posture is scarce. Chaffin et al. (1983) investigated force exertion in standing, free posture, and claim that the repeatability of the average force of a group of subjects is acceptable, as is the average posture of the group of subjects. Haslegrave et al. (1988) looked into force exertion in free posture and found little correlation between posture and normalized strength capability.

5.1.2 Objective

The aim of this research was to find out whether use of free postures during measurement of static, maximal force exertion can be recommended. To that end, the influence of the degree of freedom of postures on maximal static force exertion should be investigated. The size and reproducibility of forces in free postures that can be relevant to design should be compared to the results to those generated with standardized postures, which are considered to yield more reliable force data.

5.1.3 First experiment

Method of the first experiment

Subjects. Two women and three men of different age, height and weight took part in the experiment. All were employees of the Department of Product and Systems Ergonomics, Delft University, and all were in good health. The average age was 37 years (ranging from 24 to 54), the average body height was 1.81 m (ranging from 1.69 to 1.94) and the average body weight was 77 kg (ranging between 63 and 94). The number of subjects was limited, because after these five measurements it was suspected that more information could be obtained by slightly altering the experiment. The experiment, continued with one posture altered, was labeled 'experiment 2'.

Equipment. The horizontal component of the exerted force was measured with the aid of a force transducer with strain gauges, an amplifier and an xt-recorder. The subjects exerted force on a handle that was connected to the force transducer. For optimal force exertion, different handles were used for pushing (doorknob round model, diameter 59 mm, slightly convex) and pulling (bar with diameter 32 mm, a good size for a pulling bar according to Drury (1980) and Fähnrig et al. (1983)). The height of the handle was adjustable in 5 cm intervals. Anti-slip mats on the floor prevented the subject from sliding. A side view of the subject's posture during measurements was recorded on video.

Experimental design. Three independent variables were used:

1. Type of posture (see figure 5-1):
   . free;
   . standard 1 (s1);
   . standard 2 (s2).
2. Force direction:
   . pull;
   . push.
3. Height of handle above floor:
   . shoulder height;
   . elbow height.

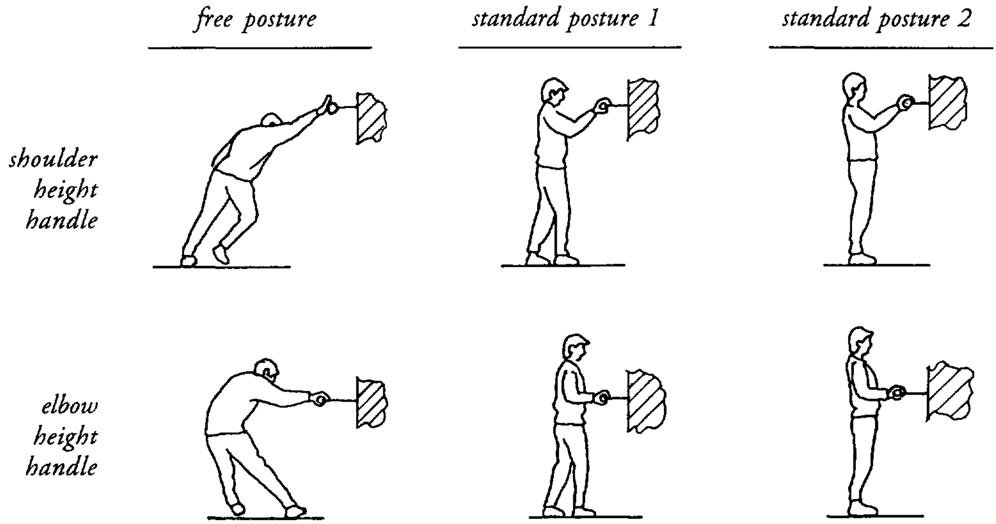


Figure 5-1: Experiment 1. Two of the experimental variables: three types of posture and two handle heights. Free posture: The member transferring force to the handle has to be the preferred hand. In all other respects the subjects is allowed to move freely. Standard posture 1 (s1): The subject stands upright, pulling or pushing hand pronated, the elbow in 90° flexion and one foot 30 cm in front of the other. Standard posture 2 (s2): As standard posture 1, but with feet together.

Combination of these variables resulted in 12 different ways to exert force. The measurements were repeated once, after a few days. If during the second free posture measurement, the position of the subject's feet differed from the position assumed the first time, the subject was requested to repeat the experiment with the feet in the original position. Thus, on the second occasion, subjects sometimes were asked to exert force in four different postures.

After ten months, part of the experiment was executed a third time, to look into the long-term reproducibility of forces and postures in free-posture experiments. This time the subjects exerted force only four times: pushing and pulling on shoulder and elbow height, in free posture. The dependent variables are: static maximal force, and the subject's posture during force exertion in free posture.

Procedure. The subjects wore ordinary indoor clothing that did not restrict them in the movements needed for the experiment. They wore flat-soled shoes which did not slip on the anti-slip mat. They were asked to exert with one hand, per combination of variables, a static maximal force for 5 s (1 s build up, 4 s maximum force), following the method of Caldwell et al. (1974). Maximal force was defined as the mean force exerted during the last 4 s. The minimum rest period between measurements was 2 minutes. The subjects were not encouraged during the experiment. They were instructed to stop pushing or pulling as soon as they started to slip, to prevent accidents, and to prevent the experiment from being biased, but this proved an unnecessary precaution.

The exerted force was read from the xt-recording paper, with an accuracy of ± 2.5 N. The postures recorded on video tape were examined visually.

Results of the first experiment

Table 5-1 gives the average maximal force of the first two trials, for all subjects per combination of variables, and the forces in free posture measured again after ten months. There is a considerable difference between the results of s1, s2 and free postures.

force		shoulder height				elbow height			
		first two times		after 10 months		first two times		after 10 months	
direction	posture	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s
pull	free	263	76	283	61	327	69	331	100
	standard 1	145	40			140	33		
	standard 2	100	30			93	17		
push	free	261	49	276	93	301	44	318	75
	standard 1	147	37			141	32		
	standard 2	70	10			73	16		

Table 5.1: Experiment 1. Average and standard deviation of the maximal force [N] exerted by all subjects (n = 5, average of the first two trials, and one trial ten months later) per combination of variables.

To establish reproducibility, the retest correlation is calculated. The correlation coefficient r between the forces exerted on the first and on the second occasion, is 0.76, 0.76 and 0.82 for free, s1 and s2 postures respectively. For the free posture measurements with the feet in identical positions, the retest correlation coefficient is 0.83. In view of the limited number of subjects, the significance of these correlation coefficients at $p < 0.05$ is questionable.

Postures of subjects during force exertion in free posture show a remarkable intra-individual reproducibility, as two-thirds of the repeated postures appeared identical. The average position of the feet is shown in figure 5-2. It is expressed as a percentage of body height, to be consistent with the way the handle height is defined, i.e., also related to the height of the subjects. With the feet in identical positions on both occasions, intra-individual free postures appear fully reproducible.

In the long term, i.e., after ten months, both forces and postures appeared to be as reproducible as in the short term, i.e., after two or three days. The average forces as they appear in the table were not significantly different, according to the Wilcoxon signed-rank test with $\alpha = 0.05$. The force correlations of the third measurement with the previous two were 0.71 and 0.81 respectively. Again about two-thirds of the repeated postures appeared identical on the video pictures.

During the experiment, subjects commented spontaneously on the standardized postures. They perceived them as unnatural and considered it impossible to exert much force.

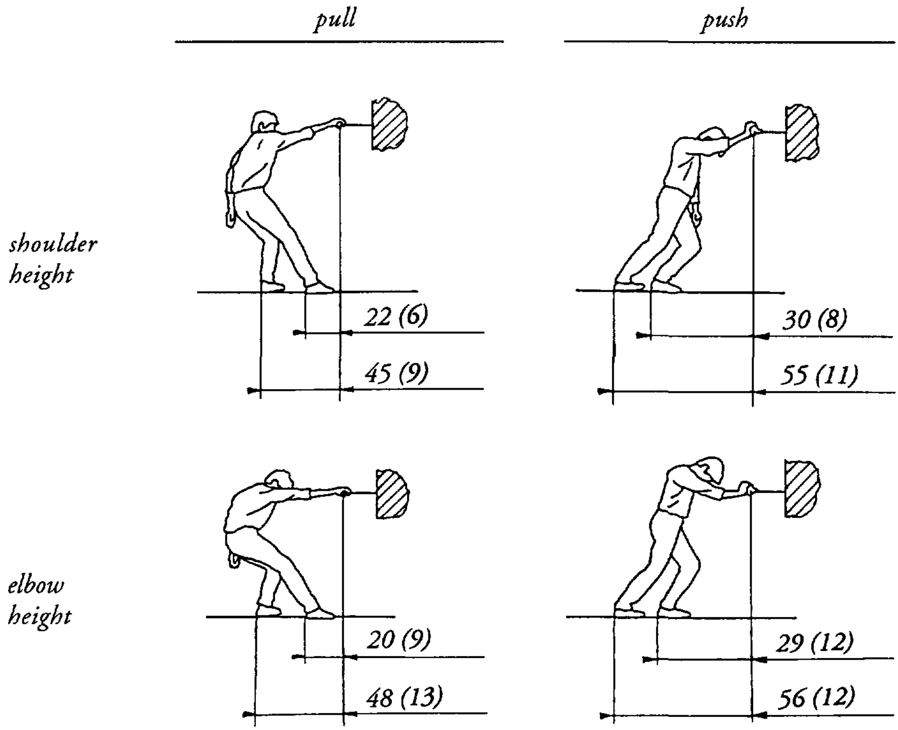


Figure 5-2: Functional posture: average position of the feet (and standard deviation) as percentage of body height during force exertion in free posture of the first experiment (n = 5, average of two trials).

Discussion of the first experiment

The differences in average magnitude of force between the three types of posture are considerable and significant. Static equations can explain these large differences. With maximal static force exertion, all forces should add up to zero, as should all moments. If not, movement will result, and the force will become dynamic rather than static. With these equations, the maximally exertable force can be calculated from handle height, weight of the subject, position of the centre of mass of the subject and the pivot around which rotation would start. This pivot is either the front of the forward foot when pulling, or the rear of the back foot with pushing.

Varying postures result in varying positions of the centre of gravity and pivot. With standardized postures, laws of statics limit the force that can be exerted. When too much force is exerted, the subjects will push or pull themselves out of position so the required posture no longer exists. In standard posture 1, more force can be exerted than in standard posture 2, mainly because of the location of the pivot. In free posture, the centre of gravity and the pivot are located in such a way that the maximally exertable force easily exceeds the capacity of the subject. Therefore the maximal force in free posture is larger and cannot be predicted from static equations. This explains the large differences in results between the postures.

The large differences in average magnitude of forces between the three types of posture clearly show the importance that should be attached to restrictions on posture when applying the results of force measurements to design guidelines, for example. Reproducibility of force exertion in free posture is nearly the same as in standardized postures. With the feet placed in their original position, reproducibility is even greater. The intra-individual reproducibilities of the forces and the postures in free posture are highly satisfactory. This supplements the findings of Chaffin et al. (1983).

Identical positioning of the feet may improve the intra-individual reproducibility of postures and, consequently, the reproducibility of force measurements. Therefore it is proposed that a 'functional posture' be defined by fixation of the position of those body members that transfer force to the outside world, while the rest of the body is allowed to move freely. An acceptable (though arbitrary) position of the members can be obtained by taking the average position assumed by subjects in free posture during preliminary research. This idea, applied to the results of this study, produces the functional postures shown in figure 5-2.

5.1.4 Second experiment

Objective of the second experiment
It was expected that a functional posture would yield a force equal to the force exerted in free posture, and with a higher reproducibility than if the force were exerted in any other posture. To verify this, a second experiment was carried out.

This second experiment also gave the opportunity to look into the repeatability of forces in free posture with both extreme handle heights and handle heights not related to body height.

Method of the second experiment
The method used for the second experiment was the same as the one used in the first experiment. This time the experiment involved 20 subjects (10 female, 10 male; see table 5-2). The majority were students of the Department of Product and Systems Ergonomics, and none had participated in the first experiment. Standard posture 2 was replaced by the functional postures that originated from the first experiment.

In addition, subjects were asked to push and pull with handle heights of 0.70, 1.30 and 1.70 meter, in free posture only. These six measurements brought the total to 18 different ways to exert force.

	females		males		both	
	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s
age [yrs]	25	4	22	3	23	4
body weight [kg]	68	7	72	8	70	7
body height [cm]	174	9	188	6	181	10
shoulder height [cm]	144	8	155	6	149	9
elbow height [cm]	108	6	117	4	112	7

Table 5-2: Experiment 2. Characteristics of subjects. 10 women and 10 men. Total n = 20.

Results of the second experiment

Table 5-3 shows the average maximal forces exerted. Table 5-5 shows the measures for reproducibility of the forces. At combined shoulder and elbow height, the retest correlation coefficient r is 0.87 for the forces measured in both free and functional postures, compared with 0.79 for the S1 posture and 0.89 for forces measured in free posture with the position of the feet identical on both occasions. At 0.70, 1.30 and 1.70 m, r is 0.90 on average, ranging from 0.86 to 0.95, for pushing and pulling at all three heights. All the above correlations are significant for $p < 0.01$. For women and men separately, the correlation coefficients will be slightly lower, but still significant. The t-tests on average group differences, comparing the results of the first and the second measurements, indicate good reproducibility: 16 of the 18 average group differences are not significantly different.

handle height	force direction	posture	females $\bar{x}$	females s	males $\bar{x}$	males s	both $\bar{x}$	both s
shoulder height	pull	free	201	56	301	65	251	79
		functional	198	51	253	48	225	56
		standard 1	122	29	145	25	134	29
	push	free	198	72	304	53	251	82
		functional	186	42	236	34	211	45
		standard 1	107	16	136	26	122	26
elbow height	pull	free	235	106	400	56	327	111
		functional	249	86	351	54	300	87
		standard 1	128	27	168	33	148	36
	push	free	225	93	349	96	287	112
		functional	194	61	285	93	240	89
		standard 1	108	18	147	25	126	28
0.70 m	pull	free	292	97	541	81	416	154
	push	free	185	57	393	134	289	147
1.30 m	pull	free	223	80	347	55	285	92
	push	free	221	103	337	83	279	109
1.70 m	pull	free	196	56	263	60	229	66
	push	free	181	75	300	50	241	87

Table 5-3: Experiment 2. Average and standard deviation of the maximal force [N], average of two trials, exerted by all subjects (10 men, 10 women) per combination of variables.

The relative deviation of the exerted force is obtained by dividing the absolute difference of the two repeated measurements by their sum. The average relative deviation of the individual mean of the two measurements is 7.4 %, 6.3 % and 6.7 % for free, functional, and s1 posture respectively.

Analysis of variance was used to find out to what extent the exerted force depends on the handle height (shoulder and elbow height), direction of force, type of posture, sex and subject variables. In the model of variance these five factors and their interactions were all included. This resulted in a multiple correlation coefficient of 0.98. The analysis showed that most of the variance may be explained by differences in posture (41 % of the variance explained by the model) and subjects (35 %). Of the last score, 15 % may be attributed to differences in sex. There are significant differences between the forces exerted with various handle heights and directions of force, but these explain only 4 % and 1.5 % respectively of the model variance. The same applies to the interactions; most are significant but contribute little to the model variance.

There seems to be little correlation between the horizontal distance between the feet and handle, and the forces exerted on shoulder and elbow height. If the distance to the handle is defined as the distance measured from the point halfway between both heels to the vertical projection point of the handle, r ranges from 0.15 to 0.49 for each of the combinations of gender, handle height and force direction. However, if the distance from one heel to the projection point of the handle is considered, i.e., from the foremost foot for pulling and from the other foot for pushing, the correlation appears only slightly better ($r = 0.36$ to 0.60). In one exception, pushing at shoulder height, the correlation coefficients were found to be 0.63 and 0.78 respectively.

Of the 18 possible combinations of variables (handle height, push/pull, posture) the correlation coefficient between the exerted force and body height is on average 0.69, ranging from 0.56 to 0.84. There seems to be less correlation between the exerted force and body weight, on average $r = 0.65$, ranging from 0.45 to 0.76. Hardly any correlation could be found between the exerted force and girth of the upper arm (relaxed), where $r = 0.19$ on average, ranging from 0.04 to 0.37. The correlation between forces exerted in 18 different situations is 0.80 on average, ranging from 0. 54 to 0.96 (with one exception of 0.38 in the case of correlation between pulling at shoulder height in s1 posture and pushing at 0.7 m in free posture). Of the 153 correlations, 84 % (129 cases) show more generality than specificity because the coefficients were larger than, or equal to, 0.71. All correlations with $r \geq 0.38$ are significant at $p < 0.05$ level.

In view of the results it appeared that any further analysis of the postures would not alter the conclusions.

Most subjects commented spontaneously on the standardized posture, as happened during the first experiment.

5.1.5 Third experiment

Objective of the third experiment
A third experiment was carried out, for two reasons. In the first place to find out whether the results of an experiment with free posture are reproducible too if the position of the handle is not fixed, as in the first two experiments. In the second place to have the people who took part in the other experiments (as described in 5.2 to 5.4) perform part of this experiment, too, in order to get a complete data set with the results of all experiments for as many subjects as possible. This complete data set was needed for the overall analysis, as discussed in chapter 6.

Method of the third experiment

This time the experiment involved 22 subjects (10 female, 12 male) who all participated in at least the endurance experiment, so their anthropometric characteristics are therefore nearly equal to those in table 5-9. Nearly all were students of the Faculty of Industrial Design Engineering, and none had participated in the first two posture experiments.

The method used for the third experiment was partially the same as the one used in the first experiment. Again, pushing and pulling at shoulder and elbow height were investigated, this time however in free posture only, as it has been established with the first two experiments that this serves the purpose. Furthermore the exertion of torque on a jam jar is measured in two postures, see figure 5-3. With the first posture the jam jar is fixed with the lid at a height of 0.95 m. The subjects should try to open the jar with only one hand on the lid, but otherwise free in their posture. With the second posture, the jam jar was held in hand and the subjects could try to open it with their hands any way they wanted.

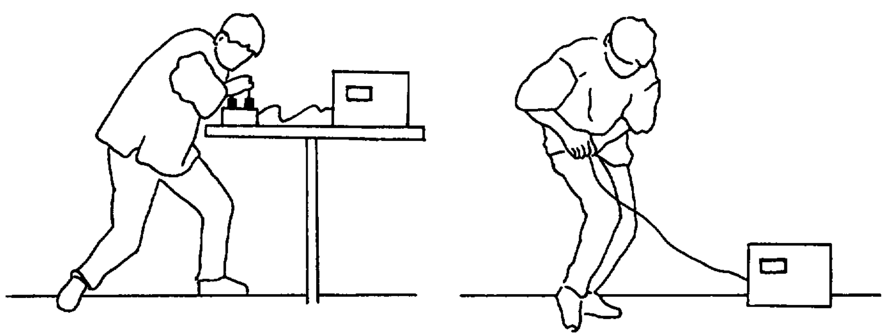


Figure 5-3: Experiment 3. Postures during torque on a jam jar. On the left with the jar fixed, on the right in free posture.

The four push and pull forces were exerted only once, and the two torque forces were repeated within an hour. Thus there were six different ways to exert force, of which two were repeated.

The jar was an aluminium model, for which the shape and weight (650 grammes, lid Ø 66 mm, jar Ø 75 mm, jar height 113.5 mm) were copied from a real jam jar. It consisted of two halves connected with a torque force transducer, as described by Daams (1987). It was not possible to actually turn the lid, so the force exertion was static. The aluminium was expected to generate a friction coefficient similar to that of the glass and lid of a real jam jar. Non-slip plastic material was placed between hand and jar when maximal torque could otherwise not be obtained.

Results of the third experiment

Table 5-4 shows the average maximal forces exerted. For pushing and pulling at shoulder and elbow height, the results are comparable to those of the first two experiments. The results of an unpaired t-test between the forces exerted during the second and the third experiment indicate that there is no significant difference at $p < 0.05$, with one exception for males pushing at shoulder height where p = 0.0299. With the jam jar fixed, slightly more force can be exerted compared to that exerted in a completely free posture. A paired t-test shows that for both situations the difference between the average group differences is not significant at $p < 0.05$.

handle height	force direction	posture	females $\bar{x}$	females s	males $\bar{x}$	males s	both $\bar{x}$	both s
shoulder height	pull (N)	free	214	49	297	50	260	64
	push (N)	free	221	69	361	112	297	117
elbow height	pull (N)	free	251	55	376	77	319	92
	push (N)	free	232	68	382	87	314	109
0.95 m	torque on jam jar (Nm)	jar fixed	6.36	1.61	11.70	3.45	9.27	3.84
no fixed height		free	5.91	1.26	9.67	2.20	7.96	2.62

Table 5-4: Experiment 3. Average and standard deviation of the maximal force [N and Nm], exerted by all subjects (10 females, 12 males) per combination of variables. For the torque on the jam jar, the average of two trials is taken.

The reproducibility of the forces exerted on the jar can be seen in table 5-5. Both the correlation coefficients and the t-tests on average group differences indicate good reproducibility, similar to that of forces exerted in free, functional and standard postures. This indicates that possibly even the fixation of the area where force is exerted is not needed for good reproducibility of the maximal force. In the third experiment, three of the subjects did not repeat the measurements.

Of the six possible combinations of variables, the correlations between the exerted force and body height is 0.61 on average, ranging from 0.52 to 0.70. There seems to be less correlation between the exerted force and body weight, on average r = 0.57, ranging from 0.42 to 0.73. The correlation between forces exerted in different situations is 0.84 on average, ranging from 0.69 to 0.93. Of the 15 correlations, 93 % (14 cases) show more generality than specificity because the coefficients were larger than 0.71. All the above correlations are significant for $p < 0.05$. These figures are similar to those generated by the second experiment.

The same correlations for the subjects of all three experiments together can be seen in appendix D.

Again, during this third free posture force exertion test, this time including a non-fixed handle position, postures of subjects appeared to be identical during the first and repeated measurements. The orientation of the hands appears to be generally equal, although some variation occurs in the height at which the jar is held and in the degree in which the subject leans over the jar.

handle height	force direction	posture	n	r	paired t-test mean (x-y)	s	p (2-tailed)
shoulder height	pull	free	20	**0.79**	-22.50	55.95	0.0880
		functional	20	**0.90**	-8.75	26.75	0.1598
		standard 1	20	**0.72**	-9.00	23.93	0.1089
	push	free	20	**0.84**	-14.00	48.84	0.2153
		functional	20	**0.85**	-2.00	26.53	0.7397
		standard 1	20	**0.74**	-0.50	20.89	0.9159
elbow height	pull	free	20	**0.87**	-21.75	58.38	0.1121
		functional	20	**0.89**	-12.25	41.09	0.1982
		standard 1	20	**0.81**	-11.00	23.15	**0.0469**
	push	free	20	**0.91**	-20.75	49.00	0.0736
		functional	20	**0.74**	-1.00	70.11	0.9498
		standard 1	20	**0.91**	2.75	12.30	0.3299
0.70 m	pull	free	19	**0.91**	-4.47	68.17	0.7781
	push	free	19	**0.95**	6.84	48.45	0.5459
1.30 m	pull	free	19	**0.89**	20.79	43.95	0.0539
	push	free	19	**0.93**	-2.37	42.04	0.8088
1.70 m	pull	free	19	**0.86**	27.90	38.88	**0.0058**
	push	free	19	**0.86**	11.58	48.88	0.3155
0.95 m	torque on jar	jar fixed	19	**0.89**	-0.13	3.77	0.8907
no fixed height		free	19	**0.92**	-0.88	2.30	0.1334

Table 5-5: Reproducibility of the repeated measures of experiment 2 (push and pull at different heights) and experiment 3 (torque on jam jar). Listed are the retest correlation coefficients and the results of a paired t-test. Bold denotes significance at $p < 0.05$. Both females and males are included.

5.1.6 Discussion

The average maximal forces of each experiment are of comparable magnitude (see figure 5-4), as is the reproducibility of these forces. Furthermore, the average positions of the feet in the first experiment are similar to those in the second experiment. The consistency of the results for random samples from different populations supports the general applicability of the conclusions.

The power of the t-tests that were performed here is low. In this case this means that chances are that the hypothesis, 'these two sets of variables are samples of the same distribution' will be erroneously accepted (a so-called Type II error). To obtain more power, either many more subjects are needed or the chance on erroneously rejecting the hypothesis (a Type I error) would have to be increased. The number of subjects that are needed for an acceptable power is hard to establish before the measurements are carried out, because the size of effect (the average difference divided by its standard deviation) is one of the variables in the equation, is not yet known beforehand and thus must be estimated. The sample size necessary to obtain a good power varies for every test, but it is estimated that the necessary group size would be at least a hundred or more, and such a large group could not be measured within the limited experiment time.

When an infinite number of subjects is measured, a small difference will probably always be found to be significant. However, it is not very relevant to establish the significance of an average group difference in the order of 1 newton, given the fact that the same measurements for individuals can vary much more.

To summarize: although in theory the power is probably very low, it is not so easy to improve on this within the time constraints of this research, and it is not desirable to improve the power to its limit, either. Furthermore it is never possible to definitely prove that no difference exists.

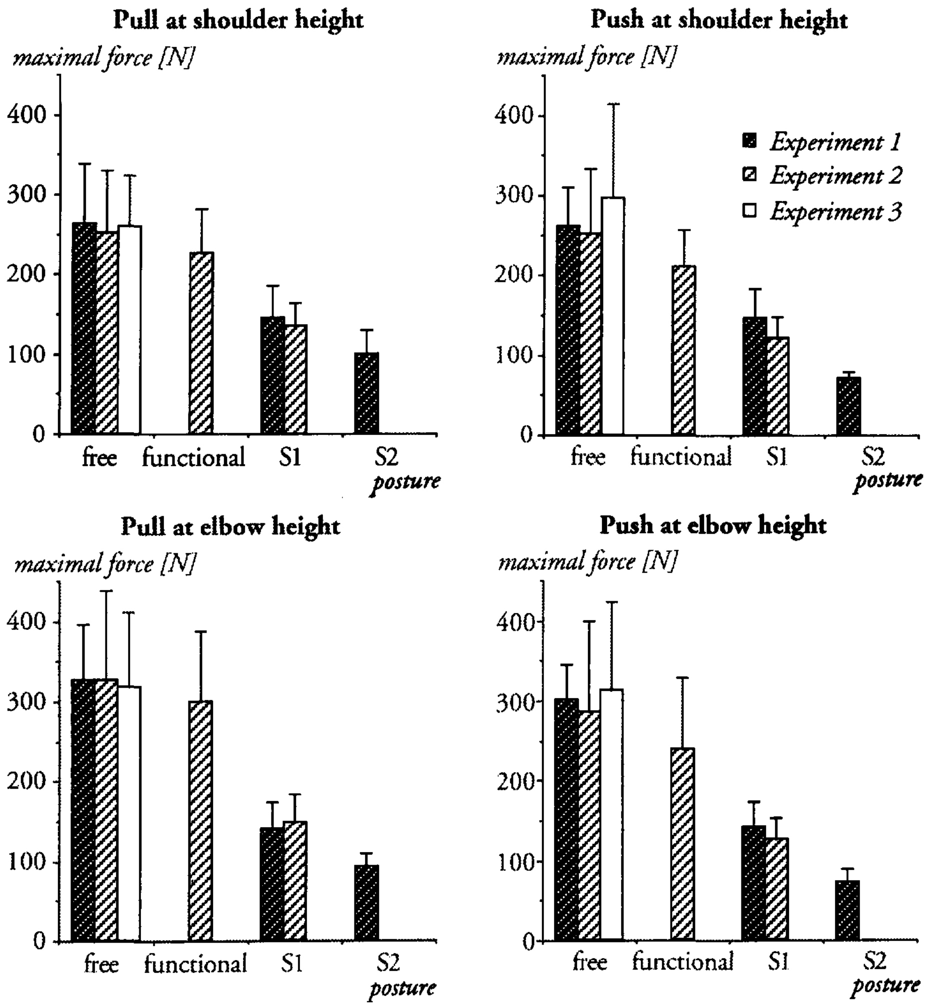


Figure 5-4: Average forces (and one standard deviation) in various postures (free, functional, standard 1 and standard 2), exerted during pushing and pulling at shoulder and elbow height, compared for the three experiments.

The correlations between exerted force and body height (0.52 to 0.84) and weight (0.42 - 0.76) are slightly higher than those found in literature, where correlations between exerted force and body height and force and weight range from 'not significant' up to 0.72 and 0.69 respectively (see table 3-4). These values are good, but not sufficiently so to justify the prediction of forces, especially as people tend to vary in physical fitness. Furthermore, these correlations were enhanced by combining the measurements of female and male subjects, which may be the cause of the relatively high correlations compared to literature.

There is hardly any correlation (0.19 on average) between force and girth of the relaxed upper arm, as Churchill et al. (1978) already found for the correlation between grip strength and relaxed biceps circumference (about 0.30), and Caldwell (1964a) found for the correlation between arm pull strength and upper arm girth (0.31 to 0.32).

The correlation between forces exerted in different situations is generally very good. For the second experiment 84 % of the correlations reach values of 0.71 or higher, and for the third experiment this is even 93 %. Opportunities for prediction of forces are discussed in chapter 6 'Overall analysis'. Kroemer (1977), in contrast, suggests that force-force correlations cannot be expected to be very high in view of the large variance of the data, and gives an example of an experiment where only 2 % of the force-force correlations obtained were 0.71 or more.

The standardized postures, as used for these experiments, were perceived by the subjects as unnatural and uncomfortable. The forces measured were less than half those exerted in free posture. Therefore the data obtained using these standardized postures cannot be used to indicate the forces exerted in unrestricted situations without taking into account the systematic differences in level.

The expected advantages of the functional posture are not entirely substantiated by the second experiment. Instead of equal force with improved reproducibility, compared to free posture the use of a functional posture yields equal reproducibility and limits the force exerted. The limited force is probably due to the fact that the functional posture cannot be the optimal posture for all the subjects involved. The finding that little (cor)relation exists between the force exerted and the position of the feet in free posture, supplements the findings of Haslegrave et al. (1988), and does not encourage the adoption of a so-called functional posture for research.

In free posture, the real maximal force is measured, unrestricted by constraints other than a fixed place to which the force is to be applied and the prescribed use of the preferred hand. The resulting values have therefore the highest predictive validity for situations without constraints on posture. Although the subjects can move freely, extreme postures are not found. It should be noted that the subjects' posture is still restricted by physical limits (range of joint movements), by their having to maintain their balance while exerting maximal force, and possibly by some habitual 'patterns of movement'. The research thus not only yields information on force, but also on the standing room needed by the subjects, which is also relevant to design. The forces measured prove to be highly reproducible, even with extreme handle heights and even when the place to which the force is to be applied is not fixed, as in the case of torque exerted on a jar in completely free posture. So it would seem that our empirical evidence casts some doubts on the desirability of adopting standardized postures, implicit in the statement of Caldwell et al. (1974, p. 203), that "The results of scientific investigations, including strength measurements, are useful only if they are so completely described that they can be repeated." For repetition of a force measurement and its results, it seems that identical handle heights are a necessary and sufficient condition, and are also the only relevant parameter, given the aim of the experiment. For portable products, a fixed position may not even be necessary for reproducibility of maximal forces and postures.

In trying to minimize the influence of posture by standardizing it, a restriction is introduced. This restriction limits the force that can be exerted. Paradoxically, then, the influence of a particular standard posture on the force exerted is measured, rather than the maximal force. The influence of restrictions on posture can already be observed in the results of forces measured using the functional posture. Contrary to measurements of muscle strength, where restrictions are necessary to separate the effects of different muscles, measurements of total body force, or even of a combination of large muscle groups, are apparently most realistic and reproducible if no restrictions on posture are imposed.

5.1.7 Conclusions

Although some caution is required in view of the limited number of subjects involved, a few tentative conclusions can be drawn. The conclusions of this research concern maximal static pushing and pulling in horizontal direction and maximal static torque on a jar, in standing postures.

Although the reproducibility of forces exerted in functional, free and standardized postures is satisfactory, the use of free postures offers added advantages. It is therefore proposed that the free posture be adopted as a tool for generating information on both maximal static force exertion and the corresponding standing room required.

Such a tool should only be used, however, to predict short time force exertion in spontaneous, free postures, which do not involve problems like fatigue and having to maintain great force for more than a few seconds. If these factors form part of the research, the exact posture of the subject could be more relevant, and the experiment should be adapted accordingly.

5.2 Comparison of moments exerted round one or more joints in the arm

Summary

The purpose of this research is to investigate a possible difference between moments exerted over one, two or three joints, and a possible difference between moments exerted round a joint in single and in multi-joint force exertions. In addition the aim is to establish the correlation coefficients between moments. Twenty-six female and male subjects exerted static flexion round wrist, elbow or shoulder separately, or round a combination of these. They did so with their arm in three different positions.

The results showed that reproducibility of forces is very good. A tendency can be seen towards larger moments and smaller forces if more joints participate. Furthermore, a correlation coefficient matrix showed that all correlations between moments were positive and nearly all were significant. Moments round a joint that is proximal during force exertion were at least as large as, and generally larger than, those round the same joint when not proximal. The weakest part of the chain would seem to be the proximal joint (in this case the shoulder), and consequently the force exertion of the whole arm would not be limited by the strength of the elbow or wrist in the postures researched.

5.2.1 Introduction

An atlas of human forces could include such data as forces measured in experiments, as well as models from which forces may be calculated. A theoretical model of human forces is called a biomechanical model.

From the maximal force measured round a joint, the maximal moment can be calculated. This may then be compared with moments that, assuming a certain load and according to biomechanical calculations, will be exerted round this joint. If, for example, the latter value is greater than the maximal (measured) value, the subject will be unable to perform the assigned task. In some models, forearm and hand are seen as one segment, in which case the wrist is not considered separately in calculations (Chaffin and Andersson, 1984; Kroemer et al., 1986).

No literature was found on a possible difference between maximal moments exerted round a joint in single and in multi-joint force exertions. Nor was any information found on a possible difference between maximal moments exerted over one, two or three joints.

5.2.2 Objective

The objective of this study is to investigate the effects of the number of participating joints on the moment that can be exerted, and to see whether the location of the joint in the force chain has any effect on the maximal moment that can be exerted round that joint. Also, correlations between moments will be assessed, with a view to the possibility of predicting one moment from another.

5.2.3 Method

Subjects. 26 healthy subjects, 13 female and 13 male, took part in the experiment. All were either students or employees of the Faculty of Industrial Design Engineering. A number of anthropometric characteristics can be seen in table 5-6.

	females		males		both	
	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s
age [yrs]	23.5	4.0	27.0	11.6	25.2	8.7
body weight [kg]	66.5	7.4	73.8	6.3	70.2	7.7
body height [cm]	171.8	5.9	185.0	7.0	178.4	9.2
elbow reach depth [cm]	33.2	1.7	37.2	1.9	35.2	2.7
arm reach depth [cm]	69.4	3.8	75.9	3.4	72.7	4.9
upper arm length [cm]	33.9	1.2	37.4	1.6	35.6	2.2
tense upper arm girth [cm]	27.6	1.7	29.9	1.8	28.7	2.1
relaxed upper arm girth [cm]	26.1	1.8	27.4	1.8	26.8	1.9

Table 5-6: Characteristics of subjects: 13 women and 13 men. Total n = 26.

Body height and weight are measured with clothes and shoes on. Elbow and arm reach depth are measured with the subjects standing with their back to a wall. The distance of the wall to a pen they held vertically in their fist was measured; for arm reach depth with the arm stretched horizontally; for elbow reach depth with the elbow in 90° flexion and the forearm in horizontal position. Upper arm length is measured from the acromion to the olecranon, with the elbow in 90° flexion and the upper arm in vertical position. Relaxed upper arm girth is measured at the largest diameter of the biceps with the whole arm relaxed, hanging vertically. Tense upper arm girth is measured while the subject made a fist and tensed the biceps.

Experimental design. Each subject was asked to exert a maximal static force in 18 different ways (see figure 5-5). Moments were exerted round wrist, elbow, or shoulder separately, or round a combination of these. The force transducer was placed successively on hand, upper arm and fore-arm, in random order. Every valid combination of the above-mentioned moments and placements of force transducer (6 in all) was exerted with the arm either horizontal, vertical or with elbow and shoulder flexed. In the latter case both joints were flexed 45 degrees, i.e. the lower arm was horizontal (see figure 5-5). Forces were measured at right angles to the segments.

Consequently, there were three independent variables: 1) the joint(s) around which a moment was exerted; 2) the segment on which the force transducer was placed; and 3) the arm posture. With 10 subjects, part of the experiment was repeated after a few days to obtain information about reproducibility.

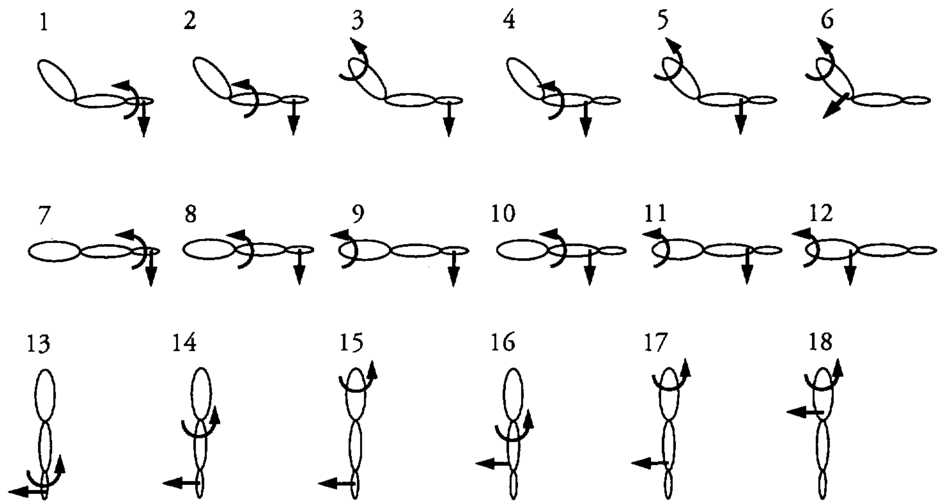


Figure 5-5: 18 configurations in which maximal static forces were exerted, combining 3 arm postures, 3 joints around which the moment (↻) is exerted and 3 segments in which force (↓) is measured.

The dependent variables were: the measured maximal force, and the exerted moment as calculated by multiplying the measured force by the lever. In cases where the arm was horizontal or flexed, the moment resulting from the weight of the arm was added. This was calculated from body weight and length of the hand and upper and lower arm, according to Dempster's formulas (Winter, 1990):

hand weight = 0.006 * body weight
forearm weight = 0.016 * body weight
upper arm weight = 0.028 * body weight
center of mass of hand = 0.506 * segment length (proximal)
center of mass of forearm = 0.430 * segment length (proximal)
center of mass of upper arm = 0.436 * segment length (proximal)
center of mass of forearm and hand = 0.682 * segment length (proximal)
center of mass of total arm = 0.530 * segment length (proximal)

Equipment. The force exerted was measured with the aid of a force transducer with strain gauges, an amplifier and a computer (see appendix A). The subjects pressed against a metal plate covered with soft plastic (size 13.5 * 4 cm), which was connected to the force transducer. The height of the pressure plate was adjustable in 5 cm intervals, and the orientation could be either horizontal, vertical or at a 45 degree angle. The subjects sat on a stool without back support (arm horizontal and flexed), or stood unsupported (arm vertical). In the sitting posture, the force exerting arm was supported to prevent premature fatigue, and to provide a reaction force for elbow or wrist when necessary. The supporting device was a plastic gutter with half circular cross-section, covered with plastic foam on the inside to accommodate the arm. It was adjustable to the required height. The inaccuracy of the force assessment was ± 0.4 N, due to the resolution of the A/D converter. Lengths and distances were measured using an anthropometer.

Procedure. The subjects wore ordinary indoor clothing. They were given extensive instructions about the ways in which they were expected to exert force: as a moment round the shoulder, elbow, wrist, or a combination of these. With moments exerted round the elbow or wrist, or elbow and wrist, the reaction force was to be restricted to the proximal participating joint, to avoid loading of the non-participating joint(s) and to prevent measurement bias by other reaction forces. While exerting a moment round the shoulder, the subject was to refrain from resting the arm on the support. Subjects were asked not to clench their fists and to maintain the required arm position during force exertion.

The pressure plate was always placed flat against and in light contact with the arm segment. Depending on posture and segment it would thus be horizontal, vertical or at a 45 degree angle. The position was chosen so as to cause the least inconvenience to the subject. On the upper arm, it was placed between the head of the biceps and the elbow joint. On the hand, the plate was placed as proximal as possible with the thumb folded over it. On the forearm it was placed as distally as possible. During the first measurement on every segment, the position of the pressure plate was marked to ensure correct repositioning.

The subjects were asked to exert force for 6 seconds (2 s buildup, 4 s maximal), following the method of Caldwell et al. (1974). This time, the subjects were given 2 seconds to build up their force, because from the posture experiments (5.1) it appeared that 1 second was barely enough time to reach the maximum. Maximal force was defined as the mean force exerted during the last 4 seconds. The minimum rest period between measurements was 2 minutes. Subjects were asked to say if their effort was limited by pain, in which case the measurements were not included in the results.

Between measurements, anthropometric variables were measured as well as levers. For elbow and wrist, the lever is the distance from the middle of the pressure plate to the point of application of the reaction force (the olecranon and the tuberculum dorsale of the radius respectively). For the shoulder the distance to the acromion is considered an adequate approximation. The inaccuracy of the lever measurements is judged to be ± 1.0 cm.

5.2.4 Results

Figure 5-6 shows the average forces measured, figure 5-7 shows the average moments exerted. In table 5-7 and 5-8, average forces and moments exerted by women and men are separately presented. In most of the 18 cases, men exerted nearly twice as much moment as women. None of the measurements was excluded due to pain limitations.

The retest correlations r of the forces measured for ten subjects in the first 12 configurations varies between 0.82 and 0.96, with one exception of 0.67. All correlations are significant at $p < 0.01$.

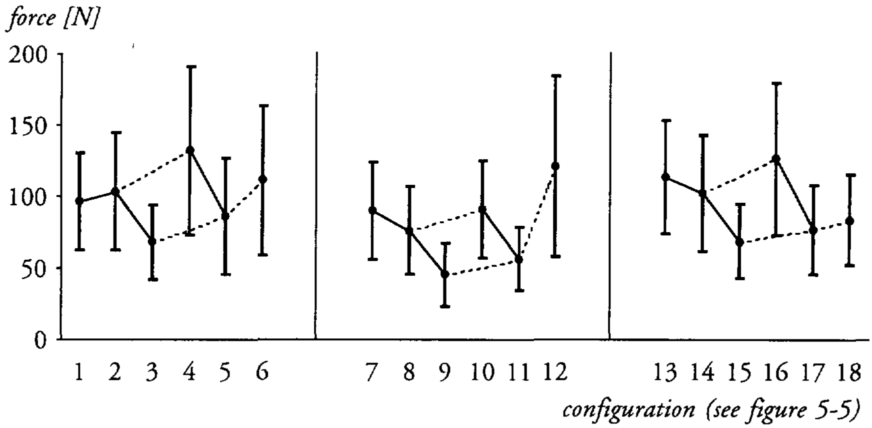


*Figure 5-6: Average **forces** [N] and two standard deviations, exerted by 13 women and 13 men. For clarity, forces exerted round the same proximal joint within one arm posture are joined by a dotted line, and forces measured at the same segment are joined by a solid line.*

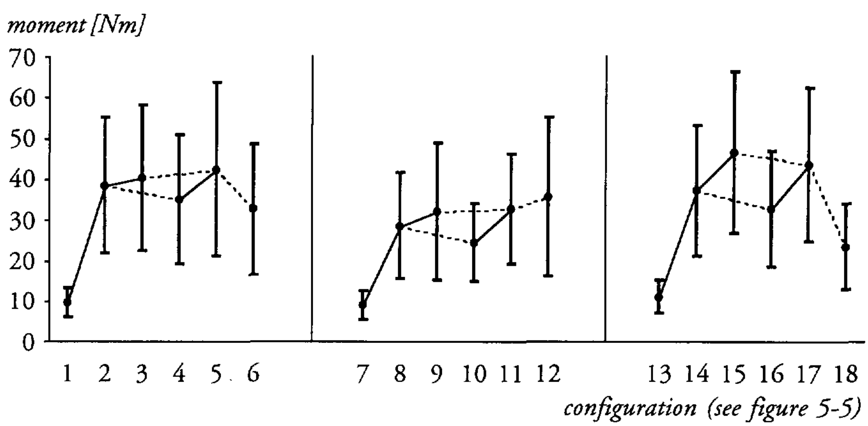


*Figure 5-7: Average **moments** [Nm] and standard deviations, exerted by 13 women and 13 men. For clarity, moments exerted round the same proximal joint within one arm posture are joined by a dotted line, and moments measured at the same segment are joined by a solid line.*

configuration	moment exerted round	force measured at	females $\bar{x}$	females s	males $\bar{x}$	males s	both $\bar{x}$	both s
1	wrist	hand	68.1	15.6	126.1	22.0	96.0	34.0
2	elbow	hand	73.0	16.9	137.1	34.1	103.0	41.0
3	shoulder	hand	49.9	14.6	83.4	26.6	68.0	26.0
4	elbow	fore-arm	94.1	35.8	175.1	52.8	132.0	59.0
5	shoulder	fore-arm	62.9	23.5	110.2	43.1	86.0	41.0
6	shoulder	upper arm	86.8	35.0	141.2	52.8	111.0	52.0
7	wrist	hand	64.5	18.6	116.0	27.9	90.0	34.0
8	elbow	hand	54.0	11.6	100.9	27.1	76.0	31.0
9	shoulder	hand	32.7	11.9	59.8	22.8	45.0	22.0
10	elbow	fore-arm	70.6	21.8	115.3	29.5	91.0	34.0
11	shoulder	fore-arm	43.6	12.5	69.6	22.2	56.0	22.0
12	shoulder	upper arm	85.9	35.3	163.3	61.7	121.0	63.0
13	wrist	hand	83.4	20.6	142.6	30.4	113.0	39.5
14	elbow	hand	70.5	16.1	134.1	31.5	102.3	40.7
15	shoulder	hand	46.6	13.7	90.5	14.3	68.5	26.2
16	elbow	fore-arm	83.5	20.0	169.1	40.1	126.3	53.5
17	shoulder	fore-arm	52.2	13.7	101.2	22.4	76.7	30.9
18	shoulder	upper arm	64.0	18.4	103.1	30.8	83.5	31.8

Table 5-7: Average ***forces****[N] and standard deviations, exerted in 18 different configurations (see figure 5-5) by 13 women and 13 men. Total n = 26.*

configuration	moment exerted round	force measured at	females $\bar{x}$	females s	males $\bar{x}$	males s	both $\bar{x}$	both s
1	wrist	hand	6.4	1.8	12.3	2.7	9.6	3.7
2	elbow	hand	25.3	6.2	49.8	14.6	38.5	16.8
3	shoulder	hand	28.2	8.6	50.4	17.3	40.2	17.8
4	elbow	fore-arm	23.4	8.9	45.0	13.5	35.0	15.8
5	shoulder	fore-arm	28.8	11.2	54.1	21.2	42.4	21.3
6	shoulder	upper arm	22.1	9.3	41.6	15.2	32.6	16.1
7	wrist	hand	6.1	2.0	11.2	3.2	8.9	3.7
8	elbow	hand	18.6	4.2	37.0	12.0	28.5	13.0
9	shoulder	hand	21.1	8.0	41.6	16.8	32.1	16.8
10	elbow	fore-arm	17.8	6.7	30.3	8.0	24.5	9.7
11	shoulder	fore-arm	23.8	7.7	40.5	12.6	32.8	13.5
12	shoulder	upper arm	21.7	9.4	47.8	17.7	35.8	19.5
13	wrist	hand	7.7	1.9	14.0	3.1	11.1	4.1
14	elbow	hand	23.8	6.3	48.7	12.3	37.2	16.0
15	shoulder	hand	28.8	9.0	62.0	11.8	46.7	19.8
16	elbow	fore-arm	20.1	4.1	43.4	10.0	32.7	14.2
17	shoulder	fore-arm	27.0	6.7	58.1	12.9	43.7	18.9
18	shoulder	upper arm	15.7	5.0	30.2	9.9	23.5	10.7

Table 5-8: Average ***moments****[Nm] and standard deviations, exerted in 18 different configurations (see figure 5-5) by 13 women and 13 men. Total n = 26.*

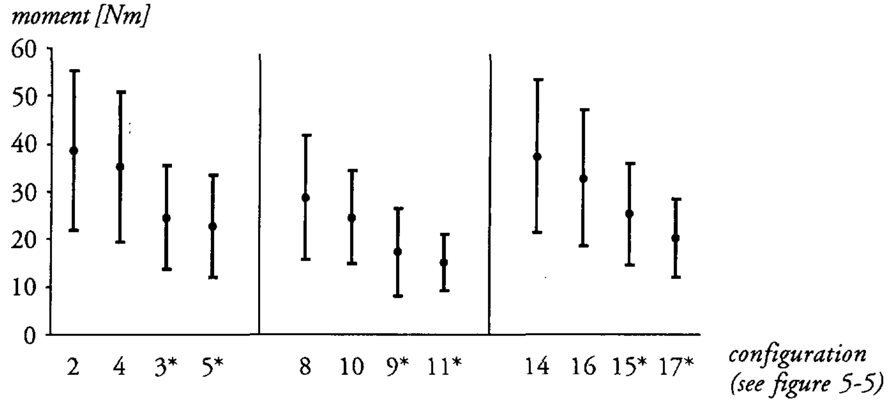


Figure 5-8: Average moments [Nm] (and two standard deviations) round the ***elbow****, exerted by 13 women and 13 men. The moments marked '*' are calculated from measured moments, e.g. 3* means the moment round the elbow is calculated from the moment measured in configuration 3 (around the shoulder).*

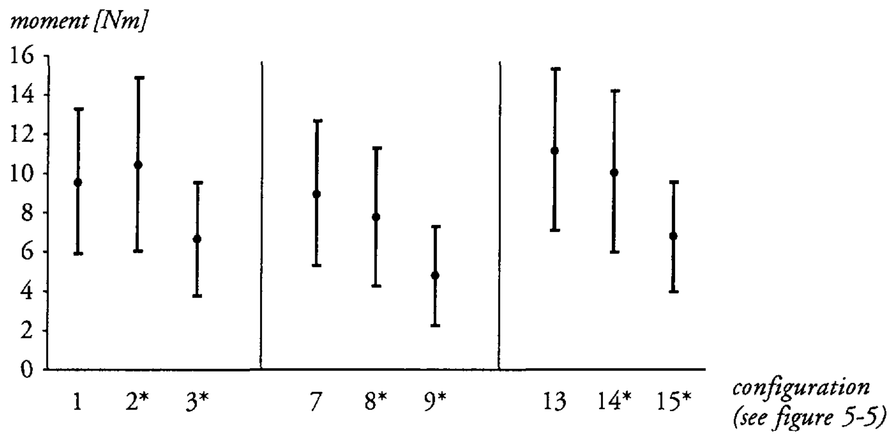


Figure 5-9: Average moments [Nm] (and two standard deviations) round the ***wrist****, exerted by 13 women and 13 men. The moments marked '*' are calculated from measured moments (see caption of figure 5-8).*

A correlation coefficient matrix was made for the 18 moments (see the large correlation coefficient matrix in appendix D). All 153 correlation coefficients are positive and all but 17 are significant at $p < 0.05$. The percentage of correlations above the specificity-level ($r \geq 0.71$) is 35 % for all subjects. For women and men separately, it is 23 % and 41 % respectively.

The correlation coefficients between moments and anthropometric variables were calculated. Hardly any correlation could be found between moments and arm reach, elbow and body weight. Some correlation, positive and significant, was found with tense upper arm girth (7 out of 18 r's ≥ 0.71), body height (12 out of 18) and grip strength (14 out of 18), though after calculating the correlations for women and men separately, they almost disappeared.

Measured moments exerted round the proximal joints exerting force were compared with theoretical moments exerted round the same joints when not proximal, as calculated from the measured moment. This was done for elbow and wrist (see figures 5-8 and 5-9). A paired t-test showed that the moments exerted in the following configurations could not be considered different at $p < 0.01$: configurations 1 and 2*, 7 and 8*, 9* and 11*, 14 and 16.

5.2.5 Discussion

The results show that there is a tendency towards larger moments and smaller forces if more joints participate. The average scores are tested for significant differences using the paired t-test. Between some scores, no significant difference could be found with $p < 0.05$. From this, the following may be deduced:

Force over 1 joint ≥ force over 2 joints ≤ force over 3 joints;

Moment over 1 joint ≤ moment over 2 joints ≤ moment over 3 joints.

This outcome is the same for women and men separately and for the three postures separately.

Looking at these results, it would seem advantageous to limit the number of joints involved while exerting force to as few as possible. This is not a realistic proposition however, for the following reasons. First, the hand is the most common and apt segment to transfer force from the subject to the outside world. Second, it may not always be a good idea to support the arm. This may depend on the frequency and the amount of force required, and on the position of the support. Still, for some applications (short submaximal force exertion) a support at the elbow or wrist may reduce the exertion required, while increasing the resulting force.

The correlation coefficients between moments are high compared to those between forces as quoted by Kroemer (1977), where only 2 % of the correlation coefficients have values of 0.7 or higher. This may be the result of the biceps brachii being the main muscle in all exertions except for force exertion involving only the wrist. The relatively good correlation coefficients between moments give good hope for future predictive use.

The correlation of moments and anthropometric variables are also high compared with those found in literature. Kroemer (1977) quotes that only 1 % of the correlation coefficients reach values of 0.7 or higher. However, the correlations in the present experiment are enhanced by combining the results from men and women.

As can be seen from figure 5-8, the elbow moments when measured are larger than those calculated from moments round the shoulder. This shows that the maximal moment exerted round the shoulder on the transducer at forearm or hand is not limited by the maximal moment that can be exerted round the elbow. At the wrist (see figure 5-9), the same applies to moments exerted round the shoulder. Wrist moments calculated from moments round the elbow and exerted on the hand, however, in two of the three positions of the arm are not significantly different from measured forces when the wrist is the only joint involved. The results indicate that the moments exerted round proximal joints are not limited by the maximal moments round distal joints.

5.2.6 Conclusions

The conclusions of this research concern flexion of the arm in the sagittal plane, between horizontal and vertical position. In order for the results to be valid for other force directions, other arm postures or other segments, further research will be necessary. The present results may be considered valid for healthy adults.

A support at elbow or wrist can reduce the exertion required, while increasing the resulting force. This support should only be applied during short submaximal force exertion.

The shoulder is the restricting joint in arm flexion. To consider the wrist as a separate joint in the biomechanical model is therefore unnecessary under these circumstances. Furthermore, if a biomechanical model is used for single short-duration force exertion with unsupported arm, the shoulder will be the limiting factor while exerting force with the whole arm. For longer duration and repeated force exertion using the whole upper body, the lower back region is of course most critical.

5.3 Endurance during submaximal, static force exertion

Summary

The objective of this research was to measure endurance time during force exertion and investigate factors influencing it, and to gather information on the subjective experience of discomfort, with the aim of establishing 'discomfort zones' for use by designers. The concept and investigation of discomfort is discussed in 5.4. Twenty-four healthy subjects (female and male, two different age groups) participated. Force was exerted in four ways: pushing with one hand, anteflexion of a shoulder, flexion of one knee, and extension of the other knee. The endurance time was measured at six different relative force levels (80 %, 60 %, 40 %, 30 %, 20 % and 15 % of maximal). During force exertion, information was gathered on the perception of discomfort by the subject. To assess the reproducibility of the experiment, it was repeated by ten of the subjects.

Endurance was found to be satisfyingly reproducible, and to be slightly shorter for arms than for legs, though generally much longer than predicted from the load/endurance formulas found in literature. The main factors influencing endurance time were the subjects themselves and the force level involved. With forces ranging from 80 to 30 % of maximal force, age and sex had no effect on the results. Both the endurance time and the significance of the influence of the use of arm or leg on endurance, however, depended on the way the maximal force was established c.q. defined. It is proposed that maximal force for endurance measurements be measured without feedback or encouragement, while endurance time be measured with feedback. Two formulas, for arm and leg muscles, describe the force level-endurance relationship between 15 and 80 % of maximal force, based on the median of the present data. To predict endurance in practice, however, additional factors beside muscle endurance must be taken into account.

5.3.1 Introduction

Literature containing data on exerted forces seems to deal mostly with maximal forces, exerted for a few seconds. What use are these data to design(ers)? For most consumer products, where ease of use is essential for product success, designing for maximal forces will simply not do, for such forces indicate only the limits that should be avoided and not values that are suitable. This applies even more to professionally and frequently used products, where too much or overlong force exertion may lead to serious injuries. Knowledge of the maximal forces exerted during a few seconds can be useful to designers, but more often they are interested in submaximal forces and forces that are exerted for periods longer than a few seconds. Therefore, information on endurance time and discomfort during submaximal force exertion by the expected group of users is indispensable. Preferably, this information should be deducible from the maximal force and/or anthropometric variables, because these have been measured already in quite a large number of situations, and a possible relationship with endurance time or discomfort would make these already existing results usable for other purposes.

For the purpose of this document, endurance time is defined as the maximal time during which a subject is able to exert or withstand a certain force. There is no standardized way to measure the endurance time for static forces. It has been investigated by a number of researchers, and in various ways. Their results are compared in 3.5.3, in which it is concluded that endurance time is strongly influenced by the individually exerted relative force. It is generally accepted that, when the force is defined as a percentage of the individual maximal force, the endurance time is mainly determined by the force level, and seems to be less influenced by subject, sex, age, posture and muscle group. The literature does not agree on the effect of these factors. Whether subject, sex and age play an essential role, otherwise than influencing the maximum force, is not yet unequivocally determined. When statistically significant differences are found, they are small. Various postures have a significant effect on endurance time, but there is no agreement in literature on the extent of the effect. For different muscle groups, no significant differences were found, even though they were expected on theoretical grounds.

Although it is suggested that a certain force level (15 % or 7.9 %, according to different sources) can be maintained indefinitely, not everybody agrees about this. The same applies to the higher force levels, where some authors found that occlusion of blood at endurance of 70 % of maximal force or more results in much shorter endurances, while this effect is not found explicitly in the results of other articles. The different formulas proposed to model force level-endurance relationship do not agree very closely, as is most apparent at very low or very high force levels.

Any of the differences between results of various researches may be caused by differences in experimental methods. No investigations were found into the influence of motivation and feedback on endurance, although it is noted by some authors that these are important factors.

5.3.2 Objective

The objective of this research was to measure endurance time at various relative force levels, and to make a model of the relationship of relative force level versus endurance time for use in design practice. To that purpose the following questions needed to be answered, to which in literature no conclusive answers could be found: Is there any difference in endurance time between women and men, younger and older people, or different muscle groups used? Do correlations exist between endurance on the one side, and maximal force, anthropometric variables and other endurance measurements on the other? Do maximal static forces differ because of the time of the day and the order in which they are exerted? Maximal force can be exerted according to different procedures, e.g. exerted with or without feedback. Is the endurance equal for different ways to measure, and thereby define, maximal force?

At the same time, the objective was to gather information on the subjective experience of discomfort during the endurance measurement, with the aim of establishing 'discomfort zones' for use in design practice. This section will deal exclusively with endurance time. Discomfort results are presented and discussed in the next section, 5.4.

5.3.3 Preliminary trials

No standard method exists to measure endurance time during force exertion. Consequently, a method should be tried and tested before applying it in an experiment. Some preliminary and explorative trials were performed to get an answer to the following questions:

Should endurance be measured with weights, or with the aid of strain gauges and a computer? There was no difference in endurance time of equal loads in equal postures measured with weights and measured with the computer. The weights were attached to a string, which ran over a pulley and had a handle attached to the other end. Subjects had to hold the handle and keep the weight at a certain height. The measurement ended as soon as the weight was lowered more than 4 cm. With the computerized method, the subjects had to exert force on a handle which was attached to strain gauges, an amplifier and a computer. The computer indicated how much force they were expected to exert, at the same time showing the actually exerted force. When the exerted force was less than or exceeded 10 % of the expected force, the measurement ended.

Most subjects preferred the computerized method over the use of weights, probably because with the latter method it was not possible to fix the position of the handle, and thus more degrees of freedom had to be taken into account and controlled. This seemed to be an extra task, leading to a higher task load. Furthermore the weight method allowed more unwanted changes of posture than the computer method. Also the computer method seemed more precise and made it both easier and quicker for the experimenter to change loads. For these reasons the computer method is preferred over the weight method.

What are suitable alarm and end limits? During the endurance time measurement, the subject has to keep to a certain force level. It is necessary to determine between which limits the force is allowed to vary. When the deviation exceeds a certain limit, the measurement ends because presumably the subject is no longer able to keep up the required force level. Furthermore a limit at which audio signals are given is determined, in order to warn subjects so that they are not caught by surprise when the end limit of the measurement is approached. The valid range for a measurement should be fairly wide to prevent unintentional, premature ending of the measurement, e.g. by muscle tremors, sneezing, flagging attention and other minor actions by the subject. Such an unintentional end of a measurement proved to be very frustrating to subjects in the preliminary measurements. The xt-recordings of the preliminary measurements showed that, with a narrow limit at which warning beeps would sound (10 % above and below the required force level) and a wide limit at which the measurement would end (50 % above and below the required force level), the forces were maintained sufficiently close to the required level, and in this respect did not vary much from those obtained with narrow end limits.

Are the intended postures feasible? The chosen postures were meant to involve different muscle groups, like with flexion and extension of the knee, to cause the least inconvenience to the subject and to measure only exerted force, without influence of limb weight. Initially both pushing and pulling with the arm was preferred, but pulling was rejected, because subjects tended to slide out of the chair they were seated in, even when they were tightly strapped in.

Is the equipment adequate? As a result of the preliminary measurements slight changes were made in the equipment. Platforms with ball bearings were fastened on the supports for the feet, to reduce friction between the foot and the support. This proved to be unnecessary for the arm support, as friction was already little and could not be reduced further by the use of ball bearings.

Is the procedure adequate? Talking to subjects and the presence of other (familiar) people both influenced the endurance time positively. Therefore it was decided to communicate as little as possible and to allow preferred music to be played in the background. It was not tested whether the presence of the experimenter had any effect. If so, it may have been different for men and women subjects (the experimenter being a woman).

The trials were restricted to a limited number of subjects, so the findings mentioned here cannot provide a solid basis for generalization.

5.3.4 Method

Subjects. Twenty-four healthy subjects participated in the experiment. This was the maximal number of subjects that could be measured within the limited time available (7 months full measuring time for the endurance and discomfort experiments together). Of these, seventeen were students, five were university staff members and two came from elsewhere. Except for the staff members, the participants received payment for participating in the experiment. Payment was per hour, not per session. Thus endurance was slightly encouraged by this financial arrangement. The students were categorized 'younger' and the other subjects 'elder'. Table 5-9 lists ages and some of the subjects' anthropometric data.

	women younger n = 8		women elder n = 4		men younger n = 9		men elder n = 3		all n = 24	
	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s
age [year]	22.0	1.6	39.3	9.7	21.8	2.1	49.0	7.0	28.2	11.2
body height [cm]	175	4	173	10	186	7	181	7	180	8
body weight [kg]	68.5	6.9	67.3	13.2	73.2	7.3	81.3	3.2	71.7	8.8
grip force [N]	36.8	3.5	30.0	8.5	49.2	11.7	58.0	8.0	43.0	12.4

Table 5-9: Characteristics of subjects, total n = 24.

Experimental design. Static force was exerted in four ways (see figure 5-10):

1) *Push:* sitting, pushing with the non-preferred hand against a doorknob mounted centrally in front of the subject. Fore-arm horizontal, elbow at an angle of about 135°, measured with an angle measuring instrument. The subject was allowed to find the most comfortable wrist angle, obtained by resting the hand on different heights of the doorknob. Back, seat, fore-arm and feet were supported;

2) *Flexion:* Sitting, knee flexion with the knee on the side of the preferred hand. Upper leg horizontal, knee at 90° flexion. Back, seat, feet and upper leg were supported;

3) *Extension:* Sitting, knee extension with the other knee. Upper leg horizontal, knee at 90° flexion. Back, seat and feet were supported;

4) *Anteflexion:* Standing, anteflexion of the shoulder on the side of the preferred hand. Arm straight and vertical, force plate on the distal part of the lower arm. One foot was allowed to be positioned one step behind the other, to prevent subjects pushing themselves over. The free hand was allowed to hold on to the construction part of the experimental equipment, for the same reason.

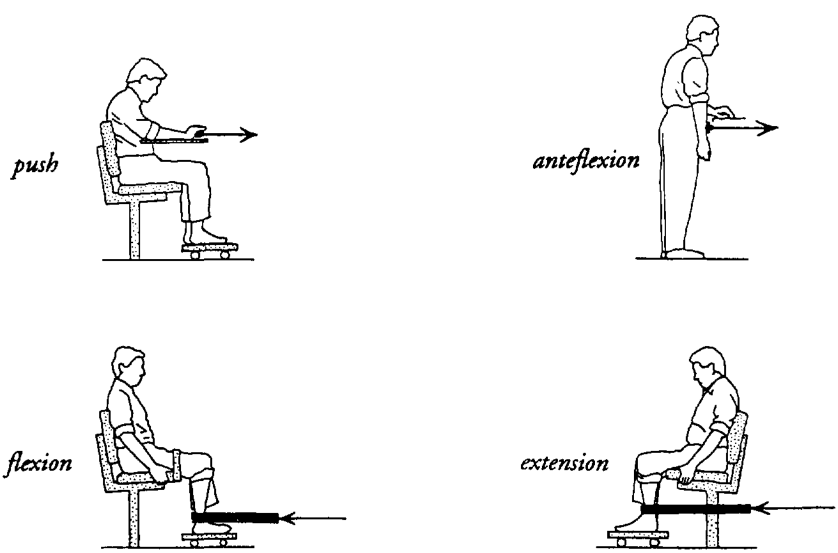


Figure 5-10: Four situations in which force is exerted.

These postures were chosen so as to cause the least inconvenience to the subject, while at the same time ensuring that the weight of the limbs would not influence force exertion, so that the measured force would equal the exerted force. The reason for using various distinct muscle groups during the experiment was to assess their possible effect on the results and the extent to which the results can be generalized.

The maximal force was determined as explained below. Subsequently, the endurance at six different relative force levels (80 %, 60 %, 40 %, 30 %, 20 % and 15 % of maximal) was measured. This resulted in 24 measurements yielding information on endurance. During force exertion, information was gathered on the perception of discomfort by the subject. Ten of the younger subjects (5 female, 5 male) repeated the experiment, to assess reproducibility.

Therefore, the independent variables are the relative level of the force and the manner in which it was exerted. The dependent variables are the endurance time, and discomfort rating. The maximal force is also a depending variable, depending on the manner in which it is exerted.

Equipment. Force was measured with the aid of a force transducer with strain gauges, an amplifier and a computer (see appendix A). The subjects either pushed against a slightly convex doorknob (round with diameter 59 mm), pushed against a metal plate covered with soft plastic (size 13.5 * 4 cm) or pulled a leather belt (width 54 mm) covered with plastic foam at the area of contact (see figure 5-10).

During knee flexion, a second leather belt was used to prevent lifting of the leg (a natural movement when flexing the knee). The belt kept the thigh down, and was intended as a reminder to the subject rather than to actually fixate the leg.

To support the feet, 12.5 x 30 cm wooden boards were used, which were adjustable in height in 4 cm steps. To reduce friction between limbs and support during knee flexion and extension, which might bias the measurement, a sliding board was mounted with ball bearings on the foot supports.

During pushing in the seated posture, the arms were supported by a wooden board, fastened at a fixed distance to the force transducer. For comfort it was covered with carpet, and a plastic bag was placed between the lower arm and the support to reduce friction. No sliding board with ball bearings was used as in this case it did not reduce the friction any further.

During the endurance measurements, subjects were looking at a monitor showing the force they exerted as a bar graph, size 17 * 2 mm (height * width), as well as the limits at which the measurement would stop, 32 mm apart. There was a distance of 1.30 to 1.70 m between the subjects' eyes and the screen, depending on the posture. The size of the bar, as seen by the subjects, was 0°57' * 0°07' to 0°7' * 0°09' minutes of arc, and the distance between the limits was 1°08' to 1°41' minutes of arc.

Procedure. Subjects wore ordinary indoor clothing with shorts, skirts or wide-legged trousers. They wore no shoes, except when, in standing position, the friction between feet or socks and the floor was insufficient. At least one day before starting the measurements, the subjects received written instructions (see appendix B) and did some trial measurements, this preparatory session taking about half an hour.

Grip force was measured with a Jamar Dynamometer. During the measurement, the subjects were standing, with the elbow in 45° flexion. They were asked to exert maximal force for four seconds.

For the actual experiment, the subjects were first asked to exert, for each posture separately, maximal force for 6 seconds (2 seconds buildup, 4 seconds maximal), following the method of Caldwell et al. (1974). No feedback or encouragement was given. Maximal force was defined as the mean force exerted during the last 4 seconds. The positions of the belt, doorknob and force plate were noted, in order to allow the situation to be reproduced with every subsequent measurement. This maximal force measurement was carried out twice, with a minimum rest period of 2 minutes in between. Maximal force was then defined as the average of the two measurements.

Next, the subject was asked to exert a percentage of this force and maintain it for as long as possible. The actual force level could be observed in real time on a computer display, which also showed the required force level and the level at which the measurement would stop (50 % above and below the required force). Not indicated was the level at which warning beeps would sound (10 % above and below the required force level).

During force exertion, every 30 seconds the subject was asked to indicate the degree of discomfort experienced (see 5.4 'Discomfort during submaximal, static force extension').

Conversation was not allowed during the measurements. No encouragement was given either. To prevent the subjects from becoming bored, a radio played music (mostly popular) in the background. Endurance measurements were interrupted after thirty minutes. Immediately after the endurance measurement, the subjects were asked to indicate the location of discomfort and the reason for breaking off the experiment.

No more than four different endurance measurements were carried out per day (no more than one per posture). The force levels were selected at random. At least six sessions were necessary to complete each experiment. Each day, before measuring the endurance, the maximal force was remeasured.

During the last session, the subjects were also asked to exert their maximal, 4 s force. This time the subjects received visual feedback of the amount of force as well as encouragement. This last effort was called a 'supermaximal force'.

5.3.5 Results

Maximal force

Description. The maximal forces measured in the four situations can be seen in table 5-10. In the case of pushing with the preferred hand, maximal forces of the second experiment on discomfort (see 5.4.4) were also included, as these were part of the same series of measurements, under the same circumstances. Men exerted on average about double the force that women exerted.

	females			males			both		
	$\bar{x}$	s	n	$\bar{x}$	s	n	$\bar{x}$	s	n
push	176.9	48.5	138	311.1	86.6	161	249.1	98.0	299
flexion	132.7	26.6	97	249.6	79.5	95	190.5	83.1	192
extension	241.8	80.6	96	524.0	207.0	104	388.6	212.7	200
anteflexion	63.8	13.8	99	114.6	29.7	100	89.3	34.4	199

Table 5-10: Maximal force [N], averages and standard deviations exerted by women (n = 12) and men (n = 12) apart and together.

To calculate the exerted moments from the measured forces, the forces are multiplied by the distances of the point of force exertion to the pivot of (intended) rotation. For the knees, this distance is from the middle of the band to the epicondylus lateralis. For the arm performing anteflexion, the distance is estimated to be from the middle of the force plate to the acromion. For pushing with the other arm, no moment is calculated. The moments can be seen in table 5-11.

	females			males			both		
	$\bar{x}$	s	n	$\bar{x}$	s	n	$\bar{x}$	s	n
push	44.9	9.1	97	87.3	28.6	95	65.9	29.9	192
flexion	87.3	30.9	96	185.8	74.4	104	138.5	75.9	200
anteflexion	33.1	6.6	99	65.0	17.2	100	49.1	20.6	199

Table 5-11: Maximal moment [N], averages and standard deviations exerted by women (n = 12) and men (n = 12) apart and together.

Analysis of variance. To see whether the maximal force increases or decreases with each measurement, or changes with the time of the day, four one-way analyses of variance were carried out. For each situation, a separate analysis was carried out. Before starting the analysis, the maximal forces were normalized for each subject, 100% being his/her average for that situation. The factors included in the model were the time of the measurement (per hour, from 8.00 to 22.00 h) and the order in which measurements were taken (1 up to maximal 17). In all four situations, there was no significant difference in maximal force on different hours of the day. There was, however, significant difference in maximal force by the order in which measurements were done. Regression analysis resulted in a regression line with a constant of 91.7 and a coefficient of 1.31, indicating that the first average maximal force exertion was about 91.7 % of the overall average, increasing on average 1.31 % with every measurement (95 % confidence interval

xth measurement	$\bar{x}$	s	n
1	94.71	11.98	90
2	95.60	12.62	90
3	94.65	15.57	90
4	95.77	14.08	89
5	96.88	11.07	90
6	99.95	11.74	87
7	98.52	14.54	48
8	101.02	12.54	46
9	101.71	11.11	46
10	107.96	13.13	44
11	105.51	13.43	43
12	109.41	19.73	42
13	108.08	11.34	19
14	110.75	16.68	14
15	112.82	22.43	13
16	114.59	16.97	10
17	111.33	20.04	8

Table 5-12: Maximal force, per occasion in order of measurement, averaged over 24 subjects (measured one to 17 times per situation, depending which of the two experiments was repeated), standardized per subject at 100 % average.

from 1.16 to 1.62 %). Average force percentages per measurement can be seen in table 5-12. Four extreme values, ranging from 160 to 199 %, are left out.

It can be concluded that training, most probably by the exertions during the measurement sessions, and possibly learning influenced the maximally exerted force significantly.

Endurance

Data treatment. The data analysis does not include any of the measurements that both show shorter endurance than at higher force levels and stopped for reasons other than muscle discomfort (e.g. not being able to sit still, or discomfort due to the contact surface of the force transducer). If the subject clearly indicated that he/she could do better, the results were also excluded. This happened only twice. If the experiment was repeated, the first measurements were used for analysis, and if results were excluded, the second measurement was taken. If a measurement was missing, and a higher force had already been endured for half an hour, the endurance time was assumed to be (at least) half an hour.

Caution is required when analyzing the results obtained at lower force levels (15 - 20 % of maximal), as a substantial number of the measurements lasted up to half an hour and had to be discontinued (see table 5-13). These figures may distort the results, so they are not included in every case. Furthermore a logarithmic scale was used for endurance, to get a more balanced view of the results in both short and long endurance tasks.

	80%			60%			40%			30%			20%			15%		
	1)	2)	3)	1)	2)	3)	1)	2)	3)	1)	2)	3)	1)	2)	3)	1)	2)	3)
pushing	23	0	0	23	0	0	23	0	0	23	2	1	23	3	3	23	2	7
flexion	22	0	0	22	0	0	22	0	3	22	1	4	22	0	7	22	4	13
extension	23	0	0	23	0	0	23	0	1	23	0	5	23	2	10	23	0	13
anteflexion	24	0	0	24	0	0	24	0	0	24	1	1	24	3	2	23	3	4

Table 5-13: Number of measurements:
1) total measured;
2) stopped for other reasons than muscle discomfort and shorter endurance than higher force level; and not possible to use a second measurement as a replacement, or extrapolate a 1800 s endurance (when higher force levels had scored already);
3) exceeding the thirty minutes measurement limit. Repeated measurements are not included, unless as replacement for a missing or unusable first measurement.
n = 24 (12 women, 12 men).

Description. The endurance time data do not have a standard normal distribution. The distribution differs per group of data (force level, arm/leg) and the sample size is so small that the frequency distribution is irregular and thus hard to describe. Therefore the average and the standard deviation are not the best indicators for the distribution of the data. As an alternative, box plots are shown in figure 5-11 for arms and in figure 5-12 for legs.

A box plot plots the median, the 25th percentile, the 75th percentile and outlying values. The lower boundary of the box indicates the 25th percentile, the upper boundary indicates the 75th percentile, the line in the middle represents the median. The length of the box corresponds to the interquartile range (the difference between the 25th and 75th percentiles). All measurements that are greater than 1.5 box length from the 75th percentile or smaller than 1.5 box length from the 25th percentile are considered outlying values and are indicated with circles. The smallest and largest respectively observed values which are not outliers are indicated by means of the whiskers on either side of the box.

The median indicates the general tendency, in this case longer endurance times at lower force levels. From the length of the box, the variability can be seen. On a logarithmic scale, the median is in most cases situated more or less in the centre of the box, so the distribution does not seem to be very skewed. There are equal amounts of outliers on either side of the box, except at the lower force levels. However, it must be noted that the data at the lower force levels are distorted as a result of the half hour (1800 s) measurement limit.

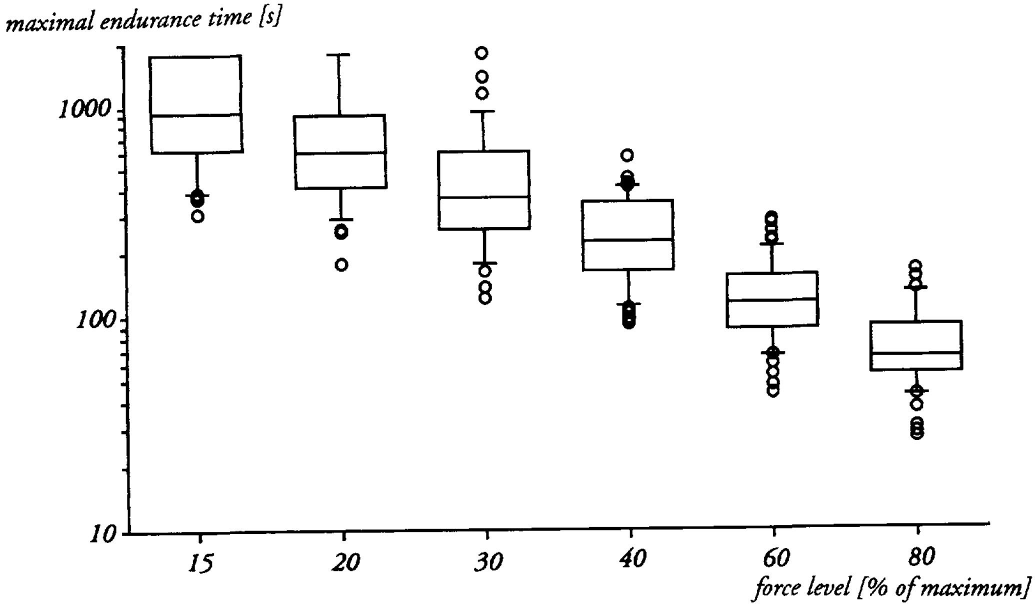


Figure 5-11: Box plot of the maximal endurance times [s] of ***arm*** *forces at different force levels. See text for explanation. Subjects are female (n = 12) and male (n = 12). Note that the data at 15 and 20 % are distorted as a result of the half hour time limit.*

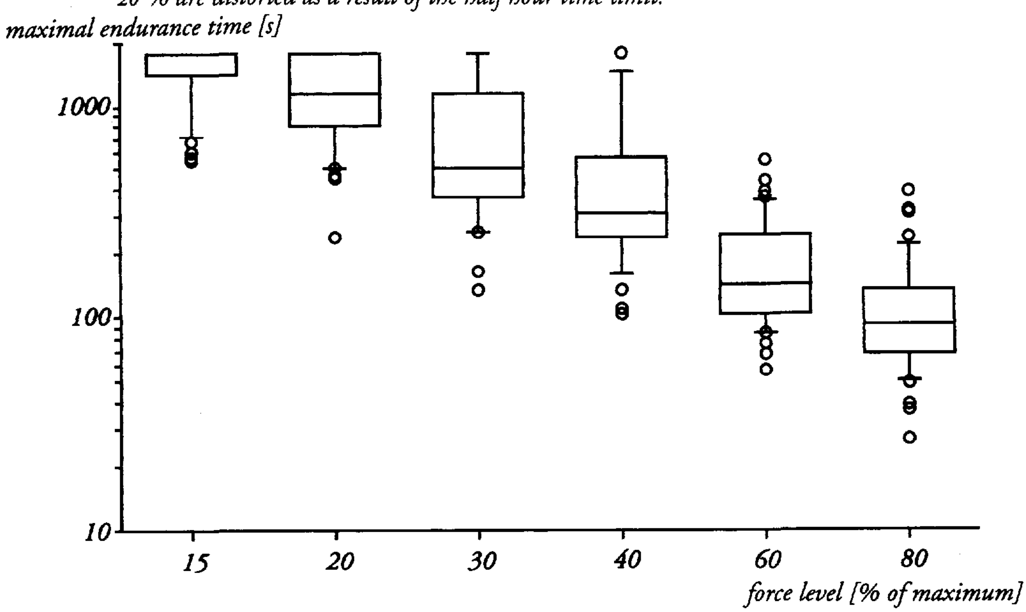


Figure 5-12: Box plot of the maximal endurance times [s] of ***leg*** *forces at different force levels. See text for explanation. Subjects are female (n = 12) and male (n = 12). Note that the data at 15 and 20 % are distorted as a result of the half hour time limit.*

	force level	P_{25}	P_{50}	P_{75}	range	$\bar{x}$	s	coeff. of variation	n
women (n=12)									
arm	80%	58.8	75.0	107.0	27 - 166	86.3	37.8	0.44	23
	60%	95.0	133.0	172.8	54 - 290	144.7	63.9	0.44	23
	40%	150.3	230.0	381.5	95 - 457	258.7	119.9	0.46	23
	30%	225.0	353.0	494.0	123 - 1389	426.6	293.8	0.69	22
	20%	385.5	485.0	732.3	182 - 1800	652.5	450.3	0.69	19
	15%	396.0	701.5	1182.0	313 - 1800	835.8	461.4	0.55	18
leg	80%	87.0	107.5	181.0	37 - 392	143.2	94.4	0.66	22
	60%	144.0	167.0	279.0	98 - 560	214.7	116.5	0.54	22
	40%	278.0	370.0	683.0	159 - 1800	560.3	488.4	0.87	22
	30%	412.0	599.0	1774.0	253 - 1800	902.8	606.1	0.67	22
	20%	810.0	1367.0	1800.0	435 - 1800	1282.7	530.4	0.41	22
	15%	1207.5	1800.0	1800.0	694 - 1800	1523.8	422.1	0.28	20
men (n=12)									
arm	80%	52.0	58.5	82.5	28 - 76	65.2	23.7	0.36	24
	60%	76.5	101.0	135.0	44 - 254	111.2	48.5	0.44	24
	40%	162.0	237.5	334.5	93 - 574	254.8	119.4	0.47	24
	30%	267.5	389.0	640.8	139 - 1800	557.7	460.0	0.82	23
	20%	418.0	729.5	1187.0	253 - 1800	855.1	525.4	0.61	22
	15%	785.0	1088.0	1800.0	409 - 1800	1229.0	535.9	0.44	23
leg	80%	64.5	76.0	112.5	27 - 245	94.5	53.8	0.57	23
	60%	89.3	106.0	215.8	56 - 446	156.3	106.6	0.68	23
	40%	193.0	274.0	501.5	104 - 1800	469.8	510.0	1.09	23
	30%	289.0	446.5	922.0	135 - 1800	684.5	583.4	0.85	22
	20%	626.5	1166.0	1800.0	242 - 1800	1210.3	543.5	0.45	21
	15%	1400.3	1800.0	1800.0	552 - 1800	1513.7	460.0	0.30	21
women and men (n=24)									
arm	80%	52.0	64.0	90.0	27 - 166	75.5	32.8	0.43	47
	60%	85.0	116.0	156.5	44 - 290	127.6	58.4	0.46	47
	40%	160.0	230.0	353.0	93 - 574	256.7	118.3	0.46	47
	30%	252.8	378.0	609.3	123 - 1800	493.6	389.1	0.79	45
	20%	401.3	621.5	915.8	182 - 1800	761.2	496.6	0.65	41
	15%	603.3	946.0	1800.0	313 - 1800	1056.4	536.2	0.51	41
leg	80%	66.0	93.0	133.8	27 - 392	118.3	79.4	0.67	45
	60%	102.8	145.0	247.8	56 - 560	184.8	114.1	0.62	45
	40%	234.0	311.0	572.3	104 - 1800	514.0	495.9	0.96	45
	30%	366.5	514.5	1158.0	135 - 1800	793.6	508.2	0.75	44
	20%	792.0	1166.0	1800.0	243 - 1800	1247.4	531.6	0.43	43
	15%	1376.0	1800.0	1800.0	552 - 1800	1518.6	436.4	0.28	41

Table 5-14: Maximal endurance times [s] of women (n = 12) and men (n = 12)

The median, 25th and 75th percentile, average and standard deviation of the endurance at different levels of force exertion for arms and legs are described in table 5-14 for women and men apart and together. Although the average and standard deviation are no good measures of distribution, as argued above, they are included nevertheless to show the discrepancy with the medians and to facilitate comparison with the data of researchers who only included the average value in their publications (as everybody did until now). In those tables, as in the box plots, 100 % force level is the average of maximal force measured twice at the beginning of the experiment.

In tables 5-15 and 5-16, descriptions of the same endurance for two differently defined maximal forces are shown. In one case, 100 % is the maximal force as measured during every session. In the other case, 100 % is the 'supermaximal force', once measured with feedback and encouragement. The data were categorized to allow them to be compared.

	% of repeated max. force	P_{25}	median	P_{75}	range	$\bar{x}$	s	coeff. of variation	n
arm	95 to 100%	*	*	*	51 - 86	*	*	*	2
	85 to 94%	34.5	61.0	75.8	27 - 90	58.1	24.1	0.4	7
	75 to 84%	52.0	63.0	89.3	28 - 177	76.3	37.3	0.5	25
	65 to 74%	59.0	95.0	136.0	44 - 254	102.8	49.7	0.5	26
	55 to 64%	85.0	112.0	141.5	48 - 290	126.6	61.2	0.5	26
	45 to 54%	117.5	145.0	187.0	93 - 457	172.8	95.5	0.6	16
	35 to 44%	178.5	254.5	371.0	93 - 672	277.0	131.6	0.5	35
	25 to 34%	256.8	389.0	595.5	139 - 1800	494.8	381.4	0.8	47
	18 to 24%	381.8	600.0	921.8	182 - 1800	732.2	489.2	0.7	39
	10 to 17%	603.0	912.5	1800.0	313 - 1800	1035.3	540.3	0.5	41
	0 to 9%	–	–	–	– –	–	–	–	0
leg	95 to 100%	*	*	*	49 - 209	*	*	*	4
	85 to 94%	101.3	104.0	141.0	37 - 245	126.0	64.7	0.5	9
	75 to 84%	73.0	92.0	166.3	27 - 392	126.8	91.5	0.7	25
	65 to 74%	91.0	130.5	257.5	39 - 345	160.0	98.7	0.6	16
	55 to 64%	91.5	139.0	208.0	56 - 560	175.2	120.9	0.7	28
	45 to 54%	131.0	236.0	326.3	67 - 547	248.6	134.1	0.5	17
	35 to 44%	253.5	365.0	498.5	104 - 1800	510.5	496.1	1.0	31
	25 to 34%	311.0	584.0	1144.0	137 - 1800	790.9	589.8	0.7	39
	18 to 24%	622.0	1364.5	1800.0	135 - 1800	1235.4	594.4	0.5	46
	10 to 17%	958.3	1800.0	1800.0	242 - 1800	1400.0	494.0	0.4	47
	0 to 9%	-	-	-	- -	-	-	-	0

Table 5-15: Maximal endurance times [s] categorized by force level as percentage of the maximal force exerted on the same day (n = 24, women and men).
** less than 5 measurements: median and average not given.*

	% of super-max. force	P25	median	P75	range		x̄	s	coeff. of variation	n
arm	95 to 100%	–	–	–	–	–	–	–	–	0
	85 to 94%	–	–	–	–	–	–	–	–	0
	75 to 84%	*	*	*	27 -	30	*	*	*	2
	65 to 74%	40.8	52.0	60.8	28 -	86	52.4	16.7	0.3	9
	55 to 64%	53.0	65.0	98.5	44 -	136	76.6	31.4	0.4	16
	45 to 54%	63.5	78.0	132.5	48 -	290	99.7	52.2	0.5	32
	35 to 44%	95.0	122.0	177.0	66 -	574	164.2	111.7	0.7	34
	25 to 34%	158.5	219.5	327.0	84 -	1800	272.4	256.9	0.9	43
	18 to 24%	290.0	389.5	494.0	123 -	1800	469.6	354.9	0.8	41
	10 to 17%	448.5	709.0	1168.5	141 -	1800	858.8	526.1	0.6	71
	0 to 9%	422.8	898.0	1783.5	322 -	1800	1061.4	631.2	0.6	11
leg	95 to 100%	–	–	–	–	–	–	–	–	0
	85 to 94%	–	–	–	–	–	–	–	–	0
	75 to 84%	*	*	*	92 -	93	*	*	*	2
	65 to 74%	34.5	81.0	119.3	27 -	219	90.0	76.7	0.9	5
	55 to 64%	59.5	74.5	119.0	55 -	144	88.1	35.5	0.4	8
	45 to 54%	67.8	89.0	143.5	39 -	392	119.2	82.2	0.7	23
	35 to 44%	94.3	129.0	250.0	56 -	374	167.8	100.7	0.6	31
	25 to 34%	135.8	252.0	383.3	104 -	1800	309.7	285.7	0.9	41
	18 to 24%	245.5	378.0	753.5	104 -	1800	597.7	532.3	0.9	48
	10 to 17%	625.0	1162.0	1800.0	228 -	1800	1184.8	559.6	0.5	68
	0 to 9%	1377.0	1800.0	1800.0	520 -	1800	1485.2	521.0	0.4	38

Table 5-16: Maximal endurance times [s] categorized by force level as percentage of the supermaximal force with feedback and encouragement (n = 24, women and men).
** less than 5 measurements: median and average not given.*

	force level	n	r	paired t-test mean (x-y)	s	p (2-tailed)
arm	80%	18	0.12	9.60	37.2	0.2904
	60%	19	**0.46**	18.60	57.3	0.1743
	40%	18	**0.75**	10.60	80.0	0.5801
	30%	16	**0.63**	61.90	354.9	0.4960
	20%	12	**0.81**	49.20	248.6	0.5072
	15%	9	0.42	67.00	466.2	0.6778
leg	80%	20	**0.80**	9.10	57.5	0.4875
	60%	20	**0.67**	-42.90	130.7	0.1588
	40%	16	**0.96**	-46.20	94.0	0.0681
	30%	12	**0.93**	34.40	182.4	0.5270
	20%	6	**0.37**	15.10	395.5	0.9294
	15%	2	*	*	*	*

Table 5-17: Reproducibility of the repeated measures of maximal endurance time (n = 10, both female and male). Listed are the number of compared measurements (n), the correlation coefficients and the results of a paired t-test of the average differences. Bold denotes significance at $p < 0.05$.
** less than 5 measurements: correlation coefficient and mean (x-y) not given.*

The medians for all three definitions of maximal force, and the average of the 'normal' definition, are plotted in figure 5-13 for arms and in figure 5-14 for legs. They will be discussed further in this section.

Reproducibility. To establish the reproducibility of the endurance times for the ten subjects who repeated the experiment, both the correlation coefficient and the average difference between the results of the first and the second measurement are calculated, see table 5-17. All endurance measurements that had been interrupted at 1800 s are left out (see table 5-13). This reduces the number of data at 15 % of leg force to such an extent, that the calculations here yield insignificant results.

Product-moment correlation coefficients between re-tested endurance times are calculated for force levels and arms and legs separately. All are positive, range between 0.42 and 0.96 (with one exception of 0.12), and 8 out of 11 values of r are significant at $p < 0.05$. This indicates that the results tend to be intra-individually constant to a varying, but significant extent.

The average difference, for force levels and arms and legs separately, is calculated by subtracting the endurance of the first measurement from the second one, after which they are added and divided by n. With t-tests, it is tested whether the average differences are significantly different from 0 (they should not be, in order to be reproducible). None were significantly different. This indicates that the group results are reproducible, too. For a discussion of the power of a t-test with a similar number of subjects, please refer to the discussion of the experiments on standardization of posture, in 5.1.6.

Analysis of variance. Either the size of the groups or the distribution within cells should be equal to allow performance of an analysis of variance. On a logarithmic scale, both requirements are met.

Analysis of variance was used to find to what extent the endurance depends on gender, age, use of arm or leg, force level, and subject. Force levels of 15 and 20 % were excluded for the reason mentioned before, and a logarithmic scale was used for endurance time. All this influences the outcome of the analysis. It was not possible to include all the factors in the model of interaction, because there would not be enough observations per cell. Therefore a preliminary analysis of variance, including all but the 'subject' factors, was carried out. The results, which are presented in table 5-18, indicated that age has no significant influence and gender does not contribute much (only 1.5 %) to the total variation.

In a second analysis of variance, the force level, subject and use of arm or leg were included in the model of interaction. The results, presented in table 5-19, show that most of the variance may be explained by differences in force level (54 % of the total variance), subject (21 %) and use of arm or leg (4 %). There is also a significant interaction between subject and use of arm of leg, which explains 5 % of the total variance and is not more important than the main effects. In this model, only 9 % of the variance remains unexplained.
A one-way analysis of variance (t-test) showed that there was no difference in endurance between the two arms and the two legs separately.

source of variance	sum of squares	DF	mean square	F	signif. of F
	analysis of variance				
main effects	34.955	6	5.826	89.181	.000
arm/leg	2.705	1	2.705	41.412	.000
sex	.881	1	.881	13.480	.000
young/old	.022	1	.022	.338	.561
force level	31.167	3	10.389	159.035	.000
2-way interactions	.740	12	.062	.945	.502
arm/leg sex	.266	1	.266	4.065	.045
arm /leg young/old	.003	1	.003	.047	.828
arm/leg force level	.081	3	.027	.415	.743
sex young/old	.235	1	.235	3.601	.059
sex force level	.127	3	.042	.649	.584
young/old force level	.012	3	.004	.061	.980
3-way interactions	.519	10	.052	.795	.634
arm/leg sex young/old	.011	1	11.000	.161	.688
arm/leg sex force level	.100	3	.033	.510	.675
arm/leg young/old force level	.025	3	.008	.127	.944
sex young/old force level	.380	3	.127	1.941	.123
4-way interactions	.006	3	.002	.031	.993
arm/leg sex young/old force level	.006	3	.002	.031	.993
explained	36.221	31	1.168	17.886	.000
residual	21.688	332	.065		
total	57.909	363	.160		

Table 5-18: Analysis of variance, with endurance as dependent variable and sex, age, use of arm or leg and force level included as factors in the model. Force levels of 15 and 20 % were excluded.

source of variance	sum of squares	DF	mean square	F	signif. of F
	analysis of variance				
main effects	46.038	27	1.705	56.494	.000
subject	11.969	23	.520	17.242	.000
arm/leg	2.282	1	2.282	75.596	.000
force level	31.462	3	10.487	347.469	.000
2-way interactions	5.051	95	.053	1.762	.001
subject arm/leg	2.613	23	.114	3.764	.000
subject force level	2.321	69	.034	1.115	.284
arm/leg force level	.088	3	.029	.973	.407
3-way interactions	1.598	68	.023	.778	.881
subject arm/leg force level	1.598	68	.023	.778	.881
explained	52.687	190	.277	9.187	.000
residual	5.222	173	.030		
total	57.909	363	.160		

Table 5-19: Analysis of variance, with endurance as dependent variable and use of arm or leg, force level and subject included as factors in the model. Force levels of 15 and 20 % were excluded.

Various definitions of maximal force. There is apparently no difference between the endurance time plotted as a function of the maximal force as defined at the start of the experiment (a series of sessions), and the endurance time plotted as a function of the maximal force measured each time before a session of the endurance measurement. The last data are categorized, and the medians of some of these categories and the corresponding original percentages can be compared for arms en legs in figures 5-13. From the graph it can be inferred that the match is so obvious that statistical tests will not contribute any further to the evidence.

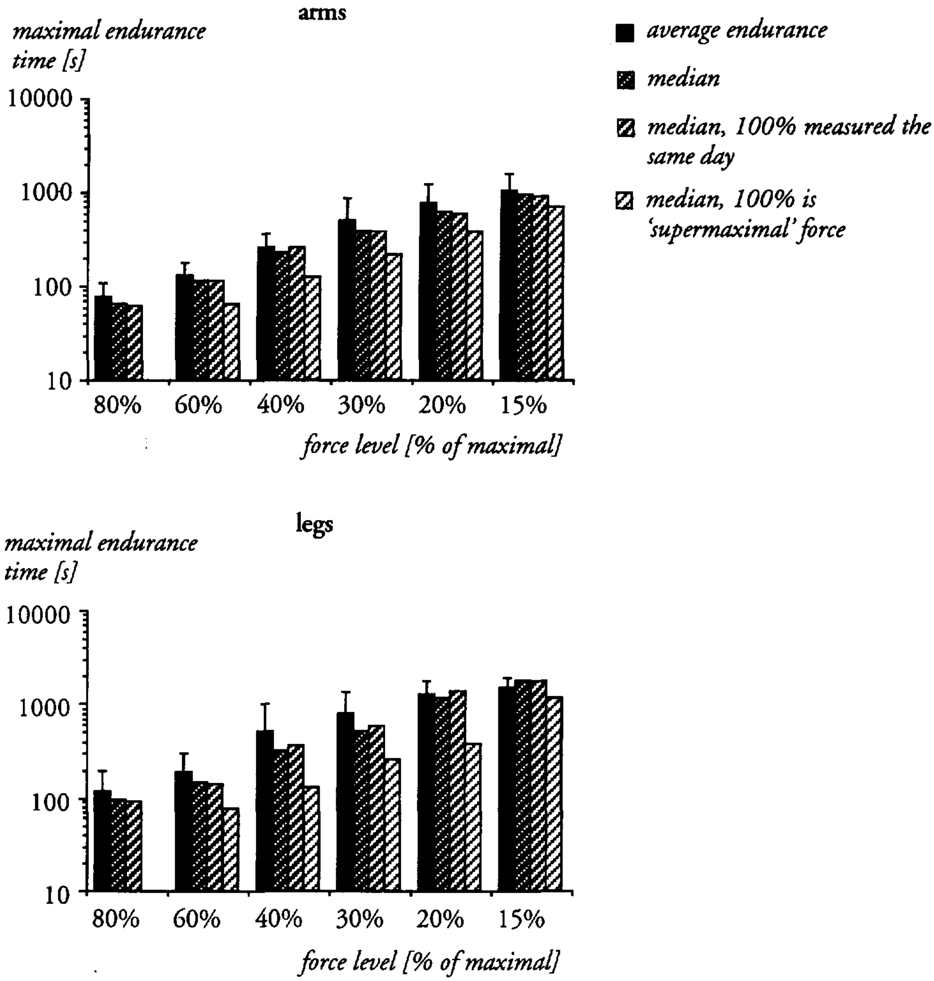


Figure 5-13: Medians of the same maximal endurance data of the arms and legs are plotted against three different ways of defining the force level (see legend). The average (and one standard deviation) is plotted against the maximal force measured at the beginning of the experiment. Subjects are female (n = 12) and male (n = 12). Note that the average endurance (and standard deviation) at 15 and 20 % is distorted as a result of the half hour time limit.

Supermaximal force, i.e. maximal force with feedback and encouragement, nearly always proved larger than either of the other maximal forces. Therefore, when using supermaximal force as the reference level (100 %), the same endurance times correspond with lower force levels. These data are also categorized and can be seen in figure 5-13, too.

Analysis of variance was used again to find whether, with a different definition of maximal force, the endurance is influenced by the same factors. In the model of interaction, the force level (defined as percentage of the supermaximal force), gender, use of arm or leg and their interactions were included. The categories from 0 to 9 % and from 10 to 17 % of the supermaximal force were excluded, to avoid influence of the measurements broken off at 1800 s. This time, gender and force level were significant factors, and use of arms or legs was not. However, an interaction between gender and use of arms or legs was noted which was more important than the main effect of gender. The model explained 60 % of the total variance, of which 53 % by the factor force level, and 1.4 % by the interaction between gender and use of arms or legs. Women have longer endurance when using their arms, while the endurance of women's legs and the endurance of men's legs and arms are not significantly different. However, when all force levels (0 - 9 % and 10 - 17 %, too) are included in the analysis of variance, use of arms or legs is again a significant factor.

Correlation. All correlations are presented in the large correlation matrix in appendix D. There is little correlation between endurance time measured at various force levels and the anthropometric variables of body height, body weight, grip force, shoulder-grip length and elbow-grip length. The values of r ranged from -0.48 to +0.38, were mostly not significant at $p < 0.05$ (only if $|r| \leq 0.34$) and not predominantly positive or negative.

Correlations between maximal force and endurance time concerning one and the same way of force exertion, assessed for force levels of 30 % up to 80 %, were mostly not significant. The coefficients ranged from -0.58 to +0.17.

Correlations between endurance times at various force levels were mainly positive, 73 of the total of 120 values of r were significant, and in 16 cases $r \geq 0.71$.

Subjects' experience. Subjects sometimes commented that at the lower force levels their endurance was hindered more by having to sit still, by muscle tremors and by trying to keep the force at the correct level, than by muscle fatigue. Sometimes a measurement was ended because of discomfort caused by the contact surface. Muscle soreness was experienced only once by one of the subjects, the day after one of the sessions.

5.3.6 Discussion

Age and sex. From the analysis of variance, the conclusion can be drawn that age and sex do not influence the endurance to the extent that these factors should be taken into account. This agrees with Elbel (1949) on age and Caldwell (1963) on gender, and contradicts Deeb and Drury (1992) on age and Byrd and Jeness (1982) on gender. However, it may well be that the age differences of the sample are not large enough to show difference in endurance. This may also explain the results of Elbel, who found no correlation between age and endurance of subjects in their early twenties.

Subject and force level. Subject and force level are the main factors affecting variation. That the force level is an important factor in endurance is generally acknowledged. The influence of the subject on endurance is dismissed by Rohmert (1960), but affirmed by both Caldwell (1964 a) and Bishu et al. (1990).

Muscle group. The use of arms or legs is a significant factor influencing endurance time when force level is defined as percentage of the maximal force, exerted twice at the beginning of the experiment, but it is not significant when force level is defined as percentage of the supermaximal force. This reveals the impact of the definition of maximal force on the results. Not only does it influence the relationship between force level and endurance relationship, it even changes the significance of factors in the analysis of variance.

The difference in endurance time for arms and legs contradicts the findings of Rohmert (1960) and Deeb and Drury (1990). The last, though, expected a difference between endurance of various muscle groups, but they did not find it. There are two possible explanations for the considerably longer maximal endurance time of legs than of arms. It may be that the ratio of slow-twitch/fast-twitch muscle fibres is different for arms and legs. According to Hultén et al. (1975), and confirmed by the results of Viitasalo and Komi (1978), the higher the percentage of slow twitch fibres, the longer the endurance. Or perhaps the friction between feet and support, in spite of being reduced, still biases the leg measurements. The friction varies considerably per subject and per session, but is estimated to be only a few percent of the maximal force. The results of the friction measurements are insufficiently constant to justify a recalculation of the force levels.

There may be even a third possible cause, indicated by the fact that there is no significant difference between endurance of arms and legs when 100 % force is defined by the supermaximal force. This means that legs exerted more supermaximal force compared to normal maximal force than arms did. For the lowest force levels, however, there was a significant difference between endurance of arms and legs, again. No explanation could be found for this change of significance of factors by both definition of force level and inclusion or exclusion of lower force levels. It is possible that this inconsistency is also at the root of the discrepancy between expectations and findings of Deeb and Drury (1990).

Blood flow. There is no indication that at or above 70 % of maximal force the endurance process changes or the curve of endurance time declines steeply, as may be expected based on the findings of Humphreys and Lind (1963). Their results indicate that intramuscular pressure during contraction can not occlude the blood supply until the tension exerted is above some value greater than 70 % of the maximal force.

Reproducibility. Reproducibility of endurance time is found to be significant, which corresponds with Caldwell (1963 and 1964 a), Carlson (1969), Elbel (1949) and Start and Graham (1964).

Correlation. Little correlation was found between maximal forces and endurance time concerning one and the same way of force exertion. This agrees with Byrd and Jeness (1982), Caldwell (1963, 1964a, 1964b), Elbel (1949) and Start and Graham (1964). Even less correlation was found between several anthropometric variables and endurance. This corresponds with Caldwell (1963 and 1964 a) and Elbel (1949).

Comparing literature. When comparing the results of this experiment to the formulas of Start and Holmes (1963), Rohmert (1965), Pottier et al. (1969), Schutz and Chaffin (1972), Hagberg (1981), Sato et al. (1984), Sjøgaard (1986) and Rose et al. (1992) (figure 5.14), it can be seen that the endurance of both arms and legs according to our findings is generally much longer. When force levels are transformed to percentages of 'supermaximal force', they are more comparable. Note that at force levels of 15 % and 20 % the results are distorted by the 1800 s limit.

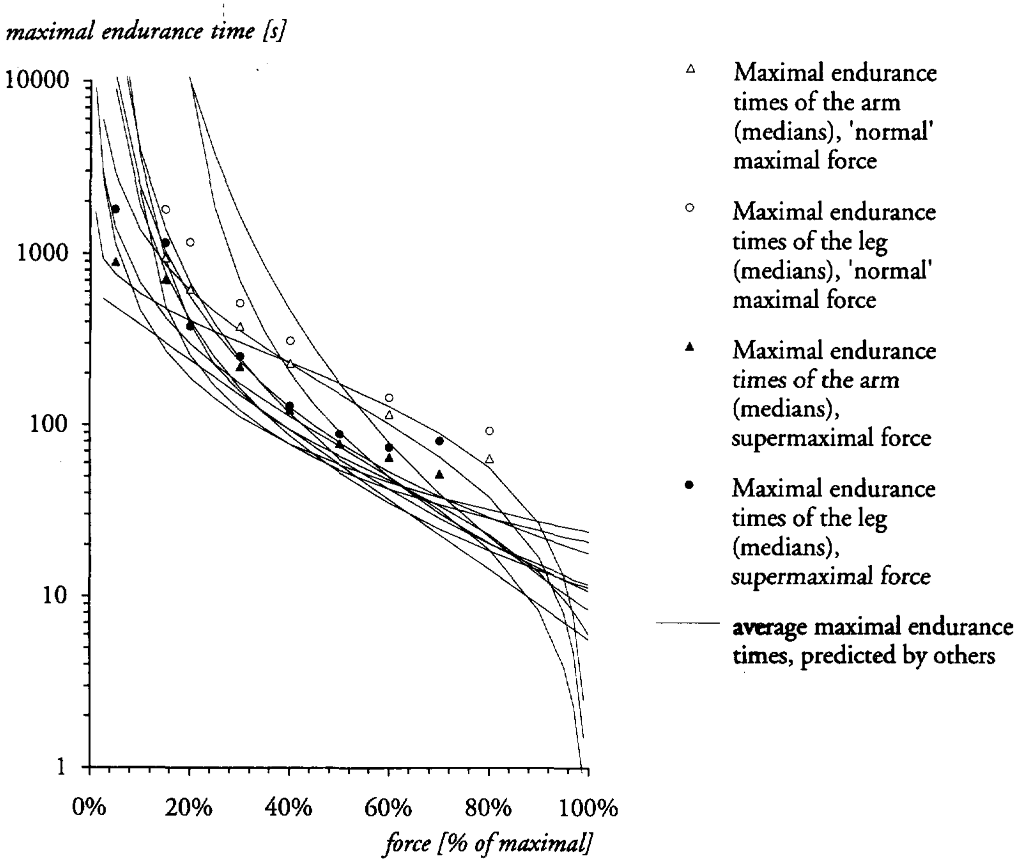


Figure 5-14: The medians of various force levels endured maximally for arms and legs in this experiment, the medians of the same maximal endurance times plotted against the supermaximal force and the average maximal endurance times as predicted by others.

Measurement procedure. It would be consistent to use similar procedures for measuring both maximum force and endurance. On the one hand, endurance measurements require feedback in order to keep the force exerted at a constant level, and in real life there will in general be feedback for the subject when exerting force for a long time, too. For use in practice it would therefore be most valid to measure with some feedback. On the other hand, it would be useful to be able to infer endurance from existing data, measured in a more or less standardized way: i.e. data on maximal force, established according to the method of Caldwell (no feedback or encouragement given). Encouragement is not advisable anyway, because it might cause the subjects to overextend themselves, especially during the endurance measurements. It is therefore proposed that maximal force for endurance measurements be measured without feedback or encouragement, and corresponding endurance be measured with feedback and without encouragement. This seems to be, if not the most consistent, certainly the most practical solution, generating results that are most useful (and therefore valid) in practice.

What then causes the discrepancy between the results obtained in this experiment and the formulas published by the other authors? The methods used, if known at all, are not comparable, and it may well be that the differences are caused by e.g. different warning and end limits during measurement, different ways of restricting movement, and a different method of defining the maximal force. Another factor influencing the measurements is the motivation of the subjects. Although no encouragement was given during the endurance measurement, the commitment of the subjects to the various experiments is not known and can therefore not be compared.

Formula. In order to generate a formula for the force level-endurance relationship, the median is chosen for curve-fitting. Firstly, because it cannot be assumed that the distribution is normal, in which case the median is preferred over the average. Secondly, because the distortion of the average by the half-hour measurement limit is absent in the median for all force levels, except for endurance measurements at of 15 % leg force where even the median reaches the limit of 1800 s. The formula is generated with stepwise regression analysis. It takes the factors 'relative force level' and 'use of arm or leg' into account, and can only be valid for the range of force levels on the medians of which the model is based, i.e. 15 % up to 80 % of the maximal force. One formula, with relative force level and use of arm or leg as variables, was the best fit. For clarity, it is divided in the following two formulas, one for arms and one for legs, which describe the relationship between relative force level and endurance time:

$$\ln t = 11.61 - 1.7 \ln F \quad \text{(for arms)}$$
$$\ln t = 12.02 - 1.7 \ln F \quad \text{(for legs)}$$

t = maximal endurance time [s];
F = force level [% of maximal force], from 15 % to 80 %.

Medians and curves can be seen in figure 5-15. For both arms and legs together, $r^2 = 0.99$. This value seems quite high due to the use of the median for modelling, disregarding the scatter of the original data.

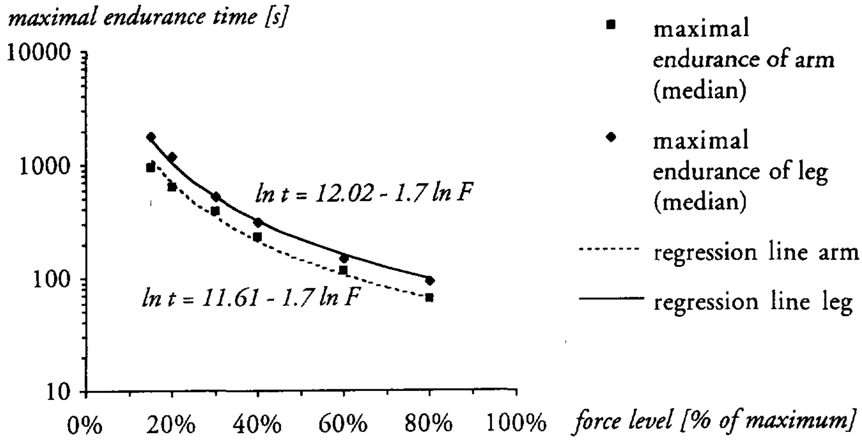


Figure 5-15: Medians of the maximal endurance times [s] of both arms and legs, as measured in this experiment, and the model that resulted from regression analysis.

With reference to the experiences during the measurements and the comments of the subjects, it is concluded that long endurance of low force levels is possible, though not desirable, nor advisable. Force is easier to maintain if the relative force level is low, if the subject is not subject to boredom, and may change his posture from time to time. These last two conditions apply even more to the lower force levels. Consequently, dynamic and/or cyclic force exertion should be considered preferable. This corresponds with old physiological insights, and with the findings of Sjøgaard (1986) and Ulmer et al. (1989). The idea that low force levels can be exerted for an unlimited time, propagated by Rohmert (1960), Monod and Scherrer (1965) and Björksten and Jonsson (1977), seems to be outdated, or to refer only to the physiological processes.

A formula to predict muscle endurance and discomfort on the basis of the exerted force cannot be simply applied to design practice. In addition to the exerted force level the weight of limbs and the strain of maintaining a posture should be taken into account. Furthermore, if the contact surface is not optimal, the discomfort caused by the contact may affect endurance to a considerable degree.

5.3.7 Conclusions

Endurance time of 15 % to 80 % of maximal force was found to be reproducible, being significantly shorter for arms than for legs, and both generally much longer than predicted on the basis of the force/endurance formulas of Start and Holmes (1963), Rohmert (1965), Pottier et al. (1969), Schutz and Chaffin (1972), Hagberg (1981), Sato et al. (1984), Sjøgaard (1986) and Rose (1992). The main factors influencing endurance time were the subjects themselves, force level and use of arm or leg. Endurance time was not affected by age or sex in the range between 80 and 30 % of maximal force. It depended, however, on the way the maximum force was established, c.q. defined. It is proposed that maximal force for endurance measurements be measured without feedback or encouragement, while endurance be measured with feedback.

Two formulas are proposed to describe the relationship between relative force level and endurance time, one geared to endurance of arms, one to that of legs. These formulas, however, cannot be used to simply predict endurance time. Forces from the weight of limbs and strain induced by posture should be included in the force level. Furthermore, both endurance and comfort will be strongly affected by the characteristics of the contact surface, the degree of immobility required of the subject, and the required degree of constancy of the force (not to mention the subject's motivation and interest). A designer should take these factors into account. The question remains: how?

5.4 Discomfort during static, submaximal force exertion

Summary

The degree of discomfort during force exertion is little investigated in literature. In daily life, however, comfort is an important aspect when using or operating products. It would therefore be useful for designers to know about the subjective experience of (dis)comfort during the exertion of submaximal forces by users of products. No standard measurement methods were found in literature. Two experiments were carried out, using different methods.

The first experiment was combined with the measurement of endurance time at different force levels and in four different postures, as described in 5.3. Subjects were asked every half minute to rate the discomfort they experienced on a five-point scale. Alas, the results generated by this method were found to be irreproducible.

The second experiment was set up in such a manner as to prevent subjects thinking explicitly about their discomfort. This time, only one posture was investigated (pushing with the arm) and a spontaneous change of posture was taken as an indication of discomfort. The time to the first change increased consistently with lower force levels and these results proved to be sufficiently reproducible. Therefore this measurement method is recommended to get an idea about the level of discomfort experienced by subjects. A formula is given to indicate the relation found between the force level and the median of the time to the first change of hand.

5.4.1 Introduction

A good product should be, among other things, comfortable to use or to handle. After all, comfort, safety and efficiency are the main goals of ergonomics. Although comfort is important, it is also a concept which is hard to define, see 3.5.4. In ergonomics, comfort is generally defined as the 'absence of discomfort', and there is a rule of thumb which states that comfortable values can be assumed to be about 1/3 of the maximal values. This applies to e.g. legibility and reach zones, where the area close to the body is referred to as the 'comfort zone'.

In literature, no standard method could be found for measuring discomfort, and no method at all was found for measuring discomfort during submaximal force exerted over extended periods of time. There are two main methods to investigate (dis)comfort.

With the first, subjects are asked to exert force on a level they judge to be comfortable, so the dependent variable is the exerted force (under presumably comfortable conditions). With the second, the force level is predetermined and the dependent variable is the amount of discomfort experienced by the subject after a certain time. In all experiments, however, there is one common factor: the subjects are asked directly to think about and indicate their feelings of (dis)comfort. The experiments that are repeated (Dirken, 1964; Arnold, 1991; van der Grinten, 1991) all generate reproducible results. Variation coefficients of comfortable forces are of the same order as those of maximal forces (Arnold, 1991; Schoorlemmer and Kanis, 1992).

5.4.2 Objective

The first objective of this research was to establish a feasible and reproducible method to 'measure' the subjective experience of discomfort during force exertion. The second objective was to gather information on discomfort during endurance of various force levels, with the aim of establishing 'discomfort zones' for use in the design of consumer products.

Two experiments are carried out, in order to compare two different measuring methods. In the first experiment, discomfort is measured by enquiring after the degree of discomfort during the endurance test (as described in 5.3). Asking the subject about his/her feelings of discomfort is a method of measurement which inherently disturbs the measured variable. Therefore in the second experiment, discomfort is measured in a non-intrusive way, using spontaneous changes of posture during force exertion as an indication of discomfort. The results of the two methods are compared.

5.4.3 Method of the first experiment

Together with the measurement of endurance, discomfort was measured, too. Consequently, subjects, experimental design, equipment and procedure are identical to those of the endurance experiment, as described in 5.3, 'Maximal endurance during submaximal, static force exertion'. In summary, endurance and discomfort are measured at six different force levels in four different postures. Additional information on the procedure of the discomfort experiment is given here.

During submaximal force exertion, every 30 seconds the subject was asked to indicate the degree of discomfort experienced, by selecting one of the following categories:

a) no discomfort;	in Dutch:	*'geen last';*
b) little discomfort;		*'weinig last';*
c) average discomfort;		*'last';*
d) much discomfort;		*'veel last';*
e) extreme discomfort.		*'heel veel last'.*

Only five categories were used, as the subjects had to know them by heart. In preliminary experiments, looking at a list with more categories distracted subjects from the endurance task and sometimes even led to an unintended end of the measurement. The number of categories used is uneven in order to have a middle value. This is said to be important in the categorization of subjective feelings. The names of the categories are chosen so that the whole range from 'no negative feelings' to 'very negative feelings' is covered, with the 'average' in the middle and appropriate names in between.

Subjects were asked to read the instructions (see appendix B) and to memorize the categories. It was indicated that 'discomfort' included the following sensations: muscle tension or pressure, fatigue, a tingling or prickling sensation, cramp, heat, stiffness, trembling, soreness and (slight) pain. The meaning of the categories was not discussed with the subjects, to prevent any influence apart from the standard instructions. After reading the instructions, some subjects were afraid the rating would be too difficult ("How do I know what 'Extreme Discomfort' feels like?"). Instead of providing an explanation, they were asked to do a trial measurement first. After their first force exertion to maximal endurance time, nearly all the subjects knew what a highly uncomfortable, albeit short, experience this is. After a second trial run, all of the subjects were familiar with the categories of discomfort.

At the moment the exertion of force stopped, subjects were asked to indicate the two parts of their body where they experienced the most discomfort. They were also asked what their reason for stopping was: the discomfort in the main muscles involved, discomfort in other parts of the body, discomfort caused by the contact surface, or some other reason.

5.4.4 Results of the first experiment

Data treatment. In the results, the same measurements are excluded as in the endurance experiment, see 5.3 'Maximal endurance during submaximal, static force exertion'. The only difference is that the measurements that exceed the 1800 s time limit have been included as they do not disturb the analysis.

Subjects' experience. In general, subjects stopped exerting force when the discomfort they experienced became unbearable, i.e. when they scored 'extreme discomfort'. Only for the highest force levels (80 and 60 %) did they sometimes end with a relative low discomfort score. In these cases, the subjects stated that, although there was no discomfort, their muscles were simply unable to continue. At the lowest force levels (15 and 20 %) muscle tremor sometimes caused the measurement to end in spite of the fact that the subject had not yet reached the 'extreme discomfort' level. Only two of the subjects never rated beyond 'much discomfort', saying that they were unable to endure 'extreme discomfort'.

Subjects sometimes commented that at the lower force levels their endurance was hindered more by having to sit still, by muscle tremors and by trying to keep the force they exerted at the correct level, than by muscle fatigue. In some cases a measurement was ended because of discomfort caused by the contact surface. Muscle soreness was experienced only once by one of the subjects, the day after one of the sessions.

Endurance time elimination. High force levels generally resulted in shorter endurance times, and thus fewer discomfort scores, than lower force levels. Individual sessions on the same force level varied substantially in endurance time, and thus again in the number of discomfort scores. Thus per endurance session, as each 30 s a judgement was required, a different number of discomfort scores was obtained. To eliminate the endurance time factor from the discomfort data, the following procedure was designed and followed.

The modus of the discomfort scores of one endurance session is taken as characteristic for that session. Furthermore, the discomfort scores of one session are divided into three groups: the initial phase, the middle phase and the final phase. When the scores are a multiple of three, all phases have an equal number of discomfort scores. In other cases, either the middle phase or both the initial and final phase contain one discomfort score more than the other phase(s). The median was taken as characteristic of each of the phases. In total there were four numbers to characterize the discomfort experienced during one endurance session: the modus of the whole, and the medians of the initial, middle and final phases.

Preliminary Analysis of Variance. In order to find which groups should be analyzed separately, preliminary analyses of variance were carried out. For the modus and the three medians, separate calculations were made. There were too many variables to handle all at once, so in the first analysis the variables entered were sex, force level and posture, and in the second analysis age and arm/leg (see table 5-20 for the results). The main conclusion is that the 'force level' variable is significant and explains between 11.6 and 20.5 % of the total variance. Thus in further analysis, calculations should be made for each force level separately. The other variables that are significant explain so little of the total variance, that they can be neglected. This means that sessions with different subjects (age, sex) and postures can all be analysed together. Note that the percentage of unexplained variation is quite high.

	modus total period	median initial period	median middle period	median final period
first Anova				
sex	2.0 %	1.2 %	3.5 %	n.s.
force level	11.6 %	13.4 %	20.5 %	19.7 %
posture	n.s.	n.s.	2.8 %	3.6 %
unexplained variance	78.3 %	78.7 %	68.2 %	68.8 %
second Anova				
age	n.s.	n.s.	0.8 %	1.5 %
arm/leg	n.s.	n.s.	2.5 %	3.4 %
unexplained variance	98.7 %	99.9 %	95.8 %	94.9 %

Table 5-20: Experiment 1. Summary of the results of two analyses of variance. The percentages indicate the percentage of variance explained by the factor in the left column. 'n.s.' means 'not significant'.

Correlation with maximal endurance time. To investigate the relation between discomfort and the total endurance time of a session, correlations were calculated between the characteristics of discomfort and the number of discomfort scores per endurance measurement. As the discomfort was rated every 30 s, the number of discomfort scores divided by two gives an indication of the endurance time in minutes. Correlation coefficients were calculated separately for different force levels and for both the one-off and the repeated measurements. Results can be seen in table 5-21.

force level	measurement	n	modus total period	median initial period	median middle period	median final period
80%	first	92	**-0.34**	**-0.75**	0.06	-0.17
	repeated	38	**-0.42**	**-0.73**	0.05	**-0.32**
60%	first	92	-0.12	**-0.47**	0.00	-0.04
	repeated	39	-0.26	**-0.33**	-0.05	-0.23
40%	first	92	0.13	-0.09	0.07	**0.24**
	repeated	38	0.02	-0.25	0.04	**0.35**
30%	first	88	0.15	**-0.22**	0.17	**0.49**
	repeated	35	-0.03	-0.16	-0.07	**0.40**
20%	first	83	0.11	-0.07	**0.36**	**0.65**
	repeated	34	0.01	-0.06	**0.30**	**0.61**
15%	first	79	0.14	0.07	**0.38**	**0.65**
	repeated	29	0.23	0.08	**0.33**	**0.48**

Table 5-21: Experiment 1. Correlations between the maximal endurance time and the four characteristics of the discomfort measurement ($n = 24$). Bold denotes significance at $p < 0.05$.

The correlation coefficients proved to be positive and negative, and range between -0.75 and +0.65. Of the 48 values of r, only 2 are smaller than -0.71, none greater than 0.71, and 20 are significant at $p < 0.05$.

Reproducibility. To establish the reproducibility of the discomfort scores for the ten subjects who repeated the experiment, both the correlation coefficient and the average difference between the results of the first and the second measurement are calculated for the modus of the whole, as well as the medians of the three phases (see table 5-22).

Product-moment correlation coefficients for the repeated discomfort characteristics are calculated separately for each of the force levels. All except one are positive, they range between -0.07 and 0.73, and 21 out of 24 values of r are significant at $p < 0.05$. The results are intra-individually constant to some extent, but they are not convincing enough to support reproducibility. Although most correlation coefficients are significant, they are small, and only one value of r out of 24 is greater than 0.71.

The average difference, again taken separately for each of the various force levels, is calculated by subtracting the endurance of the first session from the second one, after which they are added and divided by n. Using t-tests, it is tested whether the average differences are significantly different from 0. They should not be, in order to be reproducible. Four out of 24 are significantly different at $p < 0.05$. For a discussion on the power of a t-test with a similar number of subjects, please refer to the discussion of the experiments on standardization of posture, in 5.1.6.

Further analysis. The discomfort measurements are not sufficiently reproducible, and, consequently, it is of no use to calculate any further descriptive statistics, correlations or analyses of variance.

characteristic	force level	n	r	paired t-test mean (x-y)	s	p (2-tailed)
modus total period	80%	38	-0.07	0.29	2.14	0.410
	60%	39	**0.42**	0.54	1.45	**0.026**
	40%	38	**0.44**	0.53	1.27	**0.015**
	30%	35	**0.36**	0.46	1.20	**0.030**
	20%	34	**0.57**	0.18	0.87	0.245
	15%	29	0.31	0.17	1.10	0.408
median initial period	80%	38	0.30	0.09	0.56	0.314
	60%	39	**0.43**	0.17	0.66	0.124
	40%	38	**0.58**	0.05	0.50	0.524
	30%	35	**0.42**	0.23	0.75	0.081
	20%	34	**0.55**	0.10	0.55	0.281
	15%	29	0.17	0.14	0.58	0.212
median middle period	80%	38	**0.48**	0.07	0.68	0.554
	60%	39	**0.42**	0.06	0.73	0.585
	40%	38	**0.50**	0.17	0.76	0.171
	30%	35	**0.38**	0.36	0.90	**0.024**
	20%	34	**0.51**	0.25	0.73	0.054
	15%	29	**0.66**	0.21	0.63	0.090
median final period	80%	38	**0.60**	0.03	0.67	0.809
	60%	39	**0.56**	0.13	0.63	0.208
	40%	38	**0.54**	0.13	0.67	0.230
	30%	35	**0.43**	0.23	0.95	0.164
	20%	34	**0.73**	0.22	0.75	0.096
	15%	29	**0.69**	0.12	0.82	0.435

Table 5-22: Experiment 1. Reproducibility of the four characteristics of discomfort. Listed are the number of measurements ($n = 24$, both female and male), the retest correlation coefficient and the results of a paired t-test. Bold denotes significance at $p < 0.05$.

5.4.5 Discussion of the first experiment

There does not seem to be a distinct relation between the characteristics of discomfort (with endurance time eliminated), and the total endurance time of the measurement.

The reproducibility of the discomfort scores, defined by the modus and the medians of the initial, middle and final phase, is questionable. The group results are quite reproducible, but the individual results are not sufficiently so. Furthermore, the percentage of unexplained variance is very high. The cause of this is not clear. It must be concluded that either this is not the right method to measure discomfort during submaximal force exertion, or the fluctuations of discomfort feelings are indeed at random. Therefore other statistics on the results of this experiment are useless, and are not given.

It is hard to compare this result with literature. Comfortable torques are reproducible (Arnold, 1991), subjective judgement of muscle load is reproducible (Dirken, 1964) and measurement of discomfort of various postures is reproducible (Van der Grinten, 1991).

These authors, however, used different measuring methods. Unfortunately, there is no literature on discomfort during prolonged force exertion to compare the results with.

5.4.6 Method of the second experiment

The purpose of the second experiment was to measure discomfort during submaximal force exertion without consciously involving the subject in the judging process. Asking the subject to do the judging will inevitably make him or her concentrate on registering and comparing any feelings of discomfort, thereby disturbing the measured variable.

Subjects. Seventeen healthy subjects took part in the experiment. They were all students, and also took part in the endurance experiment. Some of the anthropometric characteristics of these 8 young women and 9 young men are listed in 5.3, table 5-9. Payment was per session.

Experimental design. Subjects were seated, with the lower arm supported. They were asked to exert a constant static force with one hand on a doorknob, just like the push test in the endurance/discomfort experiment (see figure 5-10). In this experiment, however, subjects were told they could change hands when they felt like it. This posture was chosen because it enabled a change of posture (hands) without too much disturbance, and because the changing of hands is a clear indication of change of posture. The idea to look at the first change of posture as indication of discomfort, could also be elaborated by looking at more subtle changes of one posture, e.g. some movement. To evade problems with definition of change/no change, the change-hand option was chosen.

The same force levels were used as in the endurance/discomfort experiment: 80, 60, 40, 30, 20 and 15 % of maximal force. Each force level had a different holding time, which was three times the maximal endurance time according to Rohmert's formula, in order to make sure that the force could not be maintained with one hand all the time and so at least three changes would occur. The holding time at 15 %, however, was restricted to 30 min. According to Rohmert this force can be maintained for more than 15 min., but measuring for much more than 45 min. was judged impractical. The duration of the measurements can be seen in table 5-24.

Seven subjects, three women and four men, repeated this experiment before they took part in the endurance/discomfort experiment.

Equipment. Force was measured with a force transducer, an amplifier and an xt-recorder. On the xt-recorder, the required force was indicated. Through an on-line video recording system, the subjects could observe both this indication and the pen of the xt-recorder, moving according to their force exertion. Time was monitored on a digital stopwatch. The xt-recorder was run at different speeds, depending on the holding time and thus on the force level. The subjects were asked, when changing hands during force exertion, to completely release the doorknob for a fraction of a second, so the change would be visible on the xt-recordings.

Procedure. This experiment was actually done before the endurance/discomfort experiment, so the subjects were not yet familiar with discomfort measurements.

The subjects received written instructions (see appendix B). First their maximal force was measured for 6 seconds (2 s build-up, 4 s maximal force), following the method of Caldwell et al. (1974). This procedure was repeated every session. The subjects were then asked to exert a constant force, being a percentage of the maximum of that day, for a certain time, but they were not told which percentage and for how long. They could choose music to listen to, either popular listening songs or a radioplay ('the hitch-hikers guide to the galaxy'). This was an attempt to provide distraction in order to prevent the subjects from getting bored, which might cause them to think about discomfort or contemplate when to change hands. The music was considered to be sufficiently low-key to prevent it disturbing the actual discomfort measurement.

Subjects started force exertion with the preferred hand. No discussion was allowed during the measurement. As soon as the predetermined holding time was reached, the experimenter would tell the subject to stop.

No more than one low or two high force level measurements were done each session, with a minimum rest period of five minutes in between.

5.4.7 Results of the second experiment

Data treatment. Two characteristics were chosen to investigate per force level, namely the time from the beginning to the first change of hand, and the number of changes during the total holding time.

Two other possible characteristics, the time from first to second change of hand and the time from second to third change of hand, were considered as scores and rejected because the data are incomplete, see table 5-23. Subjects did not always change hands as often as intended by the experimenter through the choice of holding time. In these cases, they held on for too long to allow them to change for a third, or sometimes even a second, time. This would bias statistical calculations.

The maximal forces are analysed together with the maximal forces of the endurance/discomfort experiment, because they are exerted exactly the same way. For the results, see section 5.3, 'Maximal endurance during submaximal, static force exertion'.

force level	number of measurements n	first change of hand n	second change of hand n	third change of hand n
80%	24	22	14	2
60%	23	24	22	11
40%	24	23	22	19
30%	24	24	23	22
20%	24	24	22	22
15%	24	24	21	21

Table 5-23: Experiment 2. Number of data, obtained for the four measures of discomfort. n = 17 (women and men), seven subjects repeated the experiment.

Description. Median, range, average, standard deviation, coefficient of variation and number of measurements are presented in table 5-24 for both characteristics (time to first change, and total number of changes) and for all force levels separately. The medians of the time to the first change of hands are visualized in figure 5-16.

	force level	time [s]	P_{25}	P_{50}	P_{75}	range	$\bar{x}$	s	coeff. of variation
time to the first change of hand [s]	80%	69	22.0	27	38.5	17 - > 69	31.8	14.1	0.44
	60%	144	29.0	41	56.3	14 - 87	45.0	21.4	0.48
	40%	282	58.0	92	107.0	28 - 182	89.1	39.3	0.44
	30%	474	66.8	95	125.3	44 - 344	112.3	72.2	0.64
	20%	1170	109.3	134	212.5	88 - 848	211.2	208.3	0.99
	15%	1800	143.8	212	329.0	90 - 1295	321.9	323.3	1.00
total number of changes (n)	80%	69	1.0	2	2.0	0 - 4	1.71	0.92	0.54
	60%	144	2.0	3	3.3	1 - 5	2.88	1.11	0.39
	40%	282	3.0	4	6.0	1 - 9	4.35	2.09	0.48
	30%	474	3.0	4	7.0	1 - 8	4.82	2.13	0.44
	20%	1170	4.8	9	12.0	1 - 15	7.94	4.28	0.54
	15%	1800	4.8	9	12.3	1 - 19	8.82	4.94	0.56

Table 5-24: Experiment 2. Duration of the measurements per force level, the time to the first change of hand [s] and the total number of changes during the measurements (n). The number of subjects is 17, 8 women and 9 men.

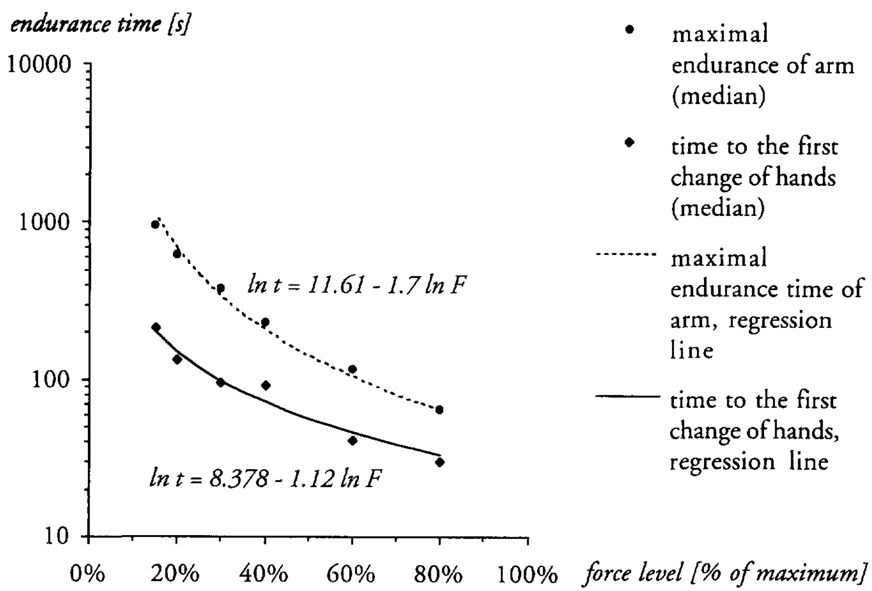


Figure 5-16: Experiment 2. Medians and interpolations of maximal endurance time and time to the first change of hand, for arms only.

The median is preferred over the average for both characteristics, because it can not be assumed that the frequency distributions are normal, as is the case with endurance. Again, a logarithmic scale was used to get a more balanced view of the results in both high and low force level tasks.

				paired t-test		
characteristic	force level	n	r	mean (x-y)	s	p (2-tailed)
time to the first change of hand [s]	80%	7	*	5.60	2.10	0.004
	60%	7	**0.92**	11.60	12.10	**0.045**
	40%	6	**0.88**	-17.80	32.30	**0.234**
	30%	7	**0.55**	0.70	45.30	**0.968**
	20%	7	**0.10**	-51.40	197.50	0.517
	15%	7	0.96	-10.30	217.90	0.905
total number of changes (n)	80%	7	0.73	0.00	0.56	1.000
	60%	7	**0.77**	-0.86	0.69	0.017
	40%	6	**0.92**	0.17	0.75	0.611
	30%	7	**0.55**	-0.29	1.80	0.689
	20%	7	**0.83**	0.43	2.30	0.639
	15%	7	0.91	0.57	2.15	0.508

Table 5-25: Experiment 2. Reproducibility of the time to the first change of hand [s] and the total number of changes during the measurements (n). Listed are the number of subjects (both female and male), the retest correlation coefficient and the results of a paired t-test. Bold denotes significance at $p < 0.05$.

Reproducibility. To establish the reproducibility of the discomfort scores for the seven subjects who repeated the experiment, both the correlation coefficient and the average difference between the results of the first and the second measurement are calculated for the two characteristics of discomfort (see table 5-25).

Product-moment correlation coefficients for the repeated discomfort characteristics are calculated for force levels separately. For the time to the first change of hand, all correlation coefficients are positive and range between 0.55 and 0.96, with one exception of 0.10. Four of the six values of r are greater than 0.71 and significant at $p < 0.05$. For the number of changes during the total holding time, all correlation coefficients are positive and range between 0.55 and 0.92. Five of the six values of r are greater than 0.71 and significant at $p < 0.05$. In both cases, the results are constant enough intra-individually to support reproducibility.

The average difference, again separately for the various force levels, is calculated by subtracting the time or number of the first measurement from the second one, after which they are averaged for the group. Using t-tests, it is tested whether the average differences are significantly different from 0. They should not be, in order to be reproducible. For the time to the first change of hand, two of the six average differences are significantly different at $p < 0.05$. For the number of changes during the total holding time, only one of the six is significantly different. Again, for a discussion on the power of a t-test with a similar number of subjects, please refer to the discussion of the experiments on standardization of posture, in 5.1.6.

Correlation. Correlations are calculated between the maximal endurance, as measured in the endurance experiment, the time to the first change of hand and the total number of changes of all force levels. This yields 153 correlation coefficients, which can be seen in appendix D. Of those, 99 are significant, and 25 are greater than or equal to 0.71.

For correlations between the same force levels, all correlation coefficients are significant and 7 out of 18 values of r are greater than 0.71, see table 5-26. The time to the first change of hand correlated positively with the maximal endurance time, and both correlated negatively in all cases with the total number of changes.

force level	correlation coefficient between		
	ET-CH	ET-TC	CH-TC
80%	0.48	-0.61	**-0.79**
60%	**0.71**	-0.65	**-0.85**
40%	0.62	-0.51	-0.69
30%	**0.73**	-0.42	**-0.77**
20%	**0.75**	-0.67	-0.67
15%	0.63	-0.66	**-0.80**

Table 5-26: Experiment 2. Correlations between the maximal endurance time (ET), the time to the first change of hand (CH) and the total number of changes during the measurement (TC) for each force level. Bold denotes more generality than specificity.

5.4.8 Discussion of the second experiment

Reproducibility. The reproducibility of both the time to the first change of hand and the total number of changes seems to acceptable, and much better than the reproducibility of the results of the first experiment. Most retest correlation coefficients are significant and quite high, and the mean group differences mostly do not differ significantly from zero.

Correlation. The correlations between the maximal endurance measurements, the time to the first change of hand and the total number of changes are quite good. Therefore, subjects who endure force for a relatively long time will also score relatively high on the time to the first change of hand. This is not surprising as these are both endurance times, the only difference being the relative limits of endurance.

Evaluation of measures. There are two disadvantages to the measuring method used in this second experiment, compared to that of the first experiment. The first is that less information is retrieved, only one level of discomfort compared to five levels in the first experiment. The second is that maybe not all postures and force exertions can be investigated with the change of posture method. Further research into the operational range of this method is required.

Which measure is more useful, the time to the first change or the total number of changes? The advantage of the time to the first change is that it is independent of the length of the session, so the session may take less time. No agreement on the length of the session is needed, which increases the chances of different experimenters obtaining comparable results.

Furthermore, the 'total number of changes' score depends entirely on the duration of the session, which may cause confusion and will not enhance the development of an unequivocal measuring method. In addition, session times should be fairly long to ensure a good number of changes. It would be preferable not to introduce such a significant and superfluous factor into the experiment if it can be avoided.

Therefore the measuring method investigating a total number of changes of posture within a certain time in order to get information on (dis)comfort, must be rejected.

Formula. The median of the time to the first change of hand is chosen as the basis for a predictive formula. The median is chosen because the average value is influenced too much by a few very long times, and also because it can not be assumed that the distribution is normal.

Using regression analysis, a formula is found to fit the medians. Three formula's were found to fit best, with values of r^2 of 0.96 and 0.97. The following formula was considered best because of its elegance and because it has the same general structure as the formula of the endurance time curve:

$$\ln t = 8.378 - 1.12 \ln F$$

t = time to the first change of hand [s];
F = force level [% of maximal force], from 15 % to 80 %.

The formula is applicable only for forces exerted with the arms, because it is based on arm measurements only. Medians and curves can be seen in figure 5-16. The explained variation r^2 is 0.96. This seems quite high due to the use of the median for modelling, disregarding the scatter of the original data.

Literature. There is little literature to make a direct comparison with the results of this experiment. The measurements of the onset of pain and fatique by Sato et al. (1984) are plotted together with the results of the present research in figure 5-17. It is striking that the median of the time, at which the first change of hands takes place, is comparable to the point at which according to Sato et al. pain sets in, and not the point at which fatigue is experienced. This can only be explained from the difference in measurement methods, or perhaps ethnic or cultural differences between the subject groups.

It can be questioned whether the comfortable force, as measured by Arnold (1991), Kanis (1993) and Schoorlemmer and Kanis (1992) is comparable to the level of discomfort as measured with the 'change of hands'-method. The ratio between the mean comfortable and mean maximal force resulting from their experiments is between 0.4 and 0.6 for healthy subjects. At the equivalent in this experiment, i.e. at 40 % and 60 % of the maximal force level, the time to the first change of hand will be 72 and 46 s respectively, according to the formula described above. These times are much longer than the 20 s and 4 s measured by Arnold, respectively Kanis and Schoorlemmer.

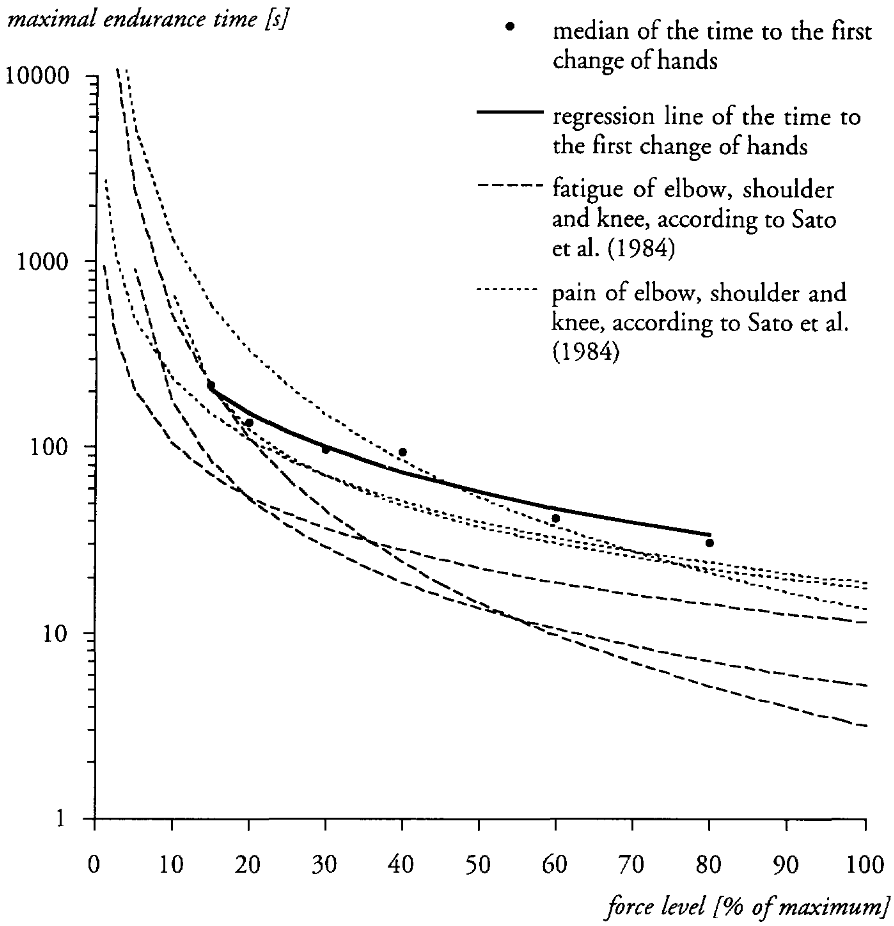


Figure 5-17: Experiment 2. Medians and interpolations of the time to the first change of hand, and the time to the onset of fatigue and pain as predicted by Sato et al. (1984).

Thus, completely different levels of (dis)comfort are measured in the various experiments. Apparently, there is not one single discomfort level, and which discomfort level is measured depends on the measuring method. Therefore it is concluded that the results of an experiment measuring change of posture should not be named in terms of comfort or discomfort (for these do not indicate the actual levels of discomfort), but simply 'the time to the first change of posture'. This description needs no further definition, it explains quite clearly what is measured, and this will facilitate interpretation of the data for further use. It also will prevent confusion with the concept of comfort as it has been used and measured before.

Use for designers. Now that the measurements are fairly reproducible, it can be questioned whether this is a valid way to measure a specific level of discomfort, and whether the results can be useful to designers.

Why do designers want to know about discomfort? They design a product and want the future users to operate, use or handle their product with ease and comfort, yes, even joy!

The situation should therefore be avoided in which a user, operating a product with one hand, becomes so tired he or she needs to change the product to the other hand. At such a moment, discomfort may be noted and annoyance with the product will set in. This is what the designer wishes to prevent. Thus, the moment when people spont-aneously stop exerting force should be anticipated in the design of a product, and is therefore important to know, perhaps even more important than a measure of (dis)comfort obtained by asking the subject.

The proposed measuring method seems to work well. The results are sufficiently reproducible, the medians are in line and the curve of that line more or less follows that of maximal endurance on a lower level (on a logarithmic scale). Standard deviations are large, but in the same order as those of maximal endurance time and maximal force exertion.

However, like the maximal endurance time formula, a formula to predict discomfort on the basis of exerted maximal force can not be simply applied to design practice, as Wiker et al. (1990) already warned against. Beside exerted force level (or force exerted on the external world), the weight of limbs and the strain of maintaining a posture (or 'internal' forces) should be taken into account. Furthermore, if the contact surface is not optimal, it may also influence discomfort.

5.4.9 Conclusions

Measuring the subjective experience of subjects during the measurement of endurance of submaximal force proved in this study to be an insufficiently reproducible method. Measurement by investigating spontaneous changes in posture, however, is satisfyingly reproducible, and easier to measure as well.

The time fo the first change of hand is a good and reproducible measurement method to get an idea about feelings of discomfort in users. The data can be very useful to designers, although they should be used with care, taking into account the other factors, as outlined above.

The level of discomfort measured depends on the method used, as shown by the differences found in literature. It is therefore proposed that the results of this second experiment not be named in terms of comfort or discomfort (which give no indication of the actual levels of discomfort), but simply 'the time to the first change of posture'. A formula is given to describe the relation found between force level and the median of the time to the first change of hand at force levels between 15 % and 80 % of maximal force.

5.5 Implications for the Atlas

The results of the research described in this chapter have implications for the way questions on force exertion for design purposes can be handled and for the way researchers can set up their design investigations. Consequently, these results will affect the contents of the envisaged Atlas of Human Force Exertion. This is discussed in the following.

Degree of posture standardization. The results of the experiment on the influence of posture on the maximal force exerted showed that the level of posture standardization determines how much force can be exerted. Considerable discrepancy can exist between the forces measured with various degrees of posture standardization. In free posture, the only fixed element, if any, is the position of the handle. Maximal static forces measured in free posture are repeatable, and these measurements also generate information on the space users need to exert the force. Care should be taken when using forces measured in free posture to predict forces that are exerted frequently or over longer periods of time, as in these cases other factors weigh more heavily in determining the force that can be exerted. The strain that can be taken by the lower back is an example of such a limiting factor.

For design purposes, an experimental situation should have the same amount of freedom (or the same level of standardization) of posture as is anticipated for the actual conditions in which the product is to be used. Only then will the results be of most value to the designer. Thus, if the real-life situation poses no restrictions, it is most useful to know what will happen when it is left to the subjects themselves to choose their posture, as they would do when using or operating a real product in daily life. This applies to nearly all household products, e.g. corkscrews, can-openers, jam jars, coffee creamer cups, doors, tap handles, bicycle pumps, vacuum cleaners (switches operated by foot or hand), hair dryers, cameras, etc..

It can be argued that with most consumer products, forces are exerted intermittently, for a short time and in free postures, rather than often, for a long time and in standardized postures. Therefore, the information gathered for the Atlas should consist mainly of forces measured in free postures. The logical conclusion is that maximal static force exertion is best measured in free posture. In addition to being easier to accomplish, free posture measurements, being 'true to life', will probably hold more appeal for designers. Consequently, designers will be more inclined to carry out measurements of their own when needed.

So the findings of this investigation enable researchers to do experiments under conditions similar to reality, something which until now was wrongly considered to be an invalid (unrepeatable) measuring method.

The number of segments involved. The second experiment investigated the influence of the number of arm segments involved on the maximal force exerted. The results showed that moments exerted around one joint are smaller than those exerted around more joints, while on the other hand forces exerted around a single joint are larger than when more joints are involved. The maximal forces correlated quite well with each other.

For designers, this means that reducing the number of segments involved in operating a product would reduce the effort needed by the user. To that end, either a support could be used, or the product can be designed in such a manner that force will be transferred to the environment not by hand but by a segment nearer the main pivot.

The support to reduce the force that needs to be exerted when flexing the hand should be placed at either elbow, forearm or wrist. Supports can for instance be used to make relatively small, short-duration and low-frequency force exertion more comfortable. For example, when opening the heavy lid of a copying machine, a support in the right place would make force exertion more comfortable. Supports can also be used to enable users to exert greater maximal force, but in this case caution is required. The elbow and wrist are not built for transferring high forces to the environment and this should be taken into account. Frequent exertion of maximal or relatively high forces can result in cumulative trauma disorders.

Elbow, upper and lower arm are hardly used when transferring force to a 'handle', although this would be efficient according to the findings of this experiment. It is, however, not advisable to do so, as the hand, by build, is best adapted to this task.

The finding that maximal forces correlate quite well with each other is more useful to the researcher than it is to the designer. Perhaps it is possible to predict one or more forces from another. This would certainly help in filling the Atlas efficiently: on the basis of one force measurement within a group, several other data of the same group could be predicted. This possibility is further elaborated on in chapter 6.

Maximal endurance times of submaximal forces, relative to the maximal force, seem to be similar for men and women, but different for arm and leg muscles. For the postures and force directions investigated in the third experiment, the two following curves predict the endurance time between 80 and 15 % of maximal force.

$\ln t = 11.61 - 1.7 \ln F$ (for arms)
$\ln t = 12.02 - 1.7 \ln F$ (for legs)

t = maximal endurance time [s];
F = force level [% of maximal force], from 15 % to 80 %.

Smaller forces are very hard to measure adequately, because it is difficult for a subject to remain seated in one posture for a long time. Even with small movements, the forces exerted can vary to such an extent as to invalidate the measurement. When measuring endurance with small forces, the capacity for sitting (or standing) still thus becomes the limiting factor instead of the exertion of a small force on e.g. a handle. For measuring a relatively small force that must be endured for a longer period of time, changes in posture are recommended. If this is not feasible, the exertion of force over very long periods of time (e.g. for hours at a time) should generally be avoided.

A designer can use the curves to estimate the median of the maximal endurance time of static forces for arm and legs as measured in this experiment (further research should establish whether the formulae can be applied also to other forces than those investigated). However, maximal endurance time often is not the aim when a consumer product is designed. Rather, it will be used to get an idea of the limit to avoid.

For the Atlas, information on maximal endurance times is useful because they apply as soon as a force must be exerted for periods longer than four or five seconds (which often is the case). Ideally, the Atlas should contain maximal endurance time limits for every force in every posture, but of course this is impossible. A practical limitation is that for most postures, to maintain the posture, a certain amount of 'internal force exertion' is needed. Maximal endurance time in those cases cannot be calculated from force exerted on a handle alone, and it really should be measured for every combination of posture and 'external force exertion'.

Discomfort of submaximal force exertion is hard to define and therefore hard to measure. However, a clear change of posture, as measured here by change of hand, appears to be a reproducible way to measure a certain degree of discomfort, i.e. the point at which the user/subject starts to get irritated by prolonged force exertion. This point the designer generally wants to avoid. The following equation predicts this point for forces between 15 and 80 % of maximal force:

$$\ln t = 8.378 - 1.12 \ln F$$

t = time to the first change of hand [s];
F = force level [% of maximal force], from 15 % to 80 %.

A designer can use the formula to estimate the median of the time to the first change of hands for pushing with the arm. Again, further research is needed to establish whether the formula can also be applied to other forces than the ones investigated. The time to the first change of hands is more useful to the design of consumer products than the maximal endurance time. With estimates from this curve, the time at which discomfort with product use may set in can be assessed. For most products, it would be wise to keep the force/time combination, required to operate or use them, at or below this limit. The formula may for instance be used to determine the combination of force and time that is acceptable to get the pilot flame of a geyser going. Note that exerting force using a finger or a thumb rather than the whole hand may result in a different time to the first change of hand. More research in this area is recommended.

Because the time to the first change of posture can be quite useful to designers, it should feature prominently in the Atlas. Alas, the problem that arises is similar to the problem encountered with maximal endurance time. Maintaining a posture also requires muscle force and force is in most situations exerted partly as an external force and partly internally to maintain posture. In those cases, the time to the first change of hands cannot just be calculated from maximal force exertion, and it really needs to be measured again for every combination of posture and 'external force exertion'. This too could be an area for future research.

For the experimenter, measuring the time to the first change of hand also holds some advantages over measuring the maximal endurance time and over measuring the total number of changes, purely from a practical, measuring, point of view. The actual measurements take much less time, and the rest periods in between can be relatively short, only a few minutes between measurements, because no maximal effort is required and changes of posture allow heavily loaded parts of the body to recover while the experiment continues. Consequently, a fair number of measurements can be carried out in one session, and the time required for this session can stay within reasonable limits. This advantage will be appreciated by anyone who has had experience with elaborate and time-consuming experiments. Academically speaking, such matters as time may be considered trivial, but time is money (even more so during the information phase of a design), and chances are that a quick experiment will be carried out, whereas plans for a more elaborate, time-consuming investigation will be defeated by time/money constraints.

Conclusion. The research in four areas resulted in recommendations for research, for design and for the Atlas in those separate areas. Although the recommendations do not contain many figures that are directly applicable to design, but mainly constitute measuring guidelines for researchers, they do show the way in which a useful Atlas of Human Force Exertion for designers can be developed and filled with information.

6 Overall analysis

Summary

The data collected from the experiments were maximal forces, maximal endurance times, discomfort scores and anthropometric measures. To gain insight into the (cor)relations between the measured variables of the different categories and within each of these categories, an overall analysis was performed. With a good relation between variables, it may be possible to predict many variables on the basis of one variable, or a few. For the Atlas this means that little effort only is needed to retrieve a lot of information and offer it to the user. Furthermore, insight into the relation between groups of variables may help further research.

A large correlation coefficient matrix with 77 variables revealed that the best correlations were found within each of the categories of anthropometry, maximal force and discomfort scores. Within these categories, 74 to 99 % of the correlations were significant at $p \leq 0.05$ and 23 to 60 % were larger than or equal to 0.71.

Factor analysis of all 77 variables for 19 subjects revealed that a three factor solution gave the most plausible results. The variables in the three factors could be categorized as 'maximal force', 'maximal endurance times' and 'discomfort scores', respectively.

Three separate factor analyses for maximal forces, endurance times and discomfort scores each time resulted in a one factor solution of which the factor characterized the group. The maximal force factor explained 73.3 % of the total variance and could be predicted by either the average of the z-scores per group for each subject, or from sex, tense upper arm girth and Quetelet index with a regression line. The maximal endurance time factor explained only 39.7 % of the total variance and could not be predicted. The discomfort factor explained 58.5 % of the total variance and could be predicted from the elbow height with an r^2 of 0.29.

Maximal forces per subject can be predicted by the average z-score of a few measured maximal forces. Maximal endurance times cannot be predicted. Discomfort scores can be predicted from 'time to the first change of hands at 30 % of the maximal force', with regression equations.

The variables that can be predicted may be useful both for the Atlas and for researchers who investigate similar problem areas.

variable	total n	posture experiment 1	2	3	seg-ment	endu-rance	dis-comfort 2nd. exp.*
anthropometric							
age	55	•	•	•	•	•	
body height	55	•	•	•	•	•	
body weight	55	•	•	•	•	•	
shoulder height	48	•	•	•			
elbow height	48	•	•	•			
elbow reach depth	31				•		
arm reach depth	31				•		
upper arm length	26				•		
tense upper arm girth	27				•		
relaxed upper arm girth	27				•		
maximal force							
grip force	31			•	•	•	
pull at shoulder height, free posture	43	•	•	•			
push at shoulder height, free posture	43	•	•	•			
pull at elbow height, free posture	43	•	•	•			
push at elbow height, free posture	43	•	•	•			
jam jar, free posture	19			•			
jam jar, fixed	19			•			
moment 1	26				•		
moment 2	26				•		
moment 3	26				•		
moment 4	26				•		
moment 5	26				•		
moment 6	26				•		
moment 7	26				•		
moment 8	26				•		
moment 9	26				•		
moment 10	26				•		
moment 11	26				•		
moment 12	26				•		
moment 13	26				•		
moment 14	26				•		
moment 15	26				•		
moment 16	26				•		
moment 17	26				•		
moment 18	26				•		
arm push	24					•	•
leg flexion	24					•	
leg extension	24					•	
arm anteflexion	24					•	

Table 6-1: Overview of the variables as used in the overall analysis and the number of values per variable as used for the correlation coefficient matrix. It is indicated with an '•' in which experiment(s) the variables were measured.

** The first experiment was not sufficiently reproducible and is therefore not included in the overall analysis.*

variable	total n	posture experiment 1	posture experiment 2	posture experiment 3	seg-ment	endu-rance	dis-comfort 2nd. exp.*
maximal endurance							
arm push endurance at 80 %	23					•	
arm push endurance at 60 %	23					•	
arm push endurance at 40 %	23					•	
arm push endurance at 30 %	22					•	
arm push endurance at 20 %	21					•	
arm push endurance at 15 %	22					•	
leg flexion endurance at 80 %	22					•	
leg flexion endurance at 60 %	21					•	
leg flexion endurance at 40 %	22					•	
leg flexion endurance at 30 %	22					•	
leg flexion endurance at 20 %	22					•	
leg flexion endurance at 15 %	18					•	
leg extension endurance at 80 %	23					•	
leg extension endurance at 60 %	23					•	
leg extension endurance at 40 %	23					•	
leg extension endurance at 30 %	23					•	
leg extension endurance at 20 %	21					•	
leg extension endurance at 15 %	23					•	
arm anteflexion endurance at 80 %	24					•	
arm anteflexion endurance at 60 %	24					•	
arm anteflexion endurance at 40 %	22					•	
arm anteflexion endurance at 30 %	22					•	
arm anteflexion endurance at 20 %	21					•	
arm anteflexion endurance at 15 %	21					•	
discomfort							
time to change of hands at 80 %	17						•
time to change of hands at 60 %	17						•
time to change of hands at 40 %	17						•
time to change of hands at 30 %	17						•
time to change of hands at 20 %	17						•
time to change of hands at 15 %	17						•
number of changes at 80 %	17						•
number of changes at 60 %	17						•
number of changes at 40 %	17						•
number of changes at 30 %	17						•
number of changes at 20 %	17						•
number of changes at 15 %	17						•

Table 6-1: (continued)

6.1 Introduction

To date, several experiments have been carried out to investigate the various aspects of human force exertion for an Atlas of Human Force Exertion. To summarize, a short overview is given of the variables measured in the experiments to be included in the overall analysis (table 6-1) and of the number of subjects involved (table 6-2). The variables are maximal force measurements, maximal endurance time measurements and discomfort measurements as well as anthropometric measurements.

With these data, gathered mainly from one large group of 19 subjects, connections between the variables can be analyzed. An attempt should be made to establish links between various maximal forces, endurance times and anthropometric measurements for two reasons. In the first place out of general scientific curiosity; in the second place, for use in the Atlas of Human Force Exertion. For the Atlas, force characteristics of user groups for a certain product or situation should be measured. But if, for example, maximal forces and endurance times are all found to be related for each individual, then it could well be that just a few, or even single, measurements will suffice to characterize each individual. From this general characterization, perhaps other variables may be predicted using specific formulas.
Example: Let us assume that an individual can be characterized by '$a + bx + cy$'. In this equation, a is a constant, x and y are anthropometric, maximal force and/or endurance time values, and b and c are coefficients, the whole adding up to characterization T. Let us also assume that pushing at shoulder height while exerting maximal force can be predicted from T as $F = 30\ T$, i.e. if T equals 10, the maximal force will be predicted as 300 N. In the same manner, more maximal forces and endurance times could be predicted.

For research purposes it would be highly useful to find a good relation between, on the one hand, the variables one wishes to establish but which are difficult to measure, and on the other hand, those one can easily measure quickly using plain equipment. For example, if subjects could be easily characterized according to strength on the basis of certain anthropometric measurements, an estimate of strength may be made for any person the anthropometry of whom has been established. Or to give another example, if endurance times can be predicted on the basis of one variable, considerable time and energy may be saved in the pursuit of knowledge about the endurance ability of large groups of individuals.

Theoretical basis. The theoretical basis which leads to the expectation that the relative muscle strengths in different parts of the same body are comparable, and thus allow characterization and prediction, is the following: In the first place it follows that an individual's genotype, as it determines sex and general build, will also affect the anthropometric characteristics of the muscles, cardiovascular and respiratory systems in a general way. In the second place, the way of life, level of training and age of the subject affects the whole subject, including all muscles, the cardiovascular and respiratory systems. This results in a certain physical condition and a certain ability to exert force, or strength. Although the muscles in arms and legs may differ, a certain uniformity of muscle strength over the whole body is plausible.

		number of subjects						
		group 1 staff	group 2 students	group 3 others	group 4 students	group 5 others	group 6 staff	total
section	experiment	n = 4	n = 19	n = 7	n = 17	n = 5	n = 3	n = 55
5.1	posture, 1st experiment	4					1	5
5.1	posture, 2nd experiment (with functional posture)		19				1	20
5.1	posture, 3rd experiment (with jam jar)				17	3	2	22
5.2	segment			7	17		2	26
5.3	endurance and discomfort 1st experiment				17	5	2	24
5.4	discomfort, 2nd exp. (changing hands)				17			17

Table 6-2: Overview of participants (students, staff and others) in the various experiments. The numbers in one column apply to the same group of people.

Literature. Until now, the relationships between variables within the groups of exerted forces, endurance times and anthropometric measurements, and between variables of different groups have not been investigated in depth. Research into relationships usually is limited to the calculation of correlation coefficients, as a by-product of research for other purposes. See also 3.2.3, 'Anthropometric variables'. Correlations found in literature between forces exerted by various muscle groups vary enormously, the values of r ranging from 0.21 to 0.99. Correlations between anthropometric measurements and exerted forces are lower, the values of r varying between 'not significant' and 0.72, which means that almost none of them shows more generality than specificity. The correlations between maximal forces and endurance times of relative forces vary to the same extent, r ranging from -0.36 to 0.56, with one exception at 0.76.

For the data of the experiments described in chapter 5, the correlation coefficients are however slightly higher than those found in literature. This justifies a more extensive search for relationships (and correlation) between data from different experiments. Investigations into the characterization of subjects according to force or endurance were not found in literature, and therefore remain an interesting pursuit.

6.2 Objective

The objective of the following overall analysis is:

- to examine which common factors exist to characterize subjects according to maximal force, maximal endurance time of submaximal force, and discomfort sensibility;
- to work out which variables can be used to approximate these common factors;
- to find out whether, and if so, how, other variables can be predicted from these last variables.

The overall analysis involves maximal force exertions, maximal endurance times of submaximal forces, discomfort scores as well as anthropometric characteristics. It is to be expected that maximal forces and maximal and submaximal (i.e. discomfort) endurance times of relative forces be unrelated, as the activities involved are different in nature, calling upon different abilities.

These investigations are conducted to explore the possibilities to predict forces and endurance times. This may be useful when collecting data for the Atlas of Human Force Exertion. On the other hand the overall analysis is carried out to satisfy scientific curiosity and gain understanding of causes or mechanisms, which may offer starting points for further research.

6.3 Approach

Most of the results of the experiments described in chapter 5 are used in this analysis. The following 77 variables are included (see table 6-1):

- *Maximal forces*
  - Six maximal forces with the whole body in free posture: pushing and pulling at shoulder and elbow height, and unscrewing the lid of a jam jar (from the experiment with posture, 5.1);
  - 18 maximal moments around wrist, elbow and shoulder (from the experiment with the number of segments, 5.2);
  - Four maximal forces: pushing, flexion, extension and anteflexion (from the endurance time experiment, 5.3);
  - Maximal grip force (as described in 5.3).
- *Maximal endurance times*
  - 24 maximal endurance time measurements, in four postures (arm push, leg flexion, leg extension and arm anteflexion) and at six force levels (from the endurance time experiment, 5.3);
- *Submaximal endurance time measurements*
  - Six 'times to the first change of hand', pushing at six force levels (from the discomfort experiment, 5.4);
  - Six 'total number of changes', pushing at six force levels (from the discomfort experiment, 5.4).
- *Anthropometric measurements*

  Gender, age, body weight, body height, elbow reach depth, arm reach depth, upper arm length, tense upper arm girth, relaxed upper arm girth, shoulder height and elbow height. The Quetelet index was added to the anthropometric measurements.

The Quetelet index consists of body weight (in kg) divided by the square of the body height (in m) and is used as a dimensionless measure for the obesity of individuals. A 'normal' Quetelet index ranges between about 20 and 25. The average Quetelet index for all 55 subjects is 22.1, with a standard deviation of 2.2, a minimum of 15.9, and a maximum of 26.8.

Not included are a number of variables from the first two posture experiments: pushing and pulling at shoulder and elbow height, in two standard postures and one functional posture. These values were excluded because they were not exerted by the subjects on which the main part of the overall analysis is based. Also excluded are the discomfort scores of the first discomfort experiment. They were measured during the endurance measurements and proved to be insufficiently reproducible, and are therefore excluded from the overall analysis.

The subjects that took part in the second discomfort experiment had all participated in the endurance experiment too. Their anthropometric variables were not measured again, for these had already been obtained for inclusion in the overall analysis. One maximal force (arm push) and the discomfort scores were measured, and also included in the overall analysis.

Data treatment. The correlation coefficient matrix combines the variables mentioned in table 6.1. Not every one of the subjects, 55 in all, participated in every experiment. Table 6.1 indicates how many subjects were measured for each variable, and table 6-2 indicates how many subjects participated in each experiment.

In the correlation matrix, the variables are grouped according to the type of measurement. The reason for this is that it is expected that variables of the same type of measurement will correlate in equal measure with other variables (e.g. all maximal forces, correlated with maximal endurance times or discomfort scores, will give similar results), and thus the matrix will be easy to read. All measurements of endurance times that lasted up to the measurement limit (1800 s) were also included. Although these may affect the real correlation, it was estimated that leaving out these longest endurance times would affect the correlations even more. A few values of 1800 s occurred, and only at the lower force percentages (15, 20 and 30 % of maximal force). For the exact amount of 1800 s measurements per variable, see table 5-13.

For the rest of the analysis, which consisted mostly of factor analyses, only the subjects who participated in nearly all of the experiments (19 in total, 9 women and 10 men, group 4 and 6 in table 6.2) were involved. This had a practical reason: for factor analysis, a complete set of data is required, so any group with missing data must be excluded from the analysis. Subjects who took part in only one or two experiments had too many data missing to be included in the factor analyses.

The 19 subjects whose data were included in the factor analyses, had only a few data missing, and these could be completed without unduly affecting the results. For maximal endurance time they were replaced by the median of the results of all subjects, and for maximal force exertion, by the median of the results of the subject of the same sex. The discomfort measurements were already complete. Of the 1444 values, 125 (8.7 %) had to be substituted in this manner (note that the Quetelet index was not taken into account here, because this was calculated from two other measurements). Most of the completions involved (part of) experiments that the subject had not participated in. For maximal endurance measurements, the 1800 s data (measurements that took so long they reached the 1800 s measurement limit) were included. This resulted in 19 subjects with complete data sets of 77 variables each. Unfortunately, the number of variables far exceeds that of subjects (or measurements per variable). Although sound statistics rule that the number of variables should be less than the number of data per variable, an attempt will be made to overcome this objection by analyzing part of the data with fewer variables in a number of separate steps.

Explanation of Factor Analysis. Factor analysis is used here to investigate the possible existence of one or more common factors for the 77 measured variables. Factor analysis is a technique for detecting underlying patterns within a set of variables. Variables that show a relation, but are largely independent of other subsets of variables, are combined into factors. These factors are thought to reflect underlying processes that have created the relations among variables. Thus, from factor analysis, a number of factors emerge, each of which explains a certain percentage of the total variance of the set of variables.

Factor analysis, however, can only be used for generating hypotheses and is not suitable for testing a hypothesis. Only those factors which explain the most variance, and which are theoretically plausible, should be accepted. The limits for acceptation are to some extent arbitrary. The success of a factor analysis therefore depends on the size of this percentage of explained variance and the possibility to label the factors according to supporting theory. Ideally, one large factor should appear explaining most of the variance, next to a few smaller ones. When the analysis results in more than one factor, these can be rotated using varimax rotation to obtain a more uniform division of explained variance across factors, which then constitute a new configuration, possibly with new labels. For the calculation of factor analyses, the SPSS computer program was used, using varimax rotation for the multi-factor solutions.

Explanation of Multiple Regression Analysis. Regression analysis comprises a set of statistical techniques used to assess the relationship between a dependent variable and independent variables, in order to predict the dependent variable from the others. Regression techniques can be applied to a data set in which the variables are correlated.

In stepwise multiple regression, instead of one variable, a number of independent variables are combined to predict the value of a dependent variable. One by one, the most promising independent variables are entered into the analysis until they no longer add to the accuracy of the prediction of the dependent variable. The result of multiple regression is an equation that represents the best prediction of a dependent variable from several independent variables. The regression equation takes the following form:

$$Y = A + B_1X_1 + B_2X_2 + B_3X_3 + \ldots + B_kX_k$$

in which Y is the predicted value of the dependent variable, A - the intercept - is the value of Y when all X values are zero, each X is the value of an independent variable (of which there are k) and each B is the coefficient assigned to the independent variable during regression. Although the intercept and the coefficients are the same for a whole sample, a different Y value is predicted for each subject as a result of inserting the subject's own X values into the equation (Tabachnick and Fidell, 1989). The SPSS computer program was also used to calculate the multiple regression equations.

Order of analyses. The strategy followed for the overall analysis is visualized in a diagram, table 6-3. Using all the original data as collected (step 1 in the diagram), a correlation matrix was calculated (step 2).

action	objective	results
1 Experiments 5.1 to 5.4		All data of 55 subjects
2 Correlation of all data	First inkling of the global relation between the data	Correlation matrix (77 * 77 variables)
3 One Factor Analysis of all data	Identification of groups of variables by factors	Data grouped by factors in 3 groups
4 Factor Analyses of three groups of data	Typefying of individuals by one factor (or limited combination of variables) per group	Three factors (and possibly representative variables)
5 Regression analysis of the three factors with anthropometric variables	Prediction of the factors from anthropometry	Three regression equations
6 Assessment of predictability of data	Prediction of data from other data or anthropometry	Method to predict maximal force, endurance times or discomfort for individuals

Table 6-3: Diagram of the strategy followed for the overall analysis. Each time, the results of one step are used for the next action.

Next, factor analyses were carried out on the 19 completed data sets, to find one or more factors to characterize the subjects. First one large factor analysis was carried out with all variables (step 3), the expectation being to find one or more factors indicating that variables can be divided into groups that have common elements. Solutions involving one to five factors were tried. The solution resulting in factors which best group the measurements according to theoretical explanation, is selected for detailing.

The resulting groups of variables are not completely consistent, and therefore another factor analysis was performed (step 4) on each corrected group of variables which seem to have a common factor. This was done in order to identify the common factor, see how it is composed, see whether there is one measure which is representative for that factor, and see how much variance the factor can explain. This information indicates whether these factors (or even representative variables) are a feasible way of characterizing strength, maximal endurance ability or discomfort sensibility of subjects.

Finally, multiple regression analyses were carried out (step 5) to further investigate the possibility of characterization and data prediction on the basis of a number of variables (including anthropometric ones), and the predictability was assessed (step 6).

6.4 Results and discussion

6.4.1 Correlations

A large correlation coefficient matrix with correlations of all subjects (27 female and 28 male) between nearly all variables (see table 6-1) was made to obtain an overview of the degree of (cor)relation between the variables. Part of the matrix is shown in table 6-4 and appendix D, showing only correlations significant at $p < 0.05$ to give a better overview. Correlation coefficients of 0.71 and higher are underlined, indicating that the percentage of the explained variance is 50 % or more, and the correlation thus shows more generality than specificity. Some correlations with endurance times may be influenced by the measurement limit of 1800 s, as indicated in section 6.3, 'Approach'.

Sex. A partial correlation coefficient matrix, with correction for sex, was calculated to see whether sex affected the correlation (as is often the case where maximal forces are involved). No table of this matrix is included, as it is quite large and the details do not affect further analysis. The partial correlation matrix shows that for maximal forces and anthropometry fewer correlation coefficients are ≥ 0.71, but for endurance the score is about the same. So, the correlations involving maximal force are slightly enhanced by the combination of female and male data, but not those involving endurance.

Grip force. The correlation between maximal grip force and any other force measurement is not notably better than the other correlations between forces. Grip strength is thought to be a good indicator of general strength, and is therefore often measured. In view of the results, it is more likely that it is so popular amongst researchers because it is so easy and quick to measure.

Quetelet index. The Quetelet index does not correlate very well with any variable. Only the coefficient of correlation with relaxed upper arm girth is greater than 0.71, being 0.74. Surprisingly, the Quetelet index does not even correlate very well with body height and body weight (with coefficients of -0.37 and 0.52 respectively), although it is derived from these variables. Maybe the deviation from the normal distribution of this index is responsible for this effect. It is suspected that the Quetelet index will not be of much value in the further analysis, but it will be included nevertheless.

Overview. A summary of the correlation coefficient matrix is given in table 6-5, listing the number and percentage of significant correlations and those greater than or equal to 0.71. These figures are given per set of correlations within two groups of variables. The variables are grouped according to the same type of measurement. Thus the resulting groups include anthropometrics, maximal forces, maximal endurance times and submaximal endurance times respectively, the last of which shall be referred to as 'discomfort scores' for practical reasons. Although this description is not the most fitting (as discussed in 5.4 'Discomfort during submaximal, static force exertion'), it prevents confusion with the maximal endurance times.

The best correlations occur within the group of maximal forces, where 99 % of the correlations are significant and nearly 60 % of the coefficients are greater than or equal to 0.71. The fact that the maximal forces correlate so well may be explained from the

correlations		total r's n	r significant n	%	|r| ≥ 0.71 n	%
within	anthropometric measurements	66	54	82 %	21	32 %
	maximal force measurements	406	402	99 %	242	60 %
	maximal endurance measurements	276	149	54 %	26	9 %
	discomfort measurements	66	49	74 %	15	23 %
between	anthropometry and maximal forces	348	270	78 %	71	20 %
	anthropometry and maximal endurance times	288	9	3 %	0	0 %
	anthropometry and discomfort	144	47	33 %	0	0 %
	maximal forces and maximal endurance times	696	114	16 %	2	0 %
	maximal forces and discomfort	348	33	10 %	0	0 %
	maximal endurance times and discomfort	288	50	17 %	1	0 %

Table 6-5: Overview of the amount of correlations, of significant correlations and coefficients greater than or equal to 0.71, between all variables, summarizing the large correlation coefficient matrix (see table 6-4).

fact that most of them are exerted using the biceps as the main muscle. These forces are referred to as 'Moment 1' up to 'Moment 18', 'Arm push' and 'Anteflexion of the arm'.

The forces involving more or less the whole body correlate slightly less with each other and with all other forces, which supports the above-mentioned assumption about the biceps. On the other hand, it may also be explained from the fact that the forces involving the whole body are exerted in free posture, and it is possible that forces in standardized postures (exerted using mostly the biceps as main muscle) show better correlation. More research is needed to ascertain the cause of this phenomenon.

Second best are the correlations within the group of anthropometric variables, followed by those within discomfort variables and those between maximal forces and anthropometric variables. In this case, over 74 % of the correlations are significant, and of these coefficients more than 20 % ≥ 0.71.

In all the other combinations of grouped variables the correlations are not very high. Less than 55 % of the correlations are significant, less than 10 % of the coefficients are greater than or equal to 0.71. These are correlations between variables of different groups, with virtually none of the correlations greater than or equal to 0.71, and the correlations between maximal endurance variables.

Summarizing, the best correlations occur within groups (except for the low correlations between maximal endurance variables) and between anthropometry and maximal forces.

6.4.2 First Factor Analysis

One factor analysis was performed on all the data collected (see table 6-6), as an exploratory investigation to get an idea of how the data could be grouped. Later on, the identified groups are analyzed separately. One to five factor solutions were calculated and judged. Varimax rotation was performed on all matrices involving more than one factor. The single-factor solution did not explain much variation (only 39.3 %).

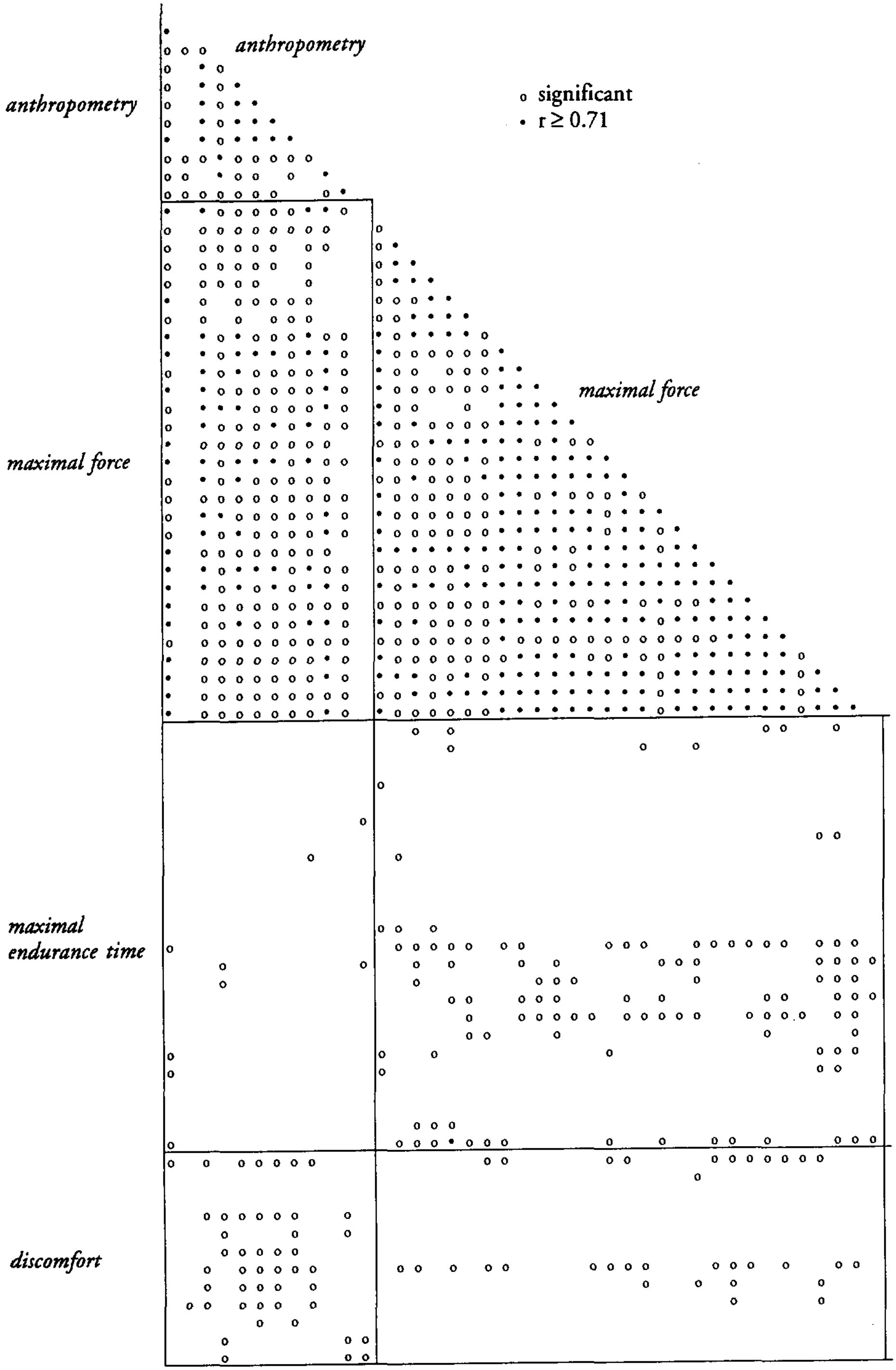
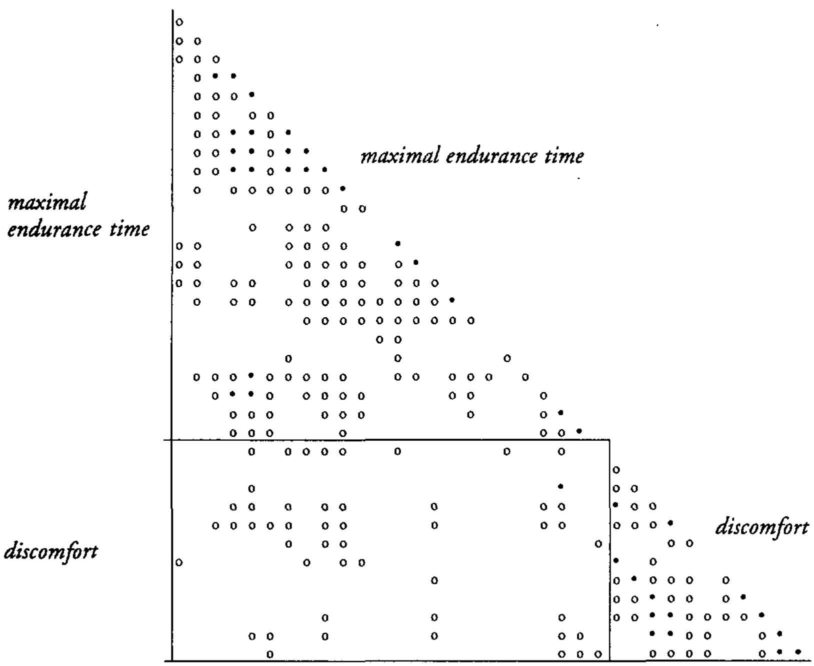


Figure 6-4: Overview of a correlation coefficient matrix including nearly all variables that resulted from the experiments described in chapter 5 'Experiments'. Only significant correlations are indicated. Full dots denote correlations which show more generality than specificity (with $r \geq 0.71$). The actual correlations can be found in appendix D.


maximal endurance time
maximal endurance time
discomfort
discomfort

factor	initial statistics eigenvalue	% of variance	cumulative %
1	30.2594	39.3	39.3
2	11.5154	15.0	54.3
3	6.1993	8.1	62.3
4	5.3138	6.9	69.2
5	3.5035	4.6	73.8
6	3.1047	4.0	77.8
7	2.6218	3.4	81.2
8	2.5700	3.3	84.5
9	2.0134	2.6	87.1
10	1.8719	2.4	89.6
11	1.5675	2.0	91.6
12	1.4678	0.9	93.5
13	1.2461	1.6	95.1
14	1.0099	1.3	96.4

Varimax rotation. Varimax converged in 9 iterations. Rotated factor matrix:

variable	communality	factor 1	factor 2	factor 3	sort of data
moment 15	.9120	.9445	-.0900	-.1064	maximal force
moment 2	.8800	.9320	-.0718	-.0783	maximal force
moment 14	.8730	.9310	-.0400	-.0631	maximal force
moment 1	.8440	.9174	.0366	-.0251	maximal force
moment 8	.8850	.9069	-.1347	-.2109	maximal force
leg extension	.8780	.8930	.1011	-.2659	maximal force
moment 13	.8690	.8904	.2205	-.1655	maximal force
moment 17	.8330	.8891	-.0644	-.1949	maximal force
arm anteflexion	.8460	.8882	.0076	-.2381	maximal force
moment 12	.8270	.8783	-.1988	-.1360	maximal force
leg flexion	.9290	.8764	.0450	-.3983	maximal force
moment 6	.7760	.8724	-.1199	-.0231	maximal force
moment 4	.7860	.8691	-.1054	-.1380	maximal force
moment 11	.7880	.8678	-.1509	-.1001	maximal force
moment 9	.7820	.8599	-.1211	-.1653	maximal force
moment 3	.7530	.8535	-.1476	-.0512	maximal force
shoulder height	.8410	.8493	.3304	.1018	anthropometry
body height	.8460	.8492	-.2254	.2712	anthropometry
sex	.7270	.8264	.1028	-.1816	anthropometry
moment 7	.7150	.8204	.1506	-.1383	maximal force
arm push	.7580	.8011	.1886	-.2839	maximal force
grip force	.6660	.7994	.1137	-.1186	maximal force
moment 5	.7240	.7983	-.2852	-.0750	maximal force
elbow reach depth	.7150	.7943	-.2784	.0828	anthropometry
upper arm length	.6490	.7821	-.1938	.0141	anthropometry
push at shoulder height	.6260	.7725	.1222	-.1535	maximal force
moment 16	.7120	.7673	.0346	-.3491	maximal force
jam jar, free posture	.6960	.7597	.2680	-.2164	maximal force
moment 10	.5840	.7588	.0881	.0080	maximal force
elbow height	.7770	.7560	-.4368	.1221	anthropometry

Table 6-6: Factor analysis of the results of the experiments described in chapter 5 (29 maximal forces, 24 maximal endurance times, 12 discomfort scores, 12 anthropometric measures), as calculated by SPSS.

	communality	factor 1	factor 2	factor 3	sort of data
pull at elbow height	.6100	.7329	.1780	-.2019	maximal force
pull at shoulder height	.5680	.7320	.0403	-.1735	maximal force
jam jar, fixed	.6290	.7170	.2391	-.2411	maximal force
push at elbow height	.7140	.6951	.5024	-.3288	maximal force
tense upper arm girth	.5950	.6877	.3266	-.1244	anthropometry
moment 18	.4740	.6698	-.1067	-.1177	maximal force
arm reach depth	.5170	.6285	-.3497	.0029	anthropometry
number of changes at 80 %	.3430	.4488	-.2801	-.2508	discomfort
arm anteflexion endurance at 80 %	.0980	-.2227	-.1129	.1881	maximal endurance
number of changes at 15 %	.8280	.0016	-.8961	.1596	discomfort
number of changes at 20 %	.7050	-.0234	-.8216	-.1718	discomfort
time to change of hands at 30 %	.7430	-.2453	.7948	.2260	discomfort
number of changes at 30 %	.6410	.1322	-.7888	.0339	discomfort
time to change of hands at 15 %	.5900	-.0716	.7528	-.1342	discomfort
time to change of hands at 20 %	.7130	-.1467	.7493	.3605	discomfort
time to change of hands at 40 %	.4890	-.0406	.6966	.0428	discomfort
arm anteflexion endurance at 15 %	.6690	.4285	.6963	.0008	maximal endurance
arm anteflexion endurance at 30 %	.5880	.0888	.6842	.3347	maximal endurance
arm push endurance at 20 %	.6840	.0259	.6768	.4742	maximal endurance
number of changes at 40 %	.5430	.2966	-.6742	.0265	discomfort
arm anteflexion endurance at 20 %	.5790	.1447	.6604	.3489	maximal endurance
arm push endurance at 15 %	.5200	.1806	.6512	.2519	maximal endurance
relaxed upper arm girth	.5050	.4870	-.4990	-.1385	anthropometry
time to change of hands at 80 %	.4790	-.4235	.4852	.2540	discomfort
arm push endurance at 60 %	.2860	-.2316	.4303	.2170	maximal endurance
quetelet index	.2260	-.0627	-.4217	-.2106	anthropometry
number of changes at 60 %	.2960	.3598	-.3897	-.1214	discomfort
time to change of hands at 60 %	.2640	-.3169	.3848	.1228	discomfort
age	.0780	.0091	-.2087	-.1861	anthropometry
leg flexion endurance at 20 %	.6670	-.0226	.0432	.8151	maximal endurance
leg flexion endurance at 30 %	.7460	-.1294	.3131	.7944	maximal endurance
leg flexion endurance at 80 %	.7210	-.1379	.3511	.7609	maximal endurance
leg flexion endurance at 60 %	.6020	-.1926	.1739	.7309	maximal endurance
leg flexion endurance at 40 %	.6590	-.1167	.3351	.7299	maximal endurance
leg extension endurance at 20 %	.6160	-.3916	.0808	.6757	maximal endurance
leg extension endurance at 30 %	.6070	-.3587	-.2081	.6595	maximal endurance
leg extension endurance at 15 %	.5440	-.3105	-.1708	.6466	maximal endurance
arm push endurance at 30 %	.5650	.1095	.4021	.6252	maximal endurance
leg extension endurance at 80 %	.5780	-.4462	.0479	.6134	maximal endurance
leg extension endurance at 60 %	.4510	-.3119	.0841	.5887	maximal endurance
arm anteflexion endurance at 40 %	.5210	.0445	.4175	.5872	maximal endurance
arm push endurance at 40 %	.4490	.0549	.3679	.5574	maximal endurance
leg extension endurance at 40 %	.4580	-.2786	.3614	.4997	maximal endurance
arm anteflexion endurance at 60 %	.2780	-.1025	.2171	.4695	maximal endurance
arm push endurance at 80 %	.2740	-.3009	-.0808	.4210	maximal endurance
leg flexion endurance at 15 %	.1120	.2104	.0423	.2567	maximal endurance

factor transformation matrix:

	factor 1	factor 2	factor 3
factor 1	.9359	-.2053	-.2862
factor 2	.3133	.8564	.4105
factor 3	.1608	-.4739	.8658

Table 6-6: (continued from previous page).

The two-factor solution explained 54.3 % of all variation and showed a distinct dichotomy with maximal forces and anthropometric variables correlating best with the first factor, and maximal endurance and discomfort variables correlating best with the second factor.

The results of the factor analysis of all 77 measurements using the three-factor solution are listed in table 6-6. The rotated factor matrix shows the correlations between the variables and the factors, ranked according to the highest correlation of the three. For the three-factor solution, 62.3 % of variation is explained. Analogous to the two-factor solution, maximal forces and nearly all anthropometric variables correlated best with the first factor, discomfort variables correlated best with the second factor and most maximal endurance variables correlated best with the third factor. Although body height and body weight correlate best with the first factor (with r values of 0.85 and 0.64 respectively), the Quetelet index, which is derived from these variables, correlates best with the second factor, with an r of -0.42.

The four-factor and five-factor solutions showed a less consistent relation of various groups of variables with the different factors. They did not add to a better understanding of the results and are therefore not further analyzed.

The three-factor solution is considered to indicate the most useful division of variables in groups, according to the correlations with the three factors. The three groups are theoretically plausible: the first consists of maximal forces and anthropometry, the second mostly of discomfort measurements and the third of maximal endurance times. So, this actually constitutes excellent confirmation of the expectations, based on the correlation coefficient matrix in figure 6-4.
The division obtained from the factor analysis is not exact, for some of the variables with low correlation landed ended up in different groups than expected. A division based on, among other things, theoretical coherence, is preferred over a division based on empirical coincidence alone. Therefore the variables are rearranged into three groups, based on the theoretical expectations, resulting in one group with maximal forces, one group with endurance times and one group with discomfort scores. The anthropometric variables are temporarily left out, as explained below (6.4.3. 'Factor Analysis of subgroups').

Next, factor analysis was performed three times, on 29 maximal force, 24 maximal endurance, and 12 discomfort variables, respectively.

6.4.3 Factor analysis of subgroups

Thus, factor analysis was performed on each of three subgroups: one with maximal forces, one with maximal endurance times and one with the so-called discomfort scores.

Factor analysis of maximal forces. The anthropometric variables are not included in the factor analysis with maximal forces, as it is not the intention to find a common factor for both maximal force and anthropometry, but rather to find a common factor for maximal forces, and to predict it later on, if possible, from anthropometric variables, which are easier to assess. So, the anthropometric variables will be involved in a later stage when regression analysis is performed.

The results of the factor analysis for maximal forces are listed in table 6-7. The first factor explains 73.3 % of all variance. Only the loadings of the first factor are calculated, as this is obviously the most important of the three factors from the overall factor analysis, where adding factors did not improve the grouping of the measurements. The communalities of factor 1 vary between 0.54 and 0.89. The communality is the square of the value from the factor matrix. This means that 54 to 89 % of the variation of the variables is explained by factor 1. The factor score coefficients vary between 0.033 and 0.044, so all variables contribute to factor 1 in about the same degree. This factor is appropriately labelled 'maximal force factor'. A subject's score for this factor gives an indication of the strength of that subject relative to the group.

factor	eigenvalue	% of variance	cumulative %
1	21.2526	73.3	73.3
2	2.5884	8.9	82.2
3	1.1345	3.9	86.1

variable	factor loadings (r): factor 1	factor score coefficients: factor 1
pull at shoulder height	.7584	.0357
push at shoulder height	.7923	.0373
pull at elbow height	.7646	.0360
push at elbow height	.7380	.0347
jam jar, free posture	.7878	.0371
jam jar, fixed	.7407	.0349
moment 1	.9065	.0427
moment 2	.9318	.0439
moment 3	.8636	.0406
moment 4	.9005	.0424
moment 5	.8255	.0388
moment 6	.8781	.0413
moment 7	.8440	.0397
moment 8	.9319	.0439
moment 9	.8820	.0415
moment 10	.7426	.0349
moment 11	.8978	.0423
moment 12	.8998	.0423
moment 13	.9171	.0432
moment 14	.9023	.0425
moment 15	.9436	.0444
moment 16	.8086	.0381
moment 17	.9137	.0430
moment 18	.7007	.0330
arm push	.8512	.0401
leg flexion	.9348	.0440
leg extension	.9254	.0435
arm anteflexion	.9383	.0442
grip force	.8157	.0384

Table 6-7: Factor analysis of 29 maximal forces, as calculated by SPSS, *after instruction to maximalize on one factor.*

Note that in table 6-7 the variables that have the highest factor loadings, i.e those which correlate best with the maximal force factor, are 'Anteflexion of the arm' and 'Moment 15'. Upon closer inspection, the forces exerted in both cases are identical. Moment 15 from the 'segment' experiment (see 5.2), exerted as anteflexion of the arm, was chosen to be included in the endurance experiment because it was the moment that correlated best with the other moments of the segment experiment. The two variables cannot be merged into one, for 'Anteflexion of the arm' is the exerted force and 'Moment 15' is the moment calculated from the exerted force. This coincidence may explain their relatively high factor loadings and score coefficients.

factor	eigenvalue	% of variance	cumulative %
1	9.5368	39.7	39.7
2	3.44591	14.4	54.1
3	2.50091	10.4	64.5
4	1.67621	7.0	71.5
5	1.50904	6.3	77.8

variable	factor loadings (r) factor 1	factor score coefficients: factor 1
arm push endurance at 80 %	.4608	.0483
arm push endurance at 60 %	.5183	.0544
arm push endurance at 40 %	.6529	.0685
arm push endurance at 30 %	.7612	.0798
arm push endurance at 20 %	.7724	.0810
arm push endurance at 15 %	.5844	.0613
leg flexion endurance at 80 %	.6561	.0688
leg flexion endurance at 60 %	.7642	.0801
leg flexion endurance at 40 %	.8360	.0877
leg flexion endurance at 30 %	.8651	.0907
leg flexion endurance at 20 %	.7216	.0757
leg flexion endurance at 15 %	.3408	.0357
leg extension endurance at 80 %	.5410	.0567
leg extension endurance at 60 %	.5893	.0618
leg extension endurance at 40 %	.6306	.0661
leg extension endurance at 30 %	.6391	.0670
leg extension endurance at 20 %	.7381	.0774
leg extension endurance at 15 %	.5382	.0564
arm anteflexion endurance at 80 %	.0368	.0039
arm anteflexion endurance at 60 %	.2277	.0239
arm anteflexion endurance at 40 %	.7616	.0799
arm anteflexion endurance at 30 %	.7082	.0743
arm anteflexion endurance at 20 %	.6728	.0705
arm anteflexion endurance at 15 %	.3818	.0400

Table 6-8: Factor Analysis of 24 maximal endurance time variables, as calculated by SPSS, *after instruction to maximalize on one factor.*

Also in table 6-7, note that the forces exerted with the whole body in free posture show a lower correlation with the maximal force factor than do the other forces (their factor loadings are slightly smaller). This is similar to the findings from the correlation coefficient matrix. Unfortunately, all forces including one main muscle (the biceps) were measured in standard postures only. Therefore the cause of this effect cannot be established.

Factor analysis of maximal endurance times. The result of the factor analysis for maximal endurance times can be seen in table 6-8. The first factor explains only 39.5 % of all variance. The communalities of factor 1 vary between 0.001 and 0.75, which means that 0.1 to 75 % of the variance of the variables is explained by factor 1. The factor score coefficients vary between 0.004 and 0.091, so the variables contribute to factor 1 in varying degrees, and there are no variables with relatively high factor score coefficients that account for the main part of factor 1. This factor is labeled 'maximal endurance time factor'. The score of a subject for this factor gives an indication of the maximal endurance ability of that subject relative to the results of the other subjects.

Factor analysis of discomfort measurements. The result of the factor analysis for discomfort measurements can be seen in table 6-9. The first factor explains 58.5 % of all variance. The communality of factor 1 varies between 0.31 and 0.82, which means that 31 to 82 % of the variance of the variables is explained by factor 1. The factor score coefficients vary between -0.13 and 0.13, so the variables contribute to factor 1 in varying degrees. The highest correlations with factor 1 are achieved by 'time to the change of hands at 30 % (of maximal force)' and 'number of changes at 30 % (of maximal force)', for which r is 0.90 and -0.88 respectively. This factor is labeled 'discomfort factor'. The score of a subject for this factor gives an indication of the subject's sensibility for discomfort due to prolonged force exertion, relative to the results of the other subjects.

factor	eigenvalue	% of variance	cumulative %
1	7.01952	58.5	58.5
2	1.9289	16.1	74.6
3	1.00698	8.4	83.0

variable	factor loadings (r) factor 1	factor score coefficients: factor 1
time to change of hands at 80 %	.7760	.1105
time to change of hands at 60 %	.6667	.0950
time to change of hands at 40 %	.8219	.1171
time to change of hands at 30 %	.9048	.1289
time to change of hands at 20 %	.8349	.1190
time to change of hands at 15 %	.5541	.0789
number of changes at 80 %	-.5906	-.0841
number of changes at 60 %	-.7175	-.1022
number of changes at 40 %	-.8510	-.1212
number of changes at 30 %	-.8780	-.1251
number of changes at 20 %	-.7803	-.1112
number of changes at 15 %	-.7120	-.1014

Table 6-9: Factor Analysis of 12 discomfort variables, as calculated by SPSS, *after instruction to maximalize on one factor.*

In table 6-9, note that half the factor loadings (or coefficients of correlation between the factor and the variables) are negative. The factor loadings of all 'time to the first change of hands' variables are positive, and those of the 'total number of changes' variables are negative. This is caused by the relation between those two sorts of measurements. For in general, the sooner hands are changed (thus the shorter the time to the first change), the more changes will be made in a period. The factor characterizes the individual for both types of variables (as both are an indication of some sort of discomfort) and correlates with them in different directions, i.e. positive and negative.

Calculation of factors. The maximal force, endurance time and discomfort factors were determined by calculating the scores for each subject. The endurance time and discomfort factor scores were calculated using the factor score coefficients, as is customary. The maximal force factor scores were calculated in an alternative way. Because the maximal force data all contribute equally to the maximal force factor score coefficients, the factor scores can be calculated for each subject by averaging his or her z scores of all maximal force data. This results in a factor with an average of 0.03 instead of 0, and a standard deviation of 0.8 instead of 1. This imperfection, however, is acceptable as the method of calculating is easy and shows the essence of the factor. The maximum forces exerted by each subject in various situations have a constant value, relative to the average of the group and taking the standard deviation into account. The constant is the z score. This applies for all maximal force variables in the present research.

Correlations between the factors. The correlations between the maximal force, endurance time and discomfort factors were calculated and the correlation coefficients are listed in table 6-10. The only significant correlation at $p < 0.05$ is between the endurance time factor and the discomfort factor.

	maximal force factor	maximal endurance time factor
maximal endurance time factor	-0.3201 n = 19 p = .091	
discomfort factor	-0.2735 n = 19 p = .129	0.4138 n = 19 p = .022

Table 6-10: Coefficients (and number of subjects) of the correlations between the three factors calculated with Factor Analysis.

Thus, the maximal force factor does not correlate significantly with either the endurance time factor or the discomfort factor. Apparently, endurance and discomfort of submaximal forces relative to maximal force, are completely different abilities compared to the exertion of maximal force. This is what one hopes for when looking for basic underlying characteristics, in this case of force exertion.

Next, regression analyses had to be carried out to investigate whether any prediction of variables or factors is possible.

6.4.4 Prediction

Figure 6-1 shows a simplified scheme of the relation between the variables and the factors, as calculated with factor analysis, regression analysis and correlation. The amount of explained variance and the calculation method are also indicated in the figure.

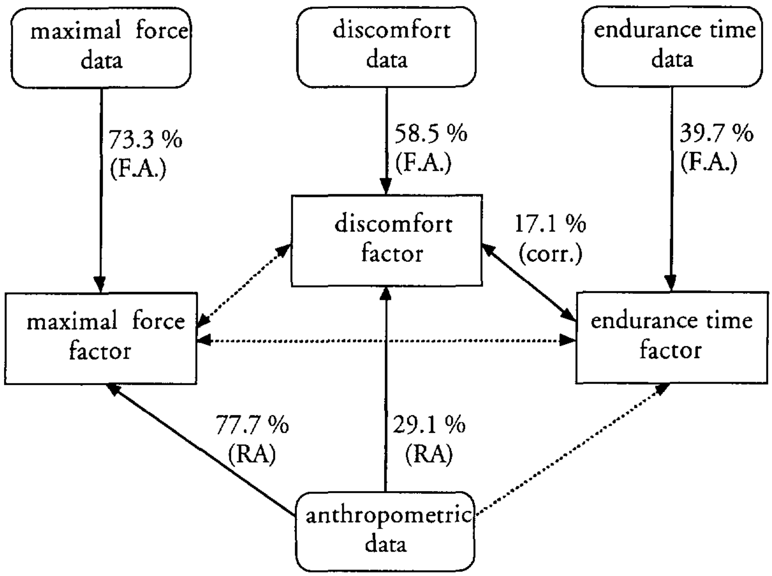


Figure 6-1: Scheme showing the relations between the data and the first factors from factor analyses. A dashed line signifies a non-significant relation, a plain lines signifies a significant relation. The percentages of explained variance are added, as well as the method used to calculate it (FA = Factor Analysis, RA = Regression Analysis, corr. = correlation). Correlations between the data are not indicated with a view to the surveyability. A correlation matrix of all data is given in table 6-4.

Regression analyses were carried out to investigate whether it is possible to predict:
- factors from anthropometric variables;
- factors from the best variable(s) participating in the factor analysis;
- variables, from any other variable(s).

Maximal force factor from anthropometry. Stepwise multiple regression analysis was carried out with the maximal force factor as dependent variable and eleven anthropometric variables and the Quetelet index as independent variables. The results can be seen in table 6-11.

The first step results in a correlation coefficient of 0.82 between the maximal force factor and the 'sex' variable. The influence of gender on maximal force hardly comes as a surprise. It is a well-known fact in real life, obvious in the present experiments and confirmed by all literature (see 3.2.1. 'Sex').

In the second step, 'tense upper arm girth' is added to the model, increasing the multiple correlation coefficient to 0.88. The influence of tense upper arm girth, rather than other anthropometric variables, may be explained by the fact that the biceps was involved in the exertion of most of the forces measured.

In the third step, the Quetelet index is added to the model, increasing the multiple correlation coefficient to 0.92. This is surprising, because the Quetelet index did not correlate significantly with any maximal force, and during the first factor analysis of all data it was grouped with the discomfort variables and not with the maximal force data. The resulting equation (with $r^2 = 0.85$) is:

$$\text{max. force factor} = -5.4 + 0.59 * G + 0.29 * T - 1.69 * Q$$

in which G equals 0 for females and 1 for males, T equals the tense upper arm girth in cm, and Q represents the Quetelet index. Other anthropometric variables do not correlate significantly ($p < 0.05$) with the maximal force factor.

Maximal force factor from the maximal forces. Subjects can be characterized according to strength by the maximal forces they exert. It is very well possible to characterize by means of the maximal force factor. In this factor, all forces measured in the present experiments contribute in more or less equal amounts. It is possible that this applies for other forces as well. This aspect merits further investigation. Therefore, to typify people, the z scores of the forces they exert should be averaged. The result is the 'maximal force factor' for the subject in question, which indicates his or her strength relative to that of other subjects. The average value of the group is set to 0 and the standard deviation to 1. For example, a negative maximal force factor means that the subject is weaker than the average.

Prediction of maximal forces. For maximal forces, as measured in the experiments described in chapter 5, it is possible to estimate the strength profile (the maximal force factor score) of an individual, either from gender and tense upper arm girth, or from the maximal forces measured. It is interesting that all forces contribute to the strength profile of the user in equal amounts. There is no single best correlating maximal force from which the maximal force factor can be predicted. The combination of all forces by averaging the z scores, however, gives a good prediction of the maximal force factor and thus is an indication of the general strength of a subject.

With this individual maximal force factor, forces that can be exerted by the individual in other situations can also be predicted. The factor is a z score which indicates what the deviation of the average maximal force of a group will be for the force, not yet measured, that can be exerted by the person concerned. The force data of a group form a prerequisite for the prediction of individual forces.

Although the minimum number of maximal forces to predict another maximal force is one, the more the number of forces that are measured (and so the more the number of z scores that are averaged), the better the factor will be approximated. There is no theoretical basis to prefer one maximal force measurement over another for predictions. Furthermore it is quite convenient that any force can be used to estimate the force factor and other maximal force values of a subject.

dependent variable..		maximal force factor	
variable entered on step number 1		sex	
r	0.816		
r^2	0.667		
variables in the equation	B	T	sign. T
sex	1.310	5.830	.0000
(constant)	-1.968	-5.453	.0000
variable entered on step number 2		tense upper arm girth	
multiple r	0.882		
r^2	0.777		
variables in the equation	B	T	sign. T
sex	0.970	4.317	.0005
tense upper arm girth	0.148	2.820	.0123
(constant)	-5.682	4.203	.0007
variable entered on step number 3		Quetelet index	
multiple r	0.922		
r^2	0.850		
variables in the equation	B	T	sign. T
sex	0.588	2.478	.0256
tense upper arm girth	0.288	4.213	.0008
Quetelet index	-1.694	-2.700	.0165
(constant)	-5.424	-4.720	.0003
variables not in the equation		T	sign. T
age		0.043	.9665
body height		0.349	.7325
body weight		0.580	.5714
elbow reach depth		0.258	.7998
arm reach depth		-0.460	.6522
upper arm length		0.516	.6142
relaxed upper arm girth		-0.138	.8924
shoulder height		0.656	.5223
elbow height		0.566	.5805

Table 6-II: Regression analysis on the maximal force factor with twelve anthropometric variables.

If, however, a choice must be made which maximal force to measure for prediction, and if there are no other requirements, a good force for measurement and prediction would be for example anteflexion of the arm with the force measured at the lower arm. This is easy to measure (no seats or supports are needed) and it correlates relatively well with the other maximal forces and the maximal force factor. Another good force to measure could be the grip force, because it is even easier to measure (with a Jamar dynamometer, no extra electronic equipment is needed) and often is already included in experiments.

Maximal endurance time factor from anthropometry. Stepwise regression analysis is carried out, too, with the endurance time factor as dependent variable and with the eleven anthropometric variables and the Quetelet index as independent variables. No variables were entered in the equation, however, because no significant ($p < 0.05$) correlation was found between the anthropometric variables and the endurance time factor.

Maximal endurance time factor from maximal endurance times. Endurance is not a very suitable factor to use for characterizing subjects. The endurance time factor only explains 39.7 % of the total variance. To predict the endurance time factor from maximal endurance times, the variable with the highest factor loading (correlating best with the maximal endurance time factor) should be entered in a regression analysis. This is the 'leg flexion endurance at 30 % of maximal force' variable, the factor loading of which is 0.87. Regression analysis produces:

maximal endurance time factor = -1.21 + 0.0015 * leg flexion endurance at 30 %

the endurance time being given in s. This equation results in an explained variance of 74 %

Prediction of maximal endurance times. The question now arises whether prediction of maximal endurance times from each other or from anthropometric variables is possible. Alas, the answer is negative. It is even hard to predict the maximal endurance time from the maximal endurance of different percentages of the same force exertion, as evidenced by the correlation coefficient matrix in table 6-4.

Discomfort factor from anthropometry. Stepwise regression analysis is carried out, too, with the discomfort factor as dependent variable and with the eleven anthropometric variables and the Quetelet index as independent variables. The result is shown in table 6-12. In this case, the only variable correlating significantly with the endurance time factor is 'elbow height' with $r = -0.54$ ($r^2 = 0.29$) and $p = 0.0171$. The resulting equation is:

discomfort factor = 13.91 - 0.13 * elbow height

the elbow height being given in cm. This result is remarkable, as it shows significant correlation between discomfort sensibility and elbow height, which would suggest a relation between the two. However, there is no theoretical basis to suggest that this is in fact the case, so the usefulness of the equation must remain doubtful.

Discomfort factor from discomfort scores. Subjects can be characterized according to discomfort sensibility on the basis of their discomfort scores. The discomfort factor explains 58.5 % of the total variance. According to the results of the regression analysis, the discomfort factor can be predicted from elbow height. Although they show significant correlation, the validity of estimating the discomfort factor from the elbow height is questionable as the explained variance is only 29.1 %. Furthermore there is no theoretical basis to explain the relation between elbow height and discomfort scores.

dependent variable..	discomfort factor		
variable entered on step number 1	elbow height		
r	0.539		
r^2	0.291		
variables in the equation	B	T	sign. T
elbow height	-0.128	-2.641	.0171
(constant)	13.914	2.644	.0171
variables not in the equation		T	sign. T
age		-0.311	.7601
body height		0.746	.4666
body weight		-0.107	.9160
elbow reach depth		0.139	.8914
arm reach depth		0.011	.9916
upper arm length		0.230	.8207
tense upper arm girth		0.242	.8118
relaxed upper arm girth		-0.376	.7118
shoulder height		1.134	.2734
sex		0.688	.5014
Quetelet index		-0.497	.6261

Table 6-12: Regression analysis on the discomfort factor with twelve anthropometric variables.

Although there is a correlation, it is suspected that there is no functional relation between elbow height and the number of changes or the time to the first change of hand. Therefore, predicting the discomfort factor on the basis of anthropometric variables is not feasible. Thus the discomfort factor should either be calculated using the factor score coefficient matrix, or it should be estimated using the measurements that correlate best with the factor. These are: the time to the first change of hands at 30 %, and the number of changes at 30 %. The calculation of the factor is laborious, because it requires all discomfort measurements (which consequently must be measured) to obtain the discomfort factor. Therefore the estimation of the discomfort factor by either the 'time to the first change of hands at 30 % (of maximal force)', or the 'number of changes at 30 % (of maximal force)' is preferred. The corresponding regression equations for estimation are:

discomfort factor = 1.14 - 0.013 * time to the first change at 30% $\quad r^2 = 0.91$

discomfort factor = -2.07 + 0.43 * number of changes at 30% $\quad r^2 = 0.92$

Prediction of discomfort scores. As discussed above, the discomfort factor scores can best be predicted using one of two discomfort measurements (the time to the first change of hands at 30 % of maximal force, or the total number of changes at 30 % of maximal force). These measurements are representative for the discomfort factor, and thus it may be convenient to predict discomfort scores for individuals straight from the correlations with one of those measurements. The resulting regression lines are given in table 6-13. The amount of explained variance (r^2) for the best of each two predictions varies between 20 and 85 %.

variable	time to the first change of hand at 30 % equation	r^2	total number of changes at 30% equation	r^2
time to first change of hands at 80 %	y = 16.46 + 0.14x	0.54	y = 51.13 - 3.96x	0.38
time to first change of hands at 60 %	y = 25.29 + 0.18x	0.35	y = 66.90 - 4.54x	0.20
time to first change of hands at 40 %	y = 50.82 + 0.34x	0.39	y = 162.64 - 15.24x	0.68
time to first change of hands at 20 %	y = -87.96 + 2.66x	0.85	y = 524.10 - 64.87x	0.44
time to first change of hands at 15 %	y = 39.25 + 2.52x	0.32	y = 740.34 - 86.77x	0.33
total number of changes at 80 %	y = 2.25 - 0.005x	0.14	y = 0.77 + 0.20x	0.20
total number of changes at 60 %	y = 3.90 - 0.009x	0.30	y = 1.44 + 0.30x	0.33
total number of changes at 40 %	y = 6.47 - 0.019x	0.43	y = 0.69 + 0.76x	0.60
total number of changes at 20 %	y = 12.72 - 0.043x	0.52	y = 0.10 + 1.63x	0.65
total number of changes at 15 %	y = 13.85 - 0.045x	0.43	y = 0.14 + 1.80x	0.60

Table 6-13: Regression equations between 'time to the first change of hand at 30 % of maximal force', 'total number of changes at 30 % of maximal force' and the other discomfort scores.

6.4.6 Implications for the Atlas

Maximal forces. Force exertion can be predicted from other forces exerted. This finding offers various possibilities for the designer who needs to know certain forces exerted by certain subjects.

In the first place, even though only a few variables are measured, much more information can be obtained. If one wishes to know the values of a number of variables that have been investigated previously, but for a different group of subjects, all that is required is to measure a few of the required variables under exactly the same conditions as the previous experiment. With the results of these few variables, the values of the other variables may be determined for the new group as described above.

The predictability of maximally exerted forces can also be exploited when a designer needs to know many variables for a large group of subjects. When one or a few maximal forces exerted by the subjects of this large group are known, a small group of subjects can be asked to exert all maximal forces that the designer is interested in. The values of all maximal force exertions of the larger group can then be predicted from the values of the small group.

It is, of course, impossible to predict a variable for which no previous measurements exist. Also, to enable a force measurement to be repeated exactly, methods should be described exhaustively when the results of force exertion measurements are published. However, this is far from usual practice. Still, the potential is enormous, as it may be possible to obtain results for a large number of variables or subjects from a limited number of force measurements or subjects. Grip force may prove to be an important variable, for it is easy to measure and already often included in experiments. Arm flexion may become an important variable, for it too is easy to measure, and it is the most representative of all the variables.

Maximal endurance times. The relation between maximal endurance on the one side, and maximal endurance times and anthropometric variables on the other, is so erratic as to be of little practical use for prediction purposes. The reproducibility of these measurements, however, is sufficient. They should therefore be measured again every time information is needed for various subject groups in different situations. No significant relation was found to exist between maximal forces and maximal endurance times of relative submaximal forces.

Discomfort scores. Discomfort measurements, especially 'time to the first change of hands', are relevant for design, easily measurable, reproducible, and predictable (just like the maximal forces) with the aid of the regression equation from table 6-13. Disadvantages at this moment are that, as far as we know, 1) before now, no-one has used, or measured, or published, the time to the first change of posture; and 2) it still remains to be shown that measurements of 'time to the first change of hands' can be generalized to other postures.

6.5 Conclusions

The conclusions of this chapter are limited to the analyzed data, which result from the experiments described in chapter 5.

The overall analysis generated the following information:

(Cor)relations between variables. The (cor)relations between variables are best within the group of maximal forces, within the group of anthropometric data, and within the group of discomfort scores. Compared with sources in literature, the correlations between the various variables are relatively good. This applies most to maximal force variables. This finding offers a starting point for further research, for example to examine the hypothesis that the correlations between forces exerted with the same main muscle group are larger than those between forces exerted with different muscles.

Grouping. The grouping of variables in factors and thus characteristics is as expected, i.e. they are divided in maximal forces, maximal endurance times and discomfort scores. This expectation was initially based on the idea that variables of the same type may yield similar results, so there would at least be a dichotomy in maximal forces and endurance times. Based on the outcome of the large correlation coefficient matrix, it was expected that the variables would be divided into anthropometrics, maximal forces, maximal endurance times and discomfort scores. The results of the factor analyses proved these expectations to be right.

Furthermore, there is no significant correlation between the various factors, except between the maximal endurance time factor and the discomfort factor (where r^2 is only 0.17). So we see the expectations more or less confirmed: maximal force, maximal endurance and sensibility for discomfort during submaximal endurance of submaximal force are independent and different personal characteristics.

Maximal endurance times. Characterization for maximal endurance ability and prediction of maximal endurance times proves impracticable. The maximal endurance factor explains only little variance and the correlations between the maximal endurance factor and anthropometrics are not significant. Prediction of maximal endurance times is not possible for the same reason: the variables do not show sufficient correlation.

Both characterization and prediction, however, are very feasible for strength and maximal forces respectively.

Maximal forces. A good characterization according to maximal force exertion is possible. Subjects appear to have a more or less constant z score for their maximally exerted forces, allowing a simple and elegant prediction. This agrees with the expectation that similar variables may be related, based on common genotype, phenotype and condition of muscles, cardiovascular and respiratory systems. Correlation with anthropometric variables is also quite good and even allows the prediction of maximal forces with 92 % explained variance.

Subjects can be characterized according to strength on the basis of the average of the z scores of their exerted maximal forces, or on the basis of sex, tense upper arm girth and Quetelet index.

Discomfort. Subjects can be characterized according to discomfort sensibility on the basis of the first change of hands at 30 % of maximal force, or the number of changes at 30 % of maximal force.

Further research. Many questions still remain and new ones have been generated by this overall analysis. For future 'fundamental' research, the following topics are conceivable:

- an investigation into the correlations between maximal forces exerted by the same main muscles versus the correlations between maximal forces exerted by different muscle groups;
- an investigation into the extent to which standardization of postures affects the correlations between maximally exerted forces.
- an investigation into the way in which the various methods and equipment to measure grip force, e.g. with different grip spans, affect the results. In particular, it should be assessed in what way they affect the ability to predict other maximal forces from the grip force.

For the Atlas, the following investigations are recommended:

- to measure the same maximal forces of various age and ethnic groups, to see whether for these, too, the same characterization of strength (by their z score) and discomfort sensibility (by the 'time to the first change of hand at 30 % of maximal force') is possible.
- to measure many different forces of a small group, after which a few forces of a large group, preferably 'nationwide', can be measured, and other forces predicted from these.
- to further investigate discomfort in order to find out whether the 'time to the first change of hands' measurement can be generalized to other postures, and if so, how the results in other postures can be predicted and how subjects in these other postures can be characterized for discomfort sensibility.

7 Towards an atlas

7.1 Structure of the Atlas

The set-up of the envisaged Atlas of Human Force Exertion for use by designers of consumer products is guided by, amongst others, generalizations from answers to questions that designers asked during the project, by ideas that occurred along the way, by recommendations from handbooks, by general physiological insights, and by newly gained insights resulting from the experiments.

The Atlas is intended to be used by designers, probably with little or no education in the fields of research, statistics, statics or ergonomics, and researchers, probably without any design education at all.

It is proposed that the Atlas be composed of five chapters.

The first chapter is a general introduction to the subject, including directions on how to go about designing for force exertion. This chapter is discussed in 7.2.

The second chapter is a manual on how to go about researching for design. Information is given on how to set up, carry out and analyze one's own small-scale experiment in a design project. In addition it gives some basic education in statics, to get some insight in the way forces work, because the target group of the Atlas includes people like art students and psychologists. This manual is discussed in 7.3.

The third chapter is a summary of literature on the influence of variables on force exertion, e.g. age, sex and so forth. No exerted forces are given, only general trends and ratios. This could be similar to the literature research of chapter 3 in this book, preferably with additional illustrating graphs.

The fourth chapter comprises data on force exertion. Most of these are presented in tables. They are arranged per posture and force direction, and are accompanied by information about the experiments. This idea is worked out in 7.4.

The fifth chapter presents summaries of the data, which are given per posture and force direction. Comparisons between data sets are made, and remarks on the suitability of data for certain purposes are added. This makes the data more easily accessible. Alternatively, these summaries could be distributed through the fourth chapter. A more detailed description is given in 7.4.

7.2 Design for force exertion

In the proposed Atlas, a brief note on the design process must be included to inform both non-designers and designers about the context for which the Atlas is intended. A methodology is described which can contribute towards a product designed for the right force. This methodology is more or less the same for ergonomical design in general. However, because it cannot be presumed that the readers are familiar with this methodology, it must be dealt with extensively in the Atlas, with the emphasis on force exertion. The information in the Atlas, preferably laced with examples, would be the following:

7.2.1 The design process

There is no clear-cut procedure for designing a good product. Some order in the activities is advised, e.g. to begin by collecting and analyzing information, then make a programme of requirements for the future product, next get ideas and make sketches, work out the good ones, select the best of these, deal with the details, make a technical drawing and/or a model, if possible test and evaluate the product and incorporate the results in an improved version. At the same time, it is recognized that designing is a cyclic or iterative process, so e.g. a new idea can create a need for more information, or when looking into the details the basic idea may need to be changed (Roozenburg and Eekels, 1991). This is the design process as it is being taught at the Faculty of Industrial Design Engineering (Delft University of Technology). Designers have been heard to claim that in reality the process is almost always highly chaotic.

Based on the basic process as described above, an attempt is made to establish which steps should be heeded, to end up with a product which allows for the force capacities of the users.

7.2.2 A design process for force exertion

Problem definition. The product to be designed should offer a solution to a certain problem. Nuts need to be cracked because people wish to eat nuts. Food must be stored, transported and should appeal to customers. Grass should not be left to grow too long. These are all problems for which a number of solutions already exist. A good and accurate definition of the problem is essential to come up with an appropriate solution which is as good as possible, given the circumstances. The problem definition should refer to the problem to which the product should be the solution. Defining the problem by stating a solution is not correct. It remains, however, common practice, in particular with principals. They may tell the designer, for example, that the problem is that she has to design a nutcracker, or that the problem is that no lawn mower suitable for elderly people exists. Such a problem definition will not do, for it limits the range of possible solutions. It will result in yet another nutcracker and the umpteenth lawn mower. To defined a problem as a solution (or product) limits creative thoughts that might lead to new, unexpected and unconventional solutions which would be better in the given situation. These solutions do not necessarily involve designed products. Thus, the sale of peeled and cracked nuts is an alternative to the sale of nutcrackers. Also, keeping a sheep or a goat can, in some situations, be a good solution to the problem of long grass. Or perhaps a walking frame with lawn-mowing option for the elderly would be feasible. Another solution can be to change the lawn into maintenance-free paving. Although these are extreme examples, they serve to illustrate the point.

A good problem definition is essential to good design in general, including design geared to force exertion.

Assessment of starting-points. Next the starting-points should be made clear. The function(s) of the product, the target user group, the situation of use and the relevant behaviour of the users should be established or estimated. For example, it makes a great difference whether the future users will be children or adults, male or female, and whether they will wear gloves or not. Will they be able to brace themselves to exert force? On a product that is hand-held and can be manipulated in the best position (like a jam jar), the maximal force that can be exerted is different from that on a fixed object where obstructions can hinder the adoption of the optimum posture. If the product is to be used frequently, this aspect should certainly be taken into account when establishing the maximum force. A product used by a person in a state of panic may demand a different force (and less precision!) of the user than one used for leisure purposes.

So after assessment, it is clear that the target group consists of, for example, the general public aged ten and upwards (all minorities that are able to walk included), that the function of the product is to mow the lawn, that the situation of use is outdoors on a lawn, often in the sun and sometimes in wind and rain, that the users may be wearing a minimum of clothing and footwear, that the product will be used for a period of a few minutes to an hour once every few weeks, that the exerted force will be dynamic, that there is no possibility for the users to brace themselves while exerting force, and that, if the force that has to be exerted is too great, people will buy a motorized lawn mower right away or next time.

Implications for design. Next, the implications for the design should be considered. Some elementary knowledge of physics and human force exertion, and some logical thinking are indispensable. The proposed function of the product should be translated into a function which can be performed optimally by the user. In this view, the product is the concrete intermediate between the two functions. At this stage, the idea is not so much to get down to product ideas already, but rather to list the most favourable ways of exerting force, and to select the best principles. To assess the direction in which to look for good solutions, a few rules of thumb can help. For example, the following generalizations:

More force can be exerted maximally with two hands than with one. More force is exerted maximally when the subjects can brace themselves, against an object or against themselves. When pushing or pulling, most force can be exerted between shoulder and elbow height. Closer to the body, more grip force can be exerted. A long and heavy task can be relieved by including periods of rest between start and finish. Exerting force with use of body weight can make a task more pleasant. The weights of limbs should be taken into account with exertion of smaller forces over extended periods of time; hence sometimes the support of limbs is favoured. In the same way, the larger the movement, the more it should be taken into account as a tiring factor. During force exertion, especially if repeated often or maintained for sustained periods of time, joints should not be in extreme flexed positions. Many of these rules can be found in ergonomic handbooks (see chapter 3).

It is of course impossible to make a complete, comprehensive set of rules. Still, it is important to work with some general rules at first. Assumptions can and ought to be tested in more detail later on. When large amounts of information are gathered right at the start, the process will be too time-consuming. Moreover the designer then runs the risk of being bogged down by an excess of information, resulting in the dreaded state of 'designer's block'.

More important, though, than exact information or any rules of thumb in this first phase, are the creative thoughts and the essential logical reasoning of the designer. This reasoning may result in a schematic idea for the product with the most comfortable, efficient or maximal force exertion.

Assessment of information needed. Once the implications for the design have been considered, it can be inferred which information on force exertion is needed. The users, their postures, the direction of the exerted force, and bracing possibilities are known within certain limits. The resulting forces are distributed over a wide range. Which part of the data distribution do we need to know? The average or the median is generally not very useful. Products designed for the average force cannot be operated by the weaker end of the population distribution, and may be damaged or broken by the strongest users. For design purposes, the weakest users are often more relevant than the strongest, and beginners more so than experienced users. The same applies to the postures and the directions of the exerted forces. It depends on the requirements of the product whether the lower maximally exertable forces, or the higher maximally exertable forces, or maybe both, should indicate the design limits.

It must be emphasized that designing for 'weak' or 'strong' users is not precise enough an indication. In addition to deciding whether the weakest or the strongest users are the most relevant for specific design purposes, the designer has to determine which percentage of users within the expected population the specific design aspect will take into account. In research and literature we are talking percentiles. A designer ought to decide and clearly define which percentile of the chosen population she is designing for: P90, P95 or even P99? Especially with extreme percentiles, this can make an enormous difference for the values involved, and consequently, for the design.

When the population is divided in percentiles, the distribution is defined for one variable, e.g. torque on a ø 25 mm screwdriver, or pull strength at shoulder height, or pinch strength, or body height, or body weight, or lower leg length, or earlobe thickness, and so on. Each person can be represented by a different percentile for different variables. The P3 of the lower arm length of a certain population can be defined, but '*the* P3 of *the* population' does not exist, because the variable concerned should always be specified.

Here again a comment should be made on the widespread habit of quoting the P5 as a 'normal' design maximum. To the annoyance of millions of people, many designers think it is accepted, standard, or even good practice, to exclude the upper or lower five percent (or both) of a population. This 'P5-P95 syndrome' results in products which in the worst cases cannot be effectively, or comfortably, used by about 1.5 million people in the Netherlands, 5.5 million in Great Britain, 22 million in the United States and 110 million in China.

It is important to note that products that are designed for the lower percentiles of the population (where forces are concerned, these are the weaker persons) can be easier to use or operate by the average user. Those products may sell even better to 'normal' users than standard products, because they too appreciate clear, simple features and light operation. Unless, of course, these products get stigmatized as being specially made for the disabled and the elderly. Neither strong nor weak users want to be seen with a product that visibly classifies them as weak. If this negative image can be avoided, products designed for the weak can be a (commercial) success with everyone.

Taking again the example of the lawn mower, one can now look up which force can be exerted, for instance, comfortably for a few minutes up to an hour by 99% of the general public aged ten years and older (all minorities that are able to walk included), pushing horizontally with two hands on a handle with a diameter of, for example, 3 cm, at elbow height while walking (dynamic force!), without bracing themselves. External factors which should be taken into account include clothing, footwear and the weather.

Gathering of information. The required information must be gathered somehow, somewhere. Private research using the right type of subjects and the required postures is advisable in order to obtain the best results. The aim is to reduce design uncertainty, preferably at minimal cost. How research can be set up, carried out and analyzed efficiently is described in the following chapter of the Atlas.

One should never take one's own strength as a measure 'to get an indication'! The large dispersion of data on force exertion (Sanchez and Grieve, 1992; Sanders and McCormick, 1993) goes unnoticed when measurements are limited to one or a few persons. We are none of us the average person, but still there are many designers who presume that if they can exert a certain force, anybody else must be able to do so too.

If private, even small-scale, research is impossible, literature is the alternative, though at best, it will give only an indication of the range of forces involved. Literature can be retrieved from journals, reports and books. Suggestions for journals to browse through are *Ergonomics, Applied Ergonomics, the International Journal of Industrial Ergonomics* and sometimes the journals of national ergonomic societies. In *Ergonomics Abstracts,* titles and abstracts of many journals are gathered. Information on where to order these journals can be included in the Atlas. Conference proceedings are another source of information: *Contemporary Ergonomics* (proceedings of the Ergonomics Society Conference), the *Proceedings of the Human Factors Society Annual Meeting,* the

Proceedings of the Congress of the International Ergonomics Association and the *Proceedings of the Symposium on Human Factors and Industrial Design in Consumer Products (Interface).* Another possible source of information is provided by Ph.D. theses.

When a relevant article is found, references can lead to more related and relevant literature. For a more sophisticated search computer databases are available. Perhaps some information on the use and usefulness of the most accessible computer databases is appropriate.

Caution, however, is required with the application of data from literature. Are the subjects and the experimental setting similar, or at least relevant, to those of the product? Generally, this will not be the case. Consequently, such figures will be tricky to use. They should be applied with the necessary comments and safety margins.

Definition of requirements. When it is known within which limits the product is to function, the programme of requirements can now be extended with requirements concerning force exertion. As with all requirements, those on force exertion should preferably be operational. This means that the requirements can later be tested for approval using dummies or prototypes, for which case clearly defined limits for approval (preferably in concrete figures) must be included in the requirements.

Design. The product now enters the design stage. The requirements are translated into a design for a product, in which they are assimilated as much as possible. Conflicting requirements sometimes lead to the inevitable compromise, a process which is inherent to designing. It is the art of the designer to come up with a good product, despite any conflicts that may have arisen.

Follow-up. The first prototypes should be tested with subjects and evaluated, and the product should, if possible, be improved accordingly. This is important, especially if the information forming the basis for the programme of requirements is obtained from literature.

Examples. In the course of this research project, design students came up with various questions concerning the forces that could be exerted on a product they were asked to design. Questions like these can never receive a standard, ready-to-use answer. Some examples of these questions are described below.

One of the products to be designed was a large professional cheese slicer, as used in supermarkets (see figure 7-1). Present cheese slicers are fitted with a handgrip at the end of a blade that rotates around a pivot. The larger the blade (or the arm of the moment), the less force is needed to slice, but also the larger the movement of the hand. The handgrip is positioned in the same direction as the blade, so that the wrist is in an uncomfortable position when exerting force. The slicer is usually positioned on a table or bench, so that the force is exerted on the handle from about shoulder height to about elbow height. The users are women and men aged between 18 and 65. Instead of trying to find out how much force can be exerted in such a situation, thought is given to a more comfortable way to slice. Suggested improvements include lower positioning of the equipment, so that the force is exerted with the hand at elbow height and lower and body weight can be utilized, and a change of the handgrip so that the wrist need not be flexed to extreme degrees. If possible, the movement should be a translation instead of a rotation, so that force needs to be exerted in one direction only. The optimal length of the arm, weighing the length of the stroke against the force needed to operate the cheese slicer, may be determined experimentally.

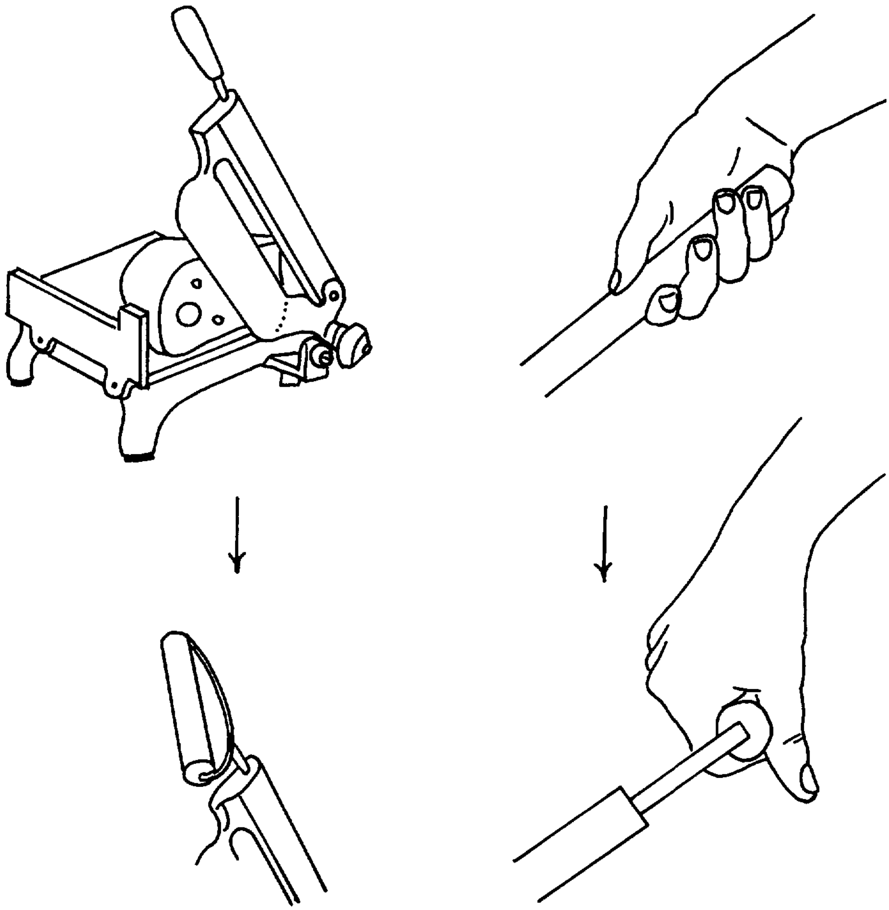


Figure 7-1: Suggestion for improvement of a professional cheese slicer.

Another product was a wheelchair for children in Sri Lanka who suffer from the consequences of polio. Their legs are paralysed, so the vehicle has to be moved by using the arms. How much force can they exert? For some mechanical reason, force was to be exerted in one direction only. Deciding on a force direction based on the direction in which the greatest force can be exerted is in this case not advisable. When pulling in a horizontal direction, the child will tend to pull itself out of the seat, which is uncomfortable and prevents maximal force exertion, even if the subject were to be strapped to the back of the seat. On the other hand, when pushing, the child will be able to brace itself against the back of the seat, which is more comfortable, and allows more force to be exerted. Therefore, if a choice has to be made, pushing against the back of the seat is preferred. It should be noted, however, that to exert force in both directions in a cyclic movement is better for the development of the muscles. Uneven development of muscle groups may lead to incorrect loading of the joints and related problems in the future. The use of two arms instead of one will, of course, allow more force to be exterted, and will also stimulate better physical development in the subject. To know the maximal forces, they should be measured for the actual children concerned. Although there are some data on maximal pushing and pulling abilities of European children in literature, this information can not be used, as it can not be assumed that children who are disabled and children from different ethnic groups exert equal maximal forces.

How much force is exerted on a paper punch? This can easily be measured with a weighing scale on a table. Place the punch on top of it and the exerted force can be read from the scale of the weighing scale. The maximal force that can be exerted is limited by the weight of the user. The results of a small experiment showed that this theoretical maximum is not attained by any of the subjects, their maximal force being slightly lower.

For the design of a portable or rolling easel, information on maximal exertable push, pull and carry forces were asked. The easel is intended to be used for outdoors painting and should be easily transportable by a person on foot. The target group consists of elderly people, so the required force forms an important aspect of the design. Carrying is no option, because it will certainly require more force and energy than simply rolling the easel along. Rather than pushing it, a wheeled object is preferably pulled along because this makes it easier to negotiate ramps and kerbs (this is everyday experience and can be backed up with statics). The force necessary to stabilize and manoeuvre the easel should be as small as possible, because energy and attention should not be diverted from the main activity, pulling the easel along. The question then arises how much force elderly people can exert when pulling something along. If the lowest part of the distribution (say the P_1) of elderly women is included in the target group, the force that can be exerted is near to zero, for these people have barely sufficient strength to walk about unsupported, and will not have much force left to pull easels around. Therefore, the less force is needed to pull the easel, the better. No measuring is needed to come to such a conclusion.

7.3 Research on force exertion for design

The information on how to set up one's own research within the context of a specific design project should be to the point, and consequently one needs a real manual with no more background theory than strictly necessary. In a nutshell, the following information can be useful:

How to set up an experiment. This paragraph deals, among other things, with the difference between explorative research and descriptive or normative research (representative collection of data). The differences between dependent and independent variables should be explained, as well as the need in some cases to control the last. Measure only what you need to know. Measure in free posture if that is appropriate. Measure discomfort by change of posture (although the applicability of this method must still be verified for other postures than investigated for the present project, see 5.4). Methods should be repeatable, and results should be reproducible. Each measurement must be carried out in the same way for all subjects.

How to carry out an experiment. Suggestions are given on how to use simple measuring equipment like scales and spring balances. More expensive equipment is listed too, for instance electronic force transducers with strain gauges and computer programs to calculate and display the results. Brand names and addresses can be given in an appendix. The following may serve as advice on the actual method of measurement to be used. Provide the subjects with clear instructions on the purpose, duration, expectations etc. of the experiment. During the actual exertion of force, allow them a few seconds to increase their force to the required level. If maximal force for a short time is measured, follow the Caldwell regimen (2 s increase, 4 s maximal, the average of the four seconds is the maximal force). Do not encourage the subjects before or during the measurements and do not provide them with any feedback (except during measurement of endurance times). For submaximal forces at a low level (40% of maximum, and less), measurement of maximal endurance can take up to more than half an hour.

Information on the measurement of dynamic force should be added, preferably with the aid of low-budget equipment, e.g. weights moving over a pulley.

How to analyze the results. Basic statistical skills and common sense are needed to make the most of the collected data. Relevant decisions concern: the symmetrical or skewed form of the distribution of data; when to use median or mean, standard deviations and percentiles; the degree in which values such as average and extreme percentiles can be generalized; the number of subjects needed; the difference between the results of two measurements for a group; correlation and relationship; significance.

Statics. Statics are explained in the Atlas to give the reader some insight in the way forces work. This knowledge forms the foundation for logical reasoning which should lead to a good product concept. With knowledge of statics, the reasons behind some of the rules of thumb can be understood. Formulas and exact calculations are to be avoided, because they will put off readers with little patience for mathematics. Emphasis is on discussion of 'action evokes reaction' (explaining the effect of bracing), 'the sum of forces and moments is zero', the influence of the arm on force/moment ratio and such.

7.4 Presentation of data

Data on force exertion consist in general of tables and graphs. In the Atlas they are ordered according to limb(s) used, direction of force, global posture, and, lastly, subject groups and various other experimental conditions, because this is the order in which designers tend to search for data. Relevant information should be added to the tables or graphs. Indispensable information include, for example, literature references (author, title, year, journal or editor), description of subjects (number, sex, age, anthropometric data, and health status and occupation if relevant), direction of exerted force, shape and size of handle or contact surface, position of handle in relation to the subject, posture (if possible with picture), bracing possibilities and method of measurement. All this information is very important. Data lacking much of this information should be excluded, if the Atlas is to become reliable and useful.

Per group of limb, posture and force direction used, a summary is composed to compare the data, to summarize them, to identify any outlying data (which may not be reliable), to identify contradictions, to advise on the use of some data in certain situations, to point at limitations of the data and to indicate where and when caution should be observed. The summaries should be aimed at direct application in design. They can be presented in a separate chapter or alternatively be distributed amongst the data themselves.

Two examples of collected information with subsequently composed summaries are given in appendix C. The first is a collection of data on pushing and pulling in standing and sitting position, the second is a compilation of information on torque on jars and knobs.

7.5 Conclusion: Will an Atlas of Human Force Exertion work?

The question to what extent an Atlas of Human Force Exertion, as described in this chapter, will meet the objectives outlined in chapter 2, should really be answered by future users, i.e. researchers and designers. First the atlas should be made and tested, only then can it be evaluated. We can guess, though, that this Atlas will satisfy a certain need. It will certainly not answer all questions, as previously stated in the demarcation (2.2). It must be emphasized that the general way of considering and approaching force exertion is even more important than specific and accurate data, as proper, logical reasoning will in itself lead to better designs. Probably even the fact that designers are giving the problem serious thought will lead to some improvement. The right data can provide the finishing touch in realizing a good design principle.

It is therefore likely that the idea for an Atlas as outlined above is worth pursuing, in order that it may be realized, tested, evaluated, and eventually (provided it is found to be of practical use) improved, edited and used.

7.6 The Future

In the future, work can be done in two areas. In the first place, research in the same vein as this project can be carried out. In the second place, efforts can be directed towards the production of an Atlas of Human Force Exertion for use by designers of consumer products.

Research into background. Within the framework of objectives of this project, some areas need further research, namely those that have not been investigated in this project for various reasons, as explained in section 4.3, 'Demarcation'. Particular problems to investigate are dynamic force exertion, various groups of individuals and combined forces. Other areas for research are the new questions generated by the present experiments. This suggests the following further research:

- To investigate whether free posture can be applied to measure maximal force in other situations.
- To investigate the correlation between maximal forces exerted with one main muscle, versus the correlation between maximal forces exerted with different muscle groups.
- To investigate whether the degree of standardization of postures influences the correlations between maximally exerted forces.
- To investigate how various methods and equipment for measuring grip force, e.g. using various grip spans, influence the results. The influence on the ability to predict other maximal forces from the grip force should be assessed in particular.
- To investigate the reproducibility of maximal endurance measurements and discomfort (or 'time to the first change of hands') measurements with a larger number of subjects.
- To investigate whether it is possible to apply the formula for maximal endurance time to other forces or situations;
- To investigate whether it is possible to apply the formula for discomfort (or 'time to the first change of hands') to other forces, situations or postures. Actually, two questions should be answered: is it possible to apply the principle to measure the time to the first change in posture to other situations? And if so, can the same formula be used to predict the time to the first change?
- To investigate the influence of various handles and grips on the maximal endurance time and discomfort (or 'time to the first change of hands'). For example, maximal forces exerted with fingers only are generally smaller than those exerted with the whole hand, and those exerted on handles with sharp edges are generally smaller than those exerted on handles with rounded edges. What is the effect on maximal endurance time and discomfort?
- To investigate the effect of the combination of (free) posture and exerted force on maximal endurance time.

- To investigate the effect of the combination of (free) posture and exerted force on discomfort.
- To investigate the maximal forces, maximal endurance times and discomfort measurements for various groups of individuals, including various age and ethnic groups and the disabled. It should be established whether for these too, the same characterization of strength (by z score) and discomfort sensibility (by 'time to the first change of hand at 30 % of maximal force') is possible.
- To investigate combined types of forces, like pushing and turning at the same time. To what extent do these different forces influence each other when they are exerted simultaneously? Can they be predicted from the single forces measured separately?
- To investigate dynamic forces, and to try to find such a way of measuring that the results are useful to designers.

Production of an Atlas. An Atlas can be composed on the basis of the guidelines as outlined in this chapter and in existing literature, e.g. to measure maximal forces in free posture. Also, to measure not only maximal forces, but also maximal endurance times and discomfort. It may be efficient to measure many different forces exerted by a small group of subjects, after which those many forces can be predicted for a large group, preferably nationwide, of which only a few forces have been measured. It is advisable to include a wide variety of subjects regarding age, sex, ethnicity, disability, and occupation. When a first version is produced, it must be tested and evaluated. If it meets with approval, the Atlas can then be improved and experiments can be conducted to obtain more data. Then a final version can be composed. The Atlas will never really be finished though, because it will always require updating with the latest test results.

All in all, this leaves enough work for a number of new projects. Although much work will have to be done, the aim is well-defined and definitely feasible. Human-product interaction ought to be a major concern for designers, manufacturers and day-to-day users of products and, as we have seen, adequate and proper force exertion is very often a relevant and critical aspect. The proposed Atlas when realized may well prove to be a major contribution towards improving the comfort, safety and effiency of the many products in our man-made culture.

Summary

Introduction

The world is full of products and crowded with people using them. Between these products and their users, various types of interactions exist. One of these categories comprises the forces that the users consciously exert on a product. Take for example a product often handled in daily life: a jam jar. Jam jar lids stick tightly to the glass as the result of the vacuum in the jar. Consequently, so much force is needed to open the jar that it exceeds the ability of many people, who must resort to some trick or another to succeed. This is just one example of user-product interaction in which the design is clearly unsuited to the purpose of object or to the force capabilities of the user.

User posture and the size and direction of the force needed to use or operate products should be such that products will be as safe, efficient and comfortable to use as possible for all groups of intended users. Weak users should be able to use the product comfortably, while at the same time the strongest should not inadvertently damage it. In order to be able to tailor a new product to the capacities of the future users, designers should know about the force characteristics of their target group and about general rules of human force exertion.

An 'Atlas of Human Force Exertion', containing all possible information relevant to (consumer) product design does not yet exist and would be of great value to designers. Until now the information on force exertion which is relevant to design is limited and scattered. Most literature on force exertion deals with the areas of occupational ergonomics, medical (rehabilitation) research, and fundamental scientific interest. Most of these investigations generate information that is of little or no use to designers. Therefore, specific research for consumer product design is needed, and all relevant information should be gathered with directions on how to use it.

Objective

The aim of this project is to provide a set-up for such an Atlas of Human Force Exertion. To do so, it is necessary to find out which information is of use to designers and which research methods should be used to generate this information. In addition, the aim is to try to find ways to make generation of data for the Atlas more efficient. This can, for example, be done by using a limited set of data to predict many more.

Some data for the Atlas can be generated as spin-off from the research with the above-mentioned objectives, although it is not the first aim of this project to collect a wealth of data to complete an Atlas.

Literature

At least 35 variables affect the force that can be exerted by an individual. These can be divided into subject variables, product variables, environment variables and interaction variables. The designer should estimate the characteristics of subjects, environments and interactions, and tailor the new product accordingly.

From literature, both concrete data and general trends can be deducted. In the present literature research, information on the influence of the various variables on force exertion is gathered, with emphasis on general trends.

Information found included, for example, the following:
- Maximal force exerted by females is about two-thirds that exerted by males.
- Gloves generally limit maximal force exertion.
- Maximal force exertion with support exceeds exertion without support.
- Anthropometric variables sometimes show significant correlation, though not very good, with maximal force and endurance times.

Approach
First, literature on the subject of force exertion was studied, and lacunae in the area of force exertion relevant to design identified. Then, areas were chosen in which to conduct investigations for this project. Research was then carried out on four topics which were not explicitly related other than through the interest of their results to the Atlas. With all the data gathered in these experiments, an overall analysis was carried out to look for connections and relations between the many variables measured. Last but certainly not least, a proposal was made for the set-up of the envisaged Atlas.

The four areas of research were:

- *Static force exertion in postures with different degrees of freedom.*
  Research on force exertion is generally carried out with the subjects assuming fixed, standardized postures. The reason for this is that the information is supposed to be reproducible only when generated in this way, but these results are generally not very useful for design purposes.

- *Comparison of moments exerted round one or more joints in the arm.*
  No literature could be found on the influence of the number of participating arm-segments on the maximally exertable force. Nor could information be found on the correlations between different forces exerted with the same main muscle (in this case the biceps), which might provide a lead for predicting one force from another.

- *Maximal endurance during submaximal, static force exertion.*
  Although there is some information on maximal endurance of submaximal force exertion, the various results often are divergent or even contradictory. Often, forces are exerted on products for more than a few seconds, so information on endurance can be very useful to designers.

- *Discomfort during static, submaximal force exertion.*
  Discomfort is a subject which has hardly been investigated, and no standardized method exists to assess and thus define the concept. This subject is important to designers because consumer products require comfortable forces more often than maximal forces.

Experiments
Static force exertion in postures with different degrees of freedom.
In assessing human force exertion, the use of standardized postures can lead to

inaccurate prediction of the forces and postures which occur in everyday life. Therefore force data obtained using postures freely chosen by the subjects themselves may be considered more relevant. A standardized posture, however, is generally considered to yield more reproducible data. The question arose whether it would be possible to combine the two in some way, calling the result a 'functional posture'. Research was necessary to determine a way of making these functional postures suitable for operational use, and to test their reproducibility.

First, a method is proposed to describe functional postures through explorative research. This includes the fixation of members that transfer force to the outside world while the rest of the body is allowed to move freely. The results of further research show that the exerted force is reproducible in free, functional and standardized postures. The difference in average force, though, is considerable and significant. Furthermore, force exertion in free posture with the handle at extreme heights, and force exerted on jam jars without any restriction on posture at all, proved to be equally reproducible. The conclusion is that force exertion in free posture is most suitable for design research.

Comparison of moments exerted round one or more joints in the arm.
The purpose of this research is to investigate a possible difference between moments exerted over one, two or three joints, and a possible difference between moments exerted round a joint in single and in multi-joint force exertions. In addition the aim is to establish the correlation coefficients between moments. Twenty-six female and male subjects exerted static flexion round wrist, elbow or shoulder separately, or round a combination of these. They did so with their arm in three different positions.

The results showed that reproducibility of forces is very good. A tendency can be seen towards larger moments and smaller forces if more joints participate. Furthermore, a correlation coefficient matrix showed that all correlations between moments were positive and nearly all were significant. Moments round a joint that is proximal during force exertion were at least as large as, and generally larger than, those round the same joint when not proximal. The weakest part of the chain would seem to be the proximal joint (in this case the shoulder), and consequently the force exertion of the whole arm would not be limited by the strength of the elbow or wrist in the postures researched.

Maximal endurance during submaximal, static force exertion.
The objective of this research was to measure maximal endurance time during force exertion and investigate factors influencing it, and to gather information on the subjective experience of discomfort, with the aim of establishing 'discomfort zones' for use by designers. The concept and investigation of discomfort is discussed in section 5.4. Twenty-four healthy subjects (female and male, two different age groups) participated. Force was exerted in four different ways: pushing with one hand, anteflexion of a shoulder, flexion of one knee, and extension of the other knee. The maximal endurance time was measured at six different relative force levels (80 %, 60 %, 40 %, 30 %, 20 % and 15 % of maximal force during 4 s). During force exertion, information was gathered on the perception of discomfort by the subject. To assess the reproducibility of the experiment, it was repeated by ten of the subjects.

Endurance was found to be satisfyingly reproducible, and to be slightly shorter for arms than for legs, though generally much longer than predicted from the load/endurance formulas found in literature. The main factors influencing endurance time were the subjects themselves and the force level involved. With forces ranging from 80 to 30 % of maximal force, age and sex had no effect on the results. Both the endurance time and the significance of the influence of the use of arm or leg on endurance, however, depended on the way the maximal force was established c.q. defined. It is proposed that maximal force for endurance measurements be measured without feedback or encouragement, while endurance time of submaximal force be measured with feedback. Two formulas, for arm and leg muscles, describe the force level-endurance relationship between 15 and 80 % of maximal force, based on the median of the present data. To predict maximal endurance in practice, however, additional factors beside muscle endurance must be taken into account.

Discomfort during static, submaximal force exertion. The degree of discomfort during force exertion has been little investigated in literature. In daily life, however, comfort is an important aspect when using or operating products. It would therefore be useful for designers to know about the subjective experience of (dis)comfort during the exertion of submaximal forces by users of products. No standard measurement methods were found in literature. Two experiments were carried out, using different methods.

The first experiment was combined with the measurement of endurance time at different force levels and in four different postures. Subjects were asked every half minute to rate the discomfort they experienced on a five-point scale. Alas, the results generated by this method were found to be insufficiently reproducible.

The second experiment was set up in such a manner as to prevent subjects thinking explicitly about their (dis)comfort. This time, only one posture was investigated (pushing with the arm) and a spontaneous change of arm was taken as an indication of discomfort. The time to the first change increased consistently with lower force levels and these results proved to be sufficiently reproducible. Therefore this measurement method is recommended to get an idea about the level of discomfort experienced by subjects. A formula is given to indicate the relation found between the force level and the median of the time to the first change of hand.

Overall analysis

The data collected from the experiments were maximal forces, maximal endurance times, discomfort scores and anthropometric measures. To gain insight into the (cor)relations between the measured variables of the different categories and within each of these categories, an overall analysis was performed. With a good relation between variables, it may be possible to predict many variables on the basis of one variable, or a few. For the Atlas this means that little effort only is needed to retrieve a lot of information and offer it to the user. Furthermore, insight into the relation between groups of variables may help further research.

A large correlation coefficient matrix with 77 variables revealed that the best correlations were found within each of the categories of anthropometry, maximal force and discomfort scores. Within these categories, 74 to 99 % of the correlations were significant at $p \leq 0.05$ and 23 to 60 % were larger than or equal to 0.71.

Factor analysis of all 77 variables for 19 subjects revealed that a three factor solution gave the most plausible results. The variables in the three factors could be categorized as 'maximal force', 'maximal endurance times' and 'discomfort scores', respectively.

Three separate factor analyses for maximal forces, endurance times and discomfort scores each time resulted in a one factor solution of which the factor characterized the group. The maximal force factor explained 73.3 % of the total variance and could be predicted by either the average of the z-scores per group for each subject, or from sex, tense upper arm girth and Quetelet index with a regression line. The maximal endurance time factor explained only 39.7 % of the total variance and could not be predicted. The discomfort factor explained 58.5 % of the total variance and could be predicted from the elbow height with an r^2 of 0.29.

Maximal forces per subject can be predicted by the average z-score of a few measured maximal forces. Maximal endurance times cannot be predicted. Discomfort scores can be predicted from 'time to the first change of hands at 30 % of the maximal force', with regression equations.

The variables that can be predicted may be useful both for the Atlas and for researchers who investigate similar problem areas.

Towards an Atlas

It is proposed that the Atlas of Human Force Exertion for Designers be composed of five chapters:

The *first chapter* contains a general introduction to the subject, including directions on how to go about designing for force exertion. The general way of considering and approaching force exertion is even more important than specific and accurate data, as proper, logical reasoning on the basis of a few principles and qualitative guidelines will in itself lead to better designs. This chapter therefore contains what can be considered the main instructions for designers.

The *second chapter* is a manual on how to go about researching force exertion for design, including basic information about research, statics and statistics.

The *third chapter* is a summary of literature on the influence of variables on force exertion.

The *fourth chapter* comprises data on force exertion. Most of these are presented in tables. They are arranged per posture and force direction, and are accompanied by information about the experiments.

The *fifth chapter* presents summaries of data per posture and/or force direction. Comparisons between data sets are made, and remarks on the suitability of data for certain purposes are added.

An example of the information that may be given in chapter 4 and 5 of such an Atlas can be seen in Appendix C.

It is very likely that the Atlas, as described here, will satisfy a need and will contribute significantly to the design of products which allow safer, more efficient and more comfortable force exertion. However, the actual assessment can only follow after production and subsequent use of the Atlas, as with any other product.

Samenvatting

Introductie

De wereld om ons heen is voor een belangrijk deel gevuld met industrieel vervaardigde produkten. Iedereen gebruikt ook dagelijks produkten en bij dat gebruik vinden er allerlei soorten interacties tussen mens en produkt plaats. Een van die interacties is het uitoefenen van kracht door gebruikers op produkten. De jampot is een voorbeeld van een produkt dat vaak 'gebruikt' wordt in het dagelijks leven. Het ongeopende deksel zit vast, omdat er onderdruk in de pot heerst. Daardoor is er zoveel kracht nodig om de pot te openen dat een groot aantal mensen daar niet toe in staat is en allerlei trucs, hulpmiddelen of zelfs hulp van derden nodig heeft. Dit is slechts één voorbeeld van interactie waar krachtuitoefening bij is betrokken en waar het ontwerp duidelijk niet gericht is op het openen, noch afgestemd is op de capaciteiten van alle gebruikers.

De grootte, houding en richting van de krachtuitoefening die nodig is om produkten te kunnen gebruiken of bedienen, moet zodanig zijn dat het veilig, efficiënt en comfortabel is voor alle toekomstige gebruikers. Zwakke gebruikers moeten in staat zijn om een produkt comfortabel te gebruiken, terwijl de sterkste gebruikers het tegelijkertijd niet per ongeluk kapot mogen maken. Om een nieuw produkt te kunnen afstemmen op de capaciteiten van de toekomstige gebruikers, moeten ontwerpers weten hoeveel kracht hun doelgroep kan uitoefenen en welke algemene regels over het uitoefenen van krachten er bekend zijn.

Een 'Atlas met Menselijke Krachten', waar zoveel mogelijk relevante informatie in staat die gebruikt kan worden bij het ontwerpen van produkten, zou zeer waardevol zijn voor ontwerpers, maar bestaat op dit moment nog niet. Tot nu toe is de krachten-informatie die relevant is voor ontwerpen dun gezaaid. De meeste literatuur over krachtuitoefening wordt gevonden op het gebied van de arbeidsergonomie, medisch (revalidatie) onderzoek en fundamenteel onderzoek. Dergelijk onderzoek levert informatie op die vaak niet zo bruikbaar is voor ontwerpers. Daarom is het nodig om onderzoek te doen speciaal voor produktontwerpen. Alle relevante informatie zou, samen met een uitgebreide gebruiksaanwijzing, verzameld moeten worden in een 'Krachtenatlas'.

Doel

Het doel van dit project is het maken van een opzet voor een dergelijke Krachtenatlas. Hiervoor is het nodig uit te vinden welke informatie bruikbaar is voor ontwerpers, en welke onderzoeksmethoden het beste gebruikt kunnen worden om deze informatie te verkrijgen. Daarnaast is het de bedoeling manieren te vinden om het verzamelen van data voor de Atlas efficiënter te maken. Dit kan bijvoorbeeld gebeuren door uit een paar data een aantal anderen te voorspellen.

Een aantal gegevens voor de Atlas kan gegenereerd worden als nevenresultaat van het onderzoek dat is opgezet met bovengenoemde uitgangspunten, hoewel het verzamelen van data voor het vullen van een Atlas dus niet het eerste doel van dit project is.

Literatuur
De kracht die kan worden uitgeoefend door een persoon wordt beïnvloed door ten minste 35 variabelen. Deze kunnen worden verdeeld in persoonlijke variabelen, produktvariabelen, omgevingsvariabelen en interactievariabelen. De ontwerper moet de eigenschappen van de personen, omgevingen en interacties inschatten en daar het te ontwerpen produkt op aanpassen.

Uit de literatuur kunnen zowel concrete data als algemene trends worden gehaald. Door middel van uitgebreid literatuuronderzoek is informatie verzameld over de invloed van de verschillende variabelen op krachtuitoefening. De nadruk lag hierbij op algemene trends.

Het soort infomatie dat werd gevonden was bijvoorbeeld:
- vrouwen oefenen ongeveer tweederde van de maximale kracht uit die mannen uitoefenen;
- handschoenen beperken over het algemeen maximale krachtuitoefening;
- maximale krachtuitoefening is groter, als men een steun heeft om tegen af te zetten, dan zonder steun;
- antropometrische variabelen correleren soms significant, maar niet erg goed, met maximale krachten en volhoudtijden.

Aanpak van het project
Eerst is er literatuur over krachtuitoefening verzameld en bestudeerd (zie hierboven) en zijn er lacunes op het gebied van krachtuitoefening voor ontwerpers opgespoord. Daarna zijn de gebieden gekozen waarin nieuw empirisch onderzoek zouden kunnen worden gedaan. Vier onderwerpen werden geselecteerd en in het laboratorium onderzocht. Deze onderwerpen stonden niet direct in relatie met elkaar, maar waren wel elk van belang voor de Krachtenatlas. Na deze vier onderzoeken werd er met de gezamenlijke resultaten een overkoepelende analyse uitgevoerd, om te kijken of er relaties tussen de gemeten variabelen konden worden gevonden. Tenslotte word er een voorstel gedaan voor de opzet van de beoogde Krachtenatlas.

De vier onderzochtte onderwerpen zijn:

- *Maximale statische krachtuitoefening in houdingen met verschillende mate van vrijheid.*
  Onderzoek naar krachtuitoefening is meestal uitgevoerd met proefpersonen in een vaste, gestandaardiseerde houding. Dit wordt gedaan omdat de resultaten die op die manier verkregen worden reproduceerbaar zijn, maar ze zijn niet erg relevant voor ontwerpers.

- *Vergelijking van momenten die uitgeoefend worden rond één of meer gewrichten in de arm.*
  Er kon geen literatuur worden gevonden over de invloed van het aantal armsegmenten dat deelneemt aan de krachtuitoefening op de maximaal uit te oefenen kracht. Ook kon er geen informatie worden gevonden over de correlaties tussen verschillende krachten die hoofdzakelijk worden uitgeoefend met dezelfde spier (in dit geval de biceps), wat een aanknopingspunt zou kunnen zijn voor het voorspellen van die krachten uit elkaar.

- *Maximale volhoudtijd van submaximale krachten.*
  Hoewel er literatuur is gevonden over onderzoek naar maximale volhoudtijd van

submaximale krachten, lopen de resultaten nogal uiteen of spreken elkaar soms zelfs tegen. Veel krachten op produkten worden in het dagelijks leven langer dan een paar seconden volgehouden, en daarom kan informatie over volhoudtijden nuttig zijn voor ontwerpers.

- *Discomfort tijdens statische, submaximale krachtuitoefening.*
  Discomfort is een onderwerp dat nauwelijks onderzocht is en er bestaat geen gestandaardiseerde methode om discomfort te meten en daarmee te definiëren. Dit is een belangrijk onderwerp voor ontwerpers omdat comfortabele krachtuitoefening vaker gewenst is bij consumentenprodukten dan maximale krachtuitoefening.

Experimenten

Maximale statische krachtuitoefening in houdingen met verschilende mate van vrijheid.
Bij het bepalen van menselijke krachten kan het gebruik van gestandaardiseerde houdingen leiden tot onjuiste voorspelling van de krachten en houdingen die in het dagelijks leven voorkomen. Krachten gemeten in houdingen die door de proefpersonen zelf zijn gekozen, zijn wellicht relevanter voor ontwerpers. Een gestandaardiseerde houding wordt echter in het algemeen geacht beter reproduceerbare data op te leveren. De vraag werd gesteld of het mogelijk zou zijn de twee te combineren tot een zogenaamde 'functionele houding', die aan alle voorwaarden zou voldoen. Er werd onderzoek gedaan om deze functionele houdingen te bepalen en om hun reproduceerbaarheid te testen.

Na een eerste, oriënterend, experiment werd een voorstel gedaan voor een methode om zogenoemde 'functionele houdingen' te beschrijven. Deze methode houdt in dat de plaatsen waar kracht wordt overgebracht van de persoon op de wereld (handvat, vloer en dergelijke) vastliggen, terwijl de houding van de proefpersoon voor de rest vrij is. De resultaten van het tweede experiment laten zien dat de uitgeoefende kracht reproduceerbaar is in vrije, functionele èn standaard houdingen. Het verschil in uitgeoefende maximale kracht is echter aanzienlijk en significant. Verder werden krachten gemeten in vrije houding met de handvatten op extreme hoogten, en in een derde experiment ook torsiekracht op jampotjes zonder enige restrictie op de houding. In alle gevallen waren de resultaten goed reproduceerbaar. De conclusie is dat krachtuitoefening in vrije houding het meest geschikt is voor onderzoek voor ontwerpen.

Vergelijking van momenten die uitgeoefend worden rond één of meer gewrichten in de arm.
Het doel van dit onderzoek is het onderzoeken van een mogelijk verschil tussen momenten die worden uitgeoefend over één, twee of drie gewrichten, en een mogelijk verschil tussen momenten die worden uitgeoefend om een gewricht in een krachtuitoefening met één of meer gewrichten. Daarnaast is het doel om de correlatiecoëfficiënten tussen de momenten te bepalen. Zesentwintig vrouwelijke en mannelijke proefpersonen oefenden statische flexiekracht uit rond pols, elleboog en schouder apart, en rond combinaties daarvan. Ze deden dat met de arm in drie verschillende houdingen.

De resultaten lieten zien dat de reproduceerbaarheid van de krachten goed is. Er is een tendens naar grotere maximaal uitgeoefende momenten en kleinere gemeten krachten naarmate er meer gewrichten deelnemen. Verder waren alle correlaties tussen de momenten positief en bijna allemaal waren ze significant. Maximale momenten om een gewricht dat, van de gewrichten die bij de krachtuitoefening betrokken zijn, proximaal (het dichtst bij het lichaam) is, waren minstens zo groot als en meestal groter dan de maximale momenten die rond hetzelfde gewricht werden uitgeoefend als het niet proximaal was. Het zwakste stuk van de keten lijkt dus het proximale gewricht te zijn (voor de hele arm is dit de schouder), en daardoor wordt de maximale krachtuitoefening van de hele arm in de hier onderzochtte houdingen bepaald door de sterkte van de schouder en niet beperkt door de sterkte van elleboog of pols.

Maximale volhoudtijd van submaximale statische krachten.
Het doel van dit onderzoek was om de tijd te meten dat krachtuitoefening maximaal kan worden volgehouden en de factoren te onderzoeken die die maximale volhoudtijd beïnvloeden. Een ander doel was om informatie te verzamelen over de subjectieve discomfort ervaringen van de proefpersonen, om daarmee 'discomfort zones' vast te kunnen stellen die gebruikt kunnen worden door ontwerpers. Het onderzoek naar discomfort is beschreven in een aparte paragraaf. Vierentwintig gezonde proefpersonen (vrouwen en mannen, twee verschillende leeftijdsgroepen) deden mee aan het experiment. Zij oefenden kracht uit op vier manieren: duwen met één hand, anteflexie van één schouder, flexie van één knie en extensie van de andere knie. De volhoudtijd werd gemeten bij zes verschillende relatieve krachtniveaus (80 %, 60 %, 40 %, 30 %, 20 % en 15 % van de maximale kracht gedurende 4 s). Tijdens de krachtuitoefening werd de proefpersonen gevraagd naar de mate van discomfort die zij voelden. Om de reproduceerbaarheid te kunnen beoordelen werd het experiment door tien proefpersonen herhaald.

De maximale volhoudtijd was voldoende reproduceerbaar en voor de armen enigszins korter dan voor de benen. De volhoudtijden waren in het algemeen veel langer dan de tijden die voorspeld worden door formules uit de literatuur. De belangrijkste factoren die maximale volhoudtijd beïnvloedden waren de proefpersonen zelf en het krachtniveau. Bij krachten van 80 % tot 30 % van de maximale kracht hadden leeftijd en geslacht geen invloed op de resultaten.

Zowel de volhoudtijd zelf als de significantie van de invloed van het gebruik van arm of been op de volhoudtijd, hingen echter af van de manier waarop de maximale kracht gedefiniëerd, c.q. gemeten was. Er wordt voorgesteld om maximale kracht voor het meten van volhoudtijden te meten zonder terugkoppeling of aanmoediging, terwijl maximale volhoudtijd van submaximale kracht daarentegen gemeten zal worden mèt terugkoppeling. Twee formules, een voor armspieren en een voor beenspieren, beschrijven de relatie tussen krachtniveau en maximale volhoudtijd van 15 tot 80 % van de maximale kracht. De formules zijn gebaseerd op de mediaan van de resultaten van het eigen onderzoek. Om de maximale volhoudtijd in de praktijk te kunnen voorspellen moet echter ook met andere factoren rekening worden gehouden.

Discomfort tijdens statische, submaximale krachtuitoefening.
De mate van discomfort tijdens krachtuitoefening is weinig onderzocht in de literatuur. In het dagelijks leven daarentegen is comfort een belangrijk aspect bij het bedienen of gebruiken van produkten. Daarom zou het nuttig zijn voor ontwerpers iets te weten over de subjectieve ervaringen op het gebied van (dis)comfort van gebruikers tijdens het uitoefenen van submaximale krachten. In de literatuur werden geen gestandaardiseerde

meetmethodes gevonden. Er werden twee experimenten uitgevoerd, waarbij verschillende methodes werden gebruikt.

Het eerste experiment werd gecombineerd met de metingen van volhoudtijd bij verschillende krachtniveaus en in vier verschillende houdingen. Iedere halve minuut werd aan de proefpersonen gevraagd hoeveel last ze hadden, aan te geven op een vijfpunts schaal. De resultaten die op deze wijze werden verkregen, bleken helaas niet voldoende reproduceerbaar te zijn.

Het tweede experiment was zo opgezet dat de proefpersonen niet expliciet over hun gevoelens hoefden na te denken. Dit keer werd slechts in één houding gemeten (zittend duwen met één arm) bij dezelfde krachtniveaus als in het experiment met volhoudtijd. Nu werd een spontane verandering van hand werd genomen als indicatie voor discomfort. De tijdsduur tot de eerste wisseling van hand werd consequent langer bij lagere krachtniveaus en deze resultaten waren voldoende reproduceerbaar. Vandaar dat deze meetmethode aanbevolen wordt om een idee te krijgen van het discomfort dat ervaren wordt door de proefpersonen. De relatie tussen het krachtniveau van 15 tot 80 % en de medianen van de tijdsduur tot de eerste wisseling van hand wordt weergegeven in een formule.

Overkoepelende analyse

De verzamelde data van de experimenten bestonden uit maximale krachten, maximale volhoudtijden, discomfort scores en antropometrische maten. Om inzicht te krijgen in de (cor)relaties tussen de gemeten variabelen van verschillende en dezelfde categoriën, werd er een overkoepelende analyse uitgevoerd. Indien er een goede relatie is tussen variabelen, dan is het wellicht mogelijk om met behulp van één of enkele variabelen een aantal andere te voorspellen. Dat zou voor de Atlas betekenen dat met relatief weinig inspanning veel meer informatie kan worden verkregen en aan de gebruiker van de Atlas kan worden aangeboden. Bovendien kan inzicht in de relaties tussen verschillende groepen van variabelen toekomstig onderzoek verder helpen.

Een grote matrix van correlatiecoëfficiënten met 77 variabelen liet zien dat de beste correlaties gevonden werden binnen elk van de categoriën antropometrische maten, maximale krachten en discomfort scores. Binnen deze categoriën waren 74 tot 99 % van de correlaties significant met $p \leq 0{,}05$, en 23 tot 60 % waren groter dan of gelijk aan 0,71.

Een factor analyse van alle 77 variabelen voor 19 proefpersonen liet zien dat een drie-factor-oplossing de best verklaarbare resultaten gaf. De variabelen in de drie factoren konden respectievelijk worden benoemd als 'maximale krachten', 'maximale volhoudtijden' en 'discomfort scores'.

Drie aparte factor analyses, de eerste voor maximale krachten, de tweede voor maximale volhoudtijden en de derde voor discomfort scores, leverden elk een één-factor-oplossing. De maximale-kracht-factor verklaarde 73,3 % van de totale variantie en kan worden voorspeld door het gemiddelde van de z-scores ten opzichte van de groep voor iedere proefpersoon, of door een regressielijn met behulp van geslacht, gespannen bovenarmomtrek en Quetelet index. De maximale-volhoudtijd-factor verklaarde slechts 39,7 % van de totale variantie en kan niet goed worden voorspeld. De discomfort-factor verklaarde 58,5 % van de totale variantie en kan worden voorspeld uit de elleboghoogte met een r^2 van 0,29.

Maximale krachten kunnen voor een individu worden voorspeld door de gemiddelde z-score van een paar gemeten maximale krachten. Maximale volhoudtijden kunnen dus slecht worden voorspeld. Discomfort scores kunnen met behulp van regressievergelijkingen voorspeld worden uit de 'tijdsduur tot de eerste wisseling van hand bij 30 % van de maximale kracht'.

De voorspelbare variabelen kunnen zowel bruikbaar zijn voor de Krachtenatlas als voor onderzoekers die vergelijkbare onderwerpen onderzoeken.

Naar een Krachtenatlas
De Atlas met Menselijke Krachten voor Ontwerpers zou kunnen bestaan uit vijf hoofdstukken.

Het *eerste hoofdstuk* is een algemene introductie van het onderwerp, inclusief aanwijzingen hoe een ontwerper in het ontwerp rekening kan houden met menselijke krachten. De manier, waarop krachten in een ontwerp worden benaderd, is belangrijker dan specifieke en precieze data, omdat logisch redeneren op basis van een aantal principes en kwalitatieve richtlijnen alleen al zal leiden tot betere ontwerpen. Dit hoofdstuk van de Krachtenatlas kan daarom gezien worden als de belangrijkste instructie voor de ontwerper.

Het *tweede hoofdstuk* is een handleiding voor het onderzoek doen naar krachtuitoefening voor ontwerpen, inclusief onontbeerlijke informatie over onderzoek, statistiek en statica. De Atlas is bedoeld voor een breed publiek, en moet daarom over deze onderwerpen informatie verschaffen waarvoor geen voorkennis vereist is.

Het *derde hoofdstuk* bestaat uit een samenvatting van literatuur over de invloed van diverse variabelen op krachtuitoefening. Een aantal principes en richtlijnen zouden als 'vuistregels' kunnen worden opgenomen.

Het *vierde hoofdstuk* omvat data op het gebied van krachtuitoefening zelf. De meeste gegevens worden gepresenteerd in tabellen. Ze zijn gerangschikt per houding en krachtrichting, en worden vergezeld van informatie over de experimenten.

Het *vijfde hoofdstuk* bestaat tenslotte uit samenvattingen van data per houding en/of krachtrichting. Vergelijkingen tussen datasets worden daarin gemaakt, en de geschiktheid van data voor bepaalde toepassingen dient te worden aangegeven.

Een aanzet tot de informatie, die in hoofdstuk 4 en 5 van een dergelijke Krachtenatlas zou kunnen worden gegeven, wordt gepresenteerd in Appendix C. Deze uitgebreide verzameling gegevens over trek-, duw- en torsiekrachten kan, mits op de juiste wijze gebruikt, een ontwerper reeds een eind op weg helpen.

Het is waarschijnlijk dat de Krachtenatlas, zoals die hier is beschreven, in een behoefte zal voorzien en significant kan bijdragen aan produkten die veiliger, efficiënter en comfortabeler krachtuitoefening toestaan. De Krachtenatlas kan echter pas werkelijk beoordeeld worden na uitgave en gebruik.

Appendices

A Specification of equipment

Hardware

The hardware of the system to measure human force exertion consists of the following parts:

- a *large metal frame*, to which two *force transducers* with strain gauges are attached. Both force transducers are manufactured by Hottinger Balwin Messtechnik. The push/pull transducer is model U2A (maximal load 200 kg); the torque transducer is model T4A (maximal load 100 Nm).
- two *amplifiers*, manufactured by Peekel. 'Transducer strain indicator type CA 690';
- an adaptor to convert and limit the signals before they enter the computer (input range 0 - 1000 mV, output range 0 - 1800 mV), designed and built by Rob den Breejen;
- a *computer*, Archimedes 310, with colour monitor and A/D converter (8 bits, input range 0 - 1800 mV);
- a *dot matrix printer*;
- a *plotter*, Hewlett-Packard 7475A;
- an *x-t recorder;*
- a *video recorder* and *monitor.*

Software

The 'BDForces' computer program visualizes signals that enter the computer, processes them and saves the results. The following elements can be set:

To be set before a measurement:

- starting period: 0 - 3 seconds;
- measuring period: 1, 4, 20 seconds and endurance measurement;
- end period: 0 - 3 seconds;
- sampling frequency: 1 - 50 samples per second;
- maximal deviation: 5 - 50 %;
- amplification factor: (with maximal force/moment and step size)

transducer scale 1000,	1800 N / 120 Nm	(7.06 N / 0.47 Nm);
transducer scale 2000,	900 N / 60 Nm	(3.53 N / 0.24 Nm);
transducer scale 3000,	600 N / 40 Nm	(2.35 N / 0.16 Nm);
transducer scale 5000,	360 N / 24 Nm	(1.41 N / 0.09 Nm);
transducer scale 6000,	300 N / 20 Nm	(1.18 N / 0.08 Nm);
transducer scale 10000,	180 N / 12 Nm	(0.71 N / 0.05 Nm).

Variables to be entered:

- force direction: push/pull/clockwise torque/anti-clockwise torque;
- posture: 1 - 5;

- handle: 1 - 5;
- height: 1 - 5;
- laterality: left/right/both.

To be set for endurance measurement:

- maximal force/moment (N/Nm): 100 - 600 N / 6 - 40 Nm;
- force preset (% of maximal force/moment): 10 - 90 %;
- alarm limit (% of set force): 5 - 50 %;
- end limit (% of set force): 5 - 50 %.

Per measurement, the following information is produced:

- Output with normal force measurement:
  graph showing the force by time;
  minimal force/moment (N/Nm);
  maximal force/moment (N/Nm);
  average force/moment (N/Nm);
  standard deviation (N/Nm).
- Output with endurance measurement:
  endurance time (s).

The results and data of both normal force and endurance measurements are saved (and can be retrieved)

B Pre-experiment instructions

Pre-experiment instruction, 5.4

Endurance time, changing hands

Subject's posture:	seated back in the chair, elbow at an angle of approx. 120°, lower arm horizontal (supported).
Location of handle:	centrally in front of the body.
Force to be exerted:	push with one hand, changing of hands permitted.

The purpose of this experiment is to investigate the exertion of force at different levels of force. First, the maximal force you are able to maintain during four seconds is measured. You will then be asked to maintain a certain force (80 %, 60 %, 40 %, 30 %, 20 % and 15 % of the maximal force measured) with one hand for extended periods of time. These times vary from 1 minute to 30 minutes, depending on the force level. You are however, permitted to change hands if you experience discomfort* in the arm/hand used to exert force.

On a monitor screen, you will be able to see how great a force you are expected to exert: when pushing, try to keep the recorder pen as close as possible to the arrow mark, i.e. try to minimize fluctuations. When you change hands, release the handle completely before grasping it with the other hand. This will be practised once before starting the experiment.

During the experiment you may ask questions if something needs explaining. Apart from this, conversation will be discouraged in order to prevent it affecting the results of the experiment in any way. For the same reason, you are asked not to look at your watch during the test. The end of the experiment will be signalled by the supervisor of the experiment.

In order not to influence the measurements, each day only one force level will be measured. Also, all measurements will be repeated to assess the repeatability. This means that six appointments will have to be made for this part of the experiment. The required time per session varies from ten minutes to half an hour. This part of the experiment will take approximately 2 hours in all.

If your physical condition is better or poorer than usual, please inform the supervisor of the experiment, as this may affect the results of the experiment.

* Discomfort includes: sensation of muscle tension/pressure, fatigue, heat, a tingling or prickling sensation, cramp, heat, stiffness, trembling, soreness and (slight) pain.

November 1991
Atlas of Human Force Exertion Project
Department of Product and Systems Ergonomics
Faculty of Industrial Design Engineering
Delft University of Technology

Pre-experiment instruction, 5.3 and 5.4

Maximum endurance, one limb

The purpose of this experiment is to investigate the endurance time when exerting force at different levels of force (again, 80 %, 60 %, 40 %, 30 %, 20 % and 15 % of the maximal force measured). Forces will be exerted in five different ways: pushing with one arm, flexion and extension of the knee, and anteflexion of the shoulder with arm stretched (see drawings on next page).
In each of these postures, the maximal forces will be measured during four seconds.

For each of the four postures, you will then be asked to maintain a certain percentage of the maximal force measured for as long as possible with one hand/foot/arm. This means that you should continue exerting force as long as possible, and stop only when you are really unable to continue.

The force you are expected to exert will be indicated by means of two red arrow markers. When you exert force, a white bar moves to the right. The bar should be kept between the two red arrows and fluctuate as little as possible. If the force becomes too great or too small, the computer will beep to indicate that adjustment is necessary. If the force drops to zero the experiment will stop and the endurance time will be shown on the monitor screen.

While you are exerting force, you will be asked at regular intervals how much discomfort* you experience. Your reply may be any of the following five categories:

a. No discomfort
b. Little discomfort
c. Average discomfort
d. Much discomfort
e. Extreme discomfort

Learn these categories by heart so that you will be able to reply swiftly when the question is asked. If you get the feeling that you are moving past the last category, 'e. Extreme discomfort', please say so. You will be given a practice run to get used to the force exertion and the questions.

After the measurement, you will be asked the following questions:

- In which two parts of your body (in descending order) did you experience the most discomfort at the end of the test?
- Was this the case during the entire duration of the test?
- Did you experience discomfort with your muscles, with your skin, or with the contact surface of the chair, handle or support?

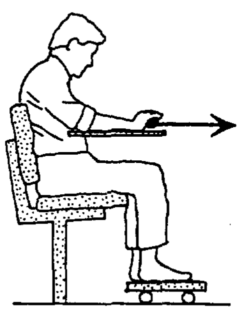
During the experiment you may ask questions if something needs explaining. Apart from this, conversation will be discouraged in order to prevent it affecting the results of the experiment in any way. For the same reason, you are asked not to look at your watch during the test. The end of the experiment will be signalled by the supervisor of the experiment.

In order not to influence the measurements, the tests will be spread out over a period of five days (20 minutes to one hour per session). Each day, the maximal force will be measured for each of the five postures, and then the endurance time for a certain force will be measured. The measurements will take approximately 4 hours in all.

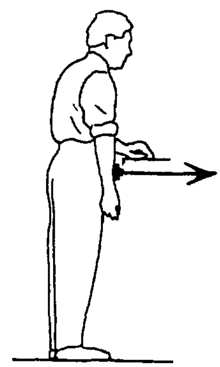
If your physical condition is better or poorer than usual, please inform the supervisor of the experiment, as this may affect the results of the experiment.

* Discomfort includes: sensation of muscle tension/pressure, fatigue, heat, a tingling or prickling sensation, cramp, heat, stiffness, trembling, soreness and (slight) pain.

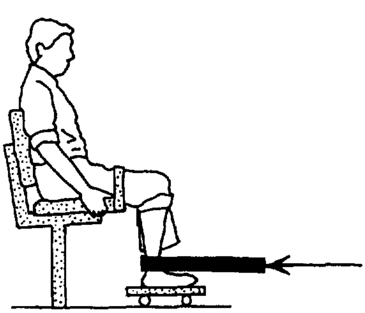
November 1991
Atlas of Human Force Exertion Project
Department of Product and Systems Ergonomics
Faculty of Industrial Design Engineering
Delft University of Technology



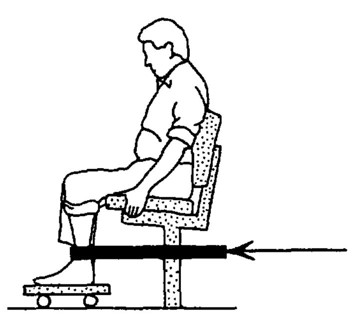
push



anteflexion



flexion



extension

C Examples of data gathered for the Atlas

Contents

Justification of the choice of tables

In the following, relevant data on force exertion gathered from literature are presented systematically, with information on subjects and methods used in the experiments.

Two groups were selected on which to gather information: push and pull (in standing and sitting postures), and torque. These groups were selected for the following reasons.

Push/pull and torque appear to be relevant to most user-product interactions involving handling.

In general, sufficient information on push/pull and torque was available. In the present and previous (Daams, 1987) research, push, pull and torque were included and information on those topics was collected for the present literature collection. It also has the advantage that the results of the present research can be included, to show what they will look like in the Atlas.

The information on push/pull and torque is estimated to be useful for designers. Some of the forces are measured in free posture, most are exerted with part of the body (using more than one body segment) and the forces are transmitted to the handle or knob using one hand only. 'Pure' elbow flexion, or 'pure' knee extension, may be less interesting for designers.

If the information in this example proves to be as valuable as estimated, it can be used in its present form by designers to partly fulfil the function of the future Atlas, and so demonstrate its usefulness.

Push and pull are combined in one group because in most research they are investigated together. Some related forces, like lift and press, that are included in some investigations, will be presented too.

Two groups are presented, and as many results per group as could be found. This is done in order to give as complete an example as possible. An extensive collection of results may be appreciated by the users of this book, and it shows the diversity of the collected data. It is important to get a good impression of the expected data, if the project is to be continued and an Atlas with more data is to be produced. The push and pull data show that the ways to define posture for similar measurements are so different as to defy comparison; torque data are available for various groups of users, which is important information to include in the Atlas.

Explanation of the tables

The information is divided in groups of similar force exertion in order to structure the data. Within the groups, investigations with similar conditions are clustered, after which information is arranged according to the alphabetical order of the researchers' names.

Before the collection of each group of data, a short overview is given to guide the designer who is looking for specific information.

Each investigation is designated by a symbol showing the type of forces measured (push or pull, standing or sitting, or torque on a jar or a vertically oriented knob, etc.). These symbols also feature in the contents. They enable the right force to be located quickly and easily.

Every investigation has its source (literature), subjects and methods described as far as this information is relevant for designers and as far as it could be found in the articles. When available, figures on posture, handle or experimental situation are presented. Next, data on exerted forces is presented in tables or, in some cases, graphs. Ideally, all information on one investigation should be visible at a single glance, which means that it should fit on two pages.

In the tables, pounds (lbs), kilopounds (kp), inches and other imperial measures, found in some original publications, are converted to the metric system (Newton, metre and second). This is done in order to arrive at a more homogeneous database, to eliminate measures not commonly known, to make comparison of various data easier and to comply with the international standards.

When figures are used, the original figures are used when possible. Only a few unclear drawings and graphs have been redrawn. This was done in order to transfer the information as unchanged as possible. Photographs were also redrawn to improve reproducibility. Where no figures are given in the original article, no figure is published here, to prevent bias.

The publications that lack information on subjects and methods, and are therefore left out of the collection, are indicated at the end of the overview.

How to use the tables

The procedure to find the maximum force that can be exerted by a certain group of users, in a certain posture, can be the following:

First the main category of force should be established. In the appendix of this book, the categories push/pull and torque are included. In the future Atlas, categories like grip, lift, pinch, and forces exerted with the feet, can be added. For each category of forces a short introduction is given to guide the designer looking for forces exerted in a specific situation or by a specific group of subjects. Where possible, a summary of (some of the) data is given.

The contents lists tables per type of force exertion. Within the categories of force exertion, tables are listed according to details in the measuring method that are shown in symbols, and after that according to the name of the author.

Therefore, once the required category of force is selected and the corresponding introduction studied, a more detailed selection of tables can be made using the symbols listed in the contents. For push and pull the characteristics indicated in the symbols are: the direction of force, and standing, sitting or kneeling force exertion. For torque, these characteristics are: the general shape of the handle or knob, and the orientation towards the subject.

The most promising tables can be looked up and browsed. The subjects and methods as used in the experiments should be compared to the expected conditions of use and the expected users of the product. If too much discrepancy is found, the results should not be used, or be used with great care to estimate the possible values.

Next, the relevant information can be extracted from the suitable tables. This may require some thought, because investigators define postures each in their own way, and especially in the case of push and pull forces this generates many different ways in which force is exerted.

When more results are found to be applicable to the expected situation and users, the various values should be compared. Picking the best one from (or making a combination of) a number of data results in a better basis for a value than when the first value found is used. Sometimes, the results of various experiments can be quite different.

Following this procedure, the user ends up with a value for the force he was looking for, provided that the desired information was included in the Atlas in the first place.

Summarized:

1) select category;
2) read introduction of category;
3) select promising tables, using introduction and list of contents;
4) browse through tables, comparing subjects and methods to those required;
5) extract the desired information from the suitable tables;
6) in case of more than one result, compare and pick the most plausible figure.

Pushing and pulling

Introduction

Maximal and comfortable force. Although the object was to gather a variety of data for this collection, only information on static force exertion could be found. Nearly all investigations concern maximal force. Only Kanis (1989), Schoorlemmer and Kanis (1992) and Daams (1994) measured comfortable force exertion. Daams (1994) also measured maximal endurance times of submaximal forces.

Free posture. Data on pushing and pulling in free posture can be obtained from Gallagher (1989) and Daams (1993).

Standardized postures. The subjects of Rohmert (1966) and Rohmert and Hettinger (1963) used standardized postures which greatly limited maximal force exertion. This is also the case with the standardized postures of Daams (1993). Note the limited number of subjects of Rohmert (5 men).

Support. Feet or back supports at various distances are included in the conditions of the experiments of Kroemer (1968), who investigated pushing with arms as well as pushing with the shoulder. Van de Kerk and Voorbij (1993) measured standing force exertion with feet support. The influence of back supports at various heights was investigated by Caldwell (1962) and at various angles by Laubach (1978).

Fingers. Most push and pull forces are exerted using the whole hand. Push force with the forefinger was measured by Kanis (1989) and Steenbekkers (1993). Push force with the thumb was measured by Kanis (1989) and Schoorlemmer and Kanis (1992). Pull force with forefinger and thumb was measured by Fothergill et al. (1992) and Steenbekkers (1993). Maximal finger forces are in general smaller than maximal forces exerted with the whole hand.

Laterality. In most cases, the strength of one hand was measured. Force exertion with two hands was measured by Gallagher (1989) and Kroemer (1968) in standing position, by Morgan et al. (1963) and Frank et al. (1985) in sitting position, and by Van de Kerk and Voorbij (1993) in both standing and sitting position.

Sex. Information on women's force exertion can be found with Hoag (1980), who measured women only, and with Daams (1993 and 1994), Thompson et al. (1975), Keyserling et al. (1978), Fothergill et al. (1992), Kanis (1989) and Schoorlemmer and Kanis (1992), who measured both sexes. Frank et al. (1985), Steenbekkers (1993) and Van de Kerk and Voorbij (1993) investigated both boys and girls. The other authors give information on men only.

Children. Frank et al. (1985) investigated push and pull forces exerted by two groups of children, 5.5 to 8.5 and 10 to 13 years old respectively. Push and pull exerted with hand and with fingers by Dutch girls and boys from 4 to 13 years old are measured by

Steenbekkers (1993). Push and pull in sitting and standing posture by girls and boys from 4 to 12 years old was investigated by Van de Kerk and Voorbij (1993). Bovend'eerdt et al. (1980) measured pull force of children from 12 to 18 years old.

Elderly. Forces in various directions exerted by elderly aged 60 to 75 were measured by Thompson (1975).

Disabled. Kanis (1989) investigated forces exerted by arthritic persons and persons suffering from muscle diseases. Schoorlemmer (1993) looked into push force with the thumb, exerted by healthy people and persons suffering from various diseases. They both measured female and male subjects.

Summary. The information gathered should preferably be summarized to facilitate comparison. However, this is not possible because all experiments describe and prescribe posture in different ways. This makes plotting of various results in one figure, or even a comparison of some of the values, virtually impossible.
For push and pull in standing posture, maximal forces exerted in free postures are higher than maximal forces exerted in standardized postures. Maximal forces exerted while standing with the feet close together are lower than those with one foot in front of the other. Maximal forces exerted with two hands are larger than those exerted with one hand, although usually less than twice as much.

Left out. Not included, because of lack of information on subjects and measuring methods, are: Burandt (1978) and The Materials Handling Research Unit (1980). Data from Chaffin et al. (1983) are not included because results of one- and two-handed force exertion were combined.
Not included either are Fähnrich et al. (1983) and Denkert et al. (1984), whose reports on various forces were too extensive.

Bovend'eerdt (1980)

Source Bovend'eerdt, J., Kemper, H. and Verschuur, R., 1980.
De Moper Fitness test. Haarlem: De Vrieseborch.

Subjects

Number: 6000

Sex: girls and boys.

Age: 12 to 18 years.

Other characteristics: -

Method

Direction of force: pull.

Posture: standing. The instruction for the subject was the following: "stand with legs apart, with the shoulder of the strongest arm furthest removed from the wall bars. Lean with your 'weak' hand horizontally and with the arm stretched against the wall bars. Grasp the dynamometer with your strongest hand, thumb up. At my sign, start pulling. Do not use your weight. Your weak hand should stay on the bar during pulling."

Sort of force: maximal static force.

Laterality: the strongest arm.

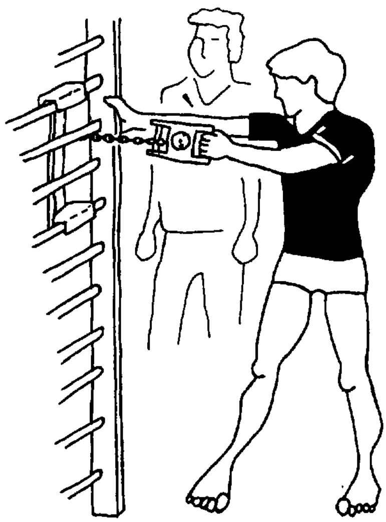
Measurement: on a given sign, subjects should pull as hard as possible. The score is the best of two trials.

Sort of handle: a dynamometer, see figure.

Size of handle: ?

Position of handle: at shoulder height, see figure for orientation.

Other characteristics: the measurements were carried out in a gymnasium with wall bars.



Results

age [years]	$\leq P_{20}$	$P_{21} - P_{40}$	$P_{41} - P_{60}$	$P_{61} - P_{80}$	$\geq P_{81}$
girls					
12	≤ 249	250 – 279	280 – 318	319 – 357	≥ 358
13	≤ 279	280 – 318	319 – 347	348 – 387	≥ 388
14	≤ 298	299 – 338	339 – 377	378 – 426	≥ 427
15	≤ 318	319 – 357	358 – 396	397 – 445	≥ 446
16	≤ 328	329 – 367	368 – 416	417 – 465	≥ 466
17	≤ 347	348 – 387	388 – 416	417 – 475	≥ 476
18	≤ 347	348 – 396	397 – 436	437 – 494	≥ 495
boys					
12	≤ 269	270 – 308	309 – 338	339 – 377	≥ 378
13	≤ 298	299 – 338	339 – 377	378 – 445	≥ 446
14	≤ 357	358 – 416	417 – 465	466 – 543	≥ 544
15	≤ 416	417 – 485	486 – 553	554 – 632	≥ 633
16	≤ 475	476 – 534	535 – 592	593 – 661	≥ 662
17	≤ 514	515 – 583	584 – 651	652 – 710	≥ 711
18	≤ 573	574 – 622	623 – 690	691 – 779	≥ 780

Pull [N], categories of percentiles of girls and boys of various ages.

Daams (1993)

Source Daams, B.J., 1993.
Static force exertion in postures with different degrees of freedom.
Ergonomics, 36 (4), 397-406.

Subjects

Number: 20

Sex: 10 female, 10 male.

Age: average 23 years (s = 4).

Other characteristics: mainly healthy students of Delft University.

Method

Direction of force: push and pull (only horizontal components measured).

Posture: see figure, standing in:
a) free posture;
b) functional posture: position of feet determined;
c) standard posture: one foot 30 cm in front of the other, elbow in 90° flexion.

Sort of force: maximal static force exertion.

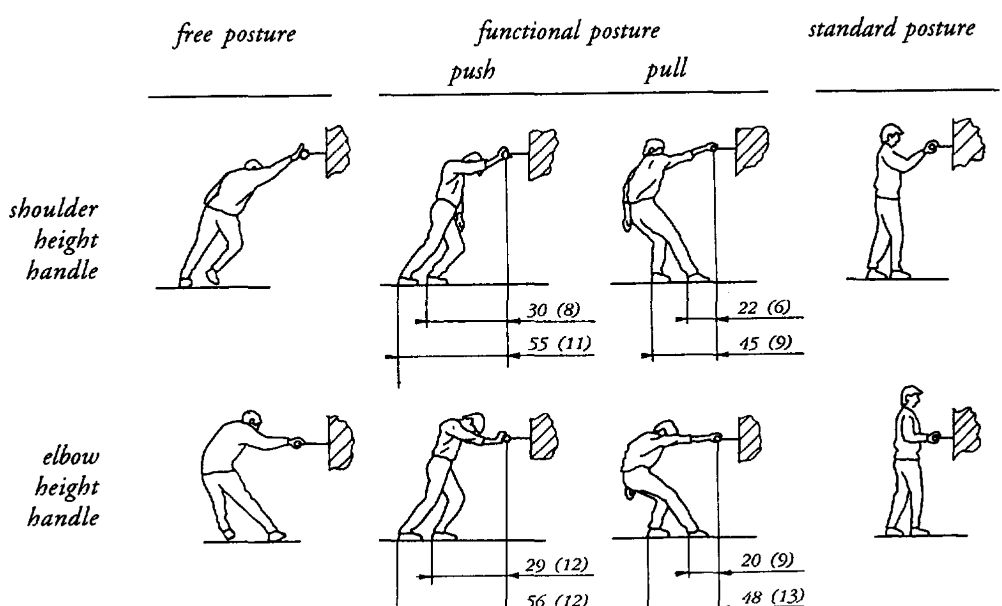
Laterality: the preferred hand.

Measurement: duration 6 s, the score is the average of the last four, the average of two trials.

Sort and size of handle: push: doorknob, round model, Ø 59 mm, slightly convex;
pull: bar Ø 32 mm.

Position of handle: at shoulder height, elbow height, 0.70 m, 1.30 m and 1.70 m.

Other characteristics: non-skid flooring was used.

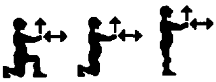


Functional posture: horizontal distance from heel to vertically projected position of handle is expressed in % of body height.

Results

handle height	force direction	posture	females $\bar{x}$	females s	males $\bar{x}$	males s	both $\bar{x}$	both s
shoulder height	pull	free	201	56	301	65	251	79
		functional	198	51	253	48	225	56
		standard	122	29	145	25	134	29
	push	free	198	72	304	53	251	82
		functional	186	42	236	34	211	45
		standard	107	16	136	26	122	26
elbow height	pull	free	235	106	400	56	327	111
		functional	249	86	351	54	300	87
		standard	128	27	168	33	148	36
	push	free	225	93	349	96	287	112
		functional	194	61	285	93	240	89
		standard	108	18	147	25	126	28
0.70 m	pull	free	292	97	541	81	416	154
	push	free	185	57	393	134	289	147
1.30 m	pull	free	223	80	347	55	285	92
	push	free	221	103	337	83	279	109
1.70 m	pull	free	196	56	263	60	229	66
	push	free	181	75	300	50	241	87

Push and pull [N], averages and standard deviations of 10 women and 10 men.



Gallagher (1989)

Source Gallagher, S., 1989.
Isometric pushing, pulling and lifting strengths in three postures. In: *Proceedings of the Human Factors Society 33rd Annual Meeting* (pp. 637-640). Santa Monica, CA: The Human Factors Society.

Subjects

Number: 9

Sex: male.

Age: 36.9 years (s = 6.3), range 29 to 47.

Other characteristics: underground coal miners, body height 163 - 189 cm, body weight 70 - 111 kg.

Method

Direction of force: push, pull and lift.

Posture: kneeling on one knee, on two knees and standing:
a) push, pull and lift with elbow in 90° flexion;
b) lift with handle 45.7 cm above the floor;
c) 'push up' (lift) with handle at eye level.

Sort of force: maximal static force.

Laterality: two-handed.

Measurement: according to Caldwell et al. (1974) (≈ 1 s built-up, 4 s maximal force, B.D.)), the score is the highest of two trials.

Sort of handle: ?

Size of handle: ?

Position of handle: 'with elbow in 90° flexion', 'at eye level' and 45.7 cm above the floor.

Other characteristics: -

Results

direction	posture	kneeling one knee $\bar{x}$	s	kneeling two knees $\bar{x}$	s	standing $\bar{x}$	s
push	elbow in 90° flexion	603.4	90.3	676.0	192.7	519.3	196.7
pull	elbow in 90° flexion	578.1	97.9	329.7	60.1	341.3	83.7
lift	elbow in 90° flexion	515.8	63.6	435.2	159.3	501.5	58.7
lift	handle at 45.7 cm above floor	1085.4	272.8	1403.1	368.5	1148.1	250.1
lift	handle at eye level	596.3	112.6	617.7	115.7	604.3	158.0

Push, pull and lift [N], averages and standard deviations of nine male coalminers.

Hoag (1980)

Source Hoag, L.L., 1980.
Anthropometric and strength data in tool design.
In: *Anthropometry and biomechanics* (pp. 253-257). Editors: R. Easterby, K.H.E. Kroemer and D.B. Chafffin. New York: Plenum Press.

Subjects

Number: 96

Sex: female.

Age: adults.

Other characteristics: industrial workers, from cities selected from different geografic regions of the United States, for the purpose of including any ethnic and racial differences found between the regions. Their average body height is 167 cm, s = 6.4 cm.

Method

Direction of force: push.

Posture: a) with the arm to the person's side and with the hand at waist height;
b) an overhead position required to install wiring in the basements of modern homes.

Sort of force: probably maximal static force exertion.

Laterality: probably one-handed.

Measurement: ?

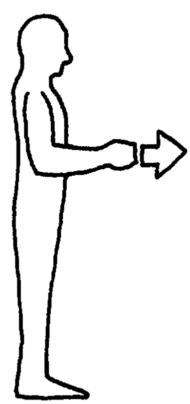
Sort of handle: ?

Size of handle: ?

Position of handle: ?

Other characteristics: -

Results



P_5 = 177 N
P_{10} = 207 N
P_{90} = 489 N
P_{95} = 543 N
$\bar{x}$ = 346 N
s = 116 N

P_5 = 33 N
P_{10} = 37 N
P_{90} = 84 N
P_{95} = 95 N
$\bar{x}$ = 61 N
s = 22 N

(drawings made after the description, B.D.)

Keyserling et al. (1978)

Source Herrin, G.D., 1980.
Standardized strength testing methods for population descriptions. In: *Anthropometry and biomechanics* (pp. 145-150). Edited by R. Easterby, K.H.E. Kroemer and D.B. Chafffin. New York: Plenum Press.

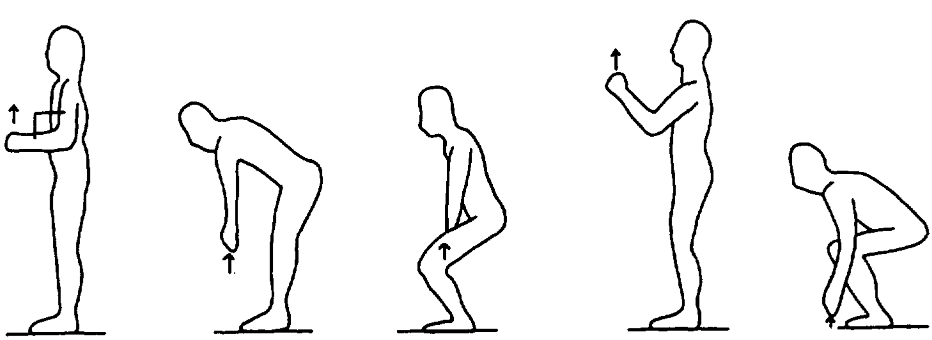
Original source: Keyserling, W.M., Herrin, G.D. and Chaffin, D.B., 1978.
An analysis of selected work muscle strengths. In: *Proceedings of the 22nd Annual Human Factors Society Meeting.* Santa Monica, C.A.: The Human Factors Society.

Subjects

Number: 35 to 1052, varying per condition.
Sex: female and male.
Age: adults.
Other characteristics: workers in rubber, aluminium, steel and electronic component processing industries.

Method

Direction of force: lift, push and pull.
Posture: see figure.
Sort of force: maximal static force exertion.
Laterality: two-handed.
Measurement: duration 6 s, with the mean of the middle 3 seconds being reported.
Sort of handle: a round handle for both hands, which allowed a full-power grip.
Size of handle: Ø 3 cm.
Position of handle: see figure.
Other characteristics: -



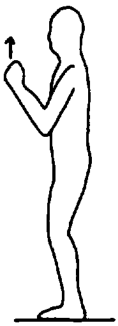
1 arm lift elbow in 90° angle

2 torso lift v = 38 cm h = 38 cm

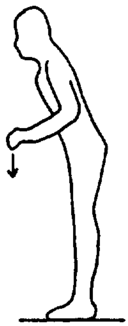
3 leg lift v = 38 cm h = 0 cm

4 high far lift v = 152 cm h = 51 cm

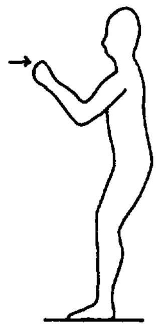
5 floor lift v = 15 cm h = 25 cm



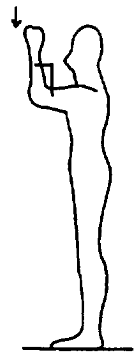
6 high near lift
v = 152 cm
h = 25 cm



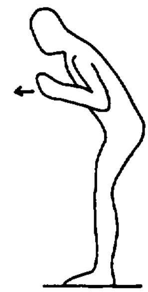
7 push down
v = 112 cm
h = 38 cm



8 pull in
v = 157 cm
h = 33 cm



9 pull down
elbow in
90° angle



10 push out
v = 124 cm
h = 25 cm

Results

test	n	coeff. of variation	P_5	P_{25}	P_{50}	P_{75}	P_{95}
			population percentile				
females							
1 arm lift	187	0.08	88	147	216	274	333
2 torso lift	187	0.10	127	167	235	323	431
3 leg lift	133	–	147	265	392	519	627
4 high far lift	35	0.12	88	108	127	157	186
5 floor lift	35	0.08	314	431	549	676	784
6 high near lift	35	0.11	157	216	284	353	412
7 push down	35	0.10	255	284	323	372	421
8 pull in	35	0.10	186	216	245	284	323
9 pull down	35	0.04	314	382	451	519	588
10 push out	35	0.11	167	186	216	245	284
males							
1 arm lift	1052	0.07	225	304	382	470	549
2 torso lift	1052	0.09	255	333	441	588	755
3 leg lift	638	–	480	676	892	1 117	1 313
4 high far lift	309	0.09	157	186	225	274	333
5 floor lift	309	0.08	578	725	892	1 058	1 205
6 high near lift	309	0.08	343	431	539	647	745
7 push down	309	0.08	333	382	431	500	568
8 pull in	309	0.07	235	265	314	363	421
9 pull down	309	0.05	480	539	608	676	735
10 push out	309	0.08	225	265	304	363	412

Push, pull and lift [N], percentiles of females and males.

Kroemer (1968)

Sources VanCott, H.P. and Kinkade, R.G. (editors), 1972.
Human engineering guide to equipment design. Washington: USGPO.

Woodson, W.E., 1981.
Human factors design handbook. New York: McGraw-Hill.

Original source: Kroemer, K.H.E., 1968.
Push forces exerted in sixty-five common working postures. ARML-TR-68-143, Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio.

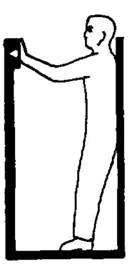
Subjects

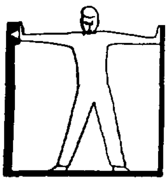
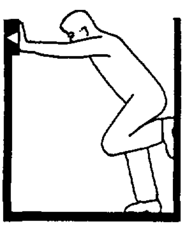
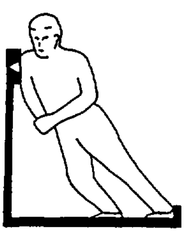
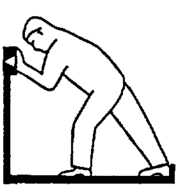
Number: 30 to 43, varying per condition.
Sex: male.
Age: adults.
Other characteristics: -

Method

Direction of force: push.
Posture: see figures.
Sort of force: maximal static force.
Laterality: see figures and tables.
Measurement: ?
Sort of handle: force plate, 20 cm high * 25 cm long.
Size of handle: -
Position of handle: vertically oriented, height of centre of force plate: see tables.
Other characteristics: all conditions include a structural support to 'push against'.

Results

posture		height of centre of force-plate	horizontal distance between force plate and vertical support	exerted force $\bar{x}$	exerted force s
	both hands	acromial height	% of thumb-tip reach		
			50	594	145
			60	680	163
			70	1002	277
			80	1311	408
			90	998	308
			100	658	259
	preferred hand	acromial height	% of thumb-tip reach		
			50	268	68
			60	304	73
			70	367	100
			80	531	145
			90	503	172
			100	435	177

	both hands*	40 % of acromial height	% of thumb-tip reach		
			80	1941	753
			90	1651	549
			100	1687	513
			110	1969	576
			120	2000	608
			130	1801	526
		acromial height	% of span		
			50	376	141
			60	354	127
			70	531	168
			80	721	195
			90	331	136
	both hands*	% of acromial height	% of acromial height		
		50	80	676	181
		50	100	789	218
		50	120	794	168
		70	80	730	163
		70	100	744	236
		70	120	835	141
		90	80	640	150
		90	100	689	200
		90	120	880	145
		% of acromial height	% of acromial height		
		60	70	776	172
		60	80	871	181
		60	90	807	145
		70	60	590	113
		70	70	712	127
		70	80	739	145
		80	60	531	132
		80	70	630	132
		80	80	649	143
	both hands*	% of acromial height	% of acromial height		
		70	70	635	150
		70	80	703	159
		70	90	599	136
		80	70	558	127
		80	80	553	127
		80	90	544	82
		90	70	440	95
		90	80	458	95
		90	90	494	82

Push [N], average and standard deviation of males.

* *not indicated in literature. However, the sizes of the exerted forces indicate that they are exerted by both hands.*

Rohmert (1966)

Source VanCott, H.P. and Kinkade, R.G. (editors), 1972.
Human engineering guide to equipment design. Washington: USGPO

Original source: Rohmert, 1966.

Subjects

Number: 5

Sex: male.

Age: ?

Other characteristics: -

Method

Direction of force: push, pull , pushing to the left and to the right, lift and press.

Posture: standing, feet 30 cm apart, see figure.

Sort of force: maximal static force .

Laterality: right-handed.

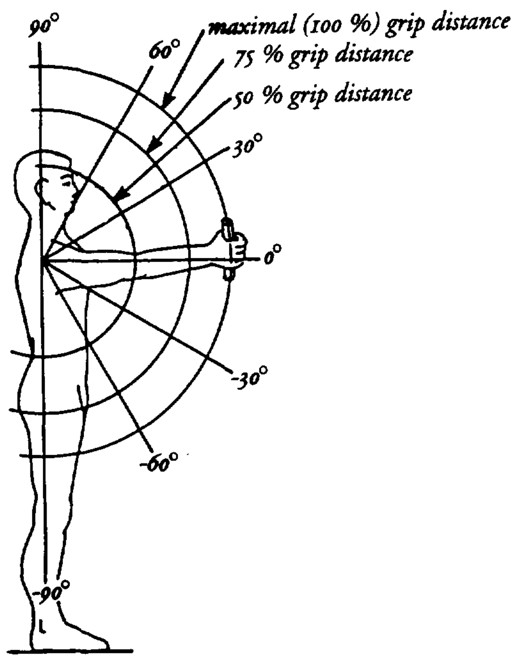
Measurement: ?

Sort of handle: 'a vertical hand-grip'.

Size of handle: ?

Position of handle: at 50, 75 and 100 % of grip distance and various angles of the arm (see figure and table).

Other characteristics: -



Results

force direction	angle (see figure)	force exerted with the handgrip at various percentages of maximal grip distance 50% x̄	75% x̄	100% x̄
push, horizontal	30°	73	109	145
	0°	136	159	181
	-30°	127	136	145
	-60°	127	145	163
pull, horizontal	30°	86	100	118
	0°	104	118	132
	-30°	127	136	141
	-60°	104	127	154
to the left, horizontal	30°	159	136	109
	0°	191	150	109
	-30°	191	154	118
	-60°	150	136	118
to the right, horizontal	30°	109	100	95
	0°	136	113	91
	-30°	150	122	100
	-60°	113	104	95
up, vertical, (lift)	30°	127	109	86
	0°	154	118	82
	-30°	227	181	127
	-60°	286	231	186
down, vertical, (press)	30°	345	263	186
	0°	254	181	150
	-30°	159	150	136
	-60°	177	163	145

Push, pull, push sideways, lift and press [N], averages of 5 men.

Rohmert et al. (1988)

Source Rohmert, W., Mainzer, J. and Kanz, U., 1988. Individuelle Unterschiede der Vektogramme von isometrischen Stellungskräften. *Zeitschrift für Arbeitswissenschaft,* 42 (2), 102-105.

Subjects

Number: 21

Sex: male.

Age: average 23.6 (s = 3.1).

Other characteristics: body height: average 180.2 cm (s = 8.1); body weight: average 70.6 kg (s = 9.6).

Method

Direction of force: push, pull, lift, press, and forces in various other directions in the sagittal plane.

Posture: standing, with the handle at shoulder height at a distance of 80 % of arm reach, and the feet in a fixed position (see figures).

Sort of force: maximal static force.

Laterality: one or two hands? (the exerted forces are limited by the posture, so this may not affect the results).

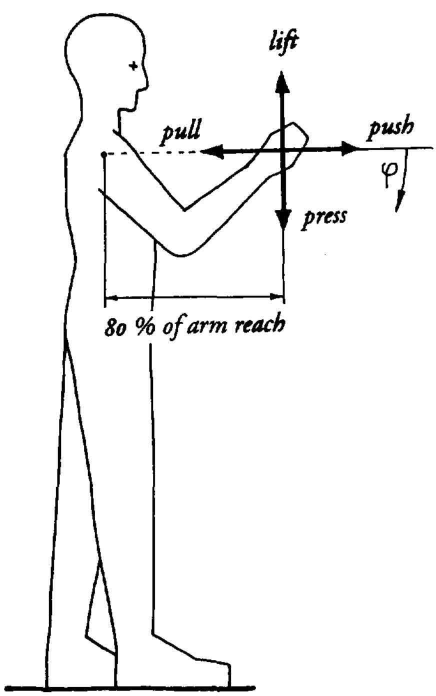
Measurement: ?

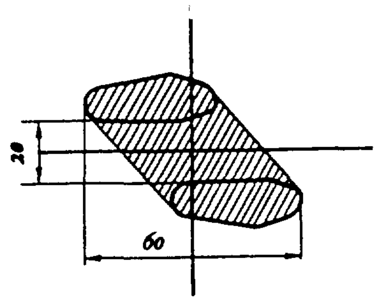
Sort of handle: ?

Size of handle: ?

Position of handle: at shoulder height, at a distance of 80 % of arm reach.

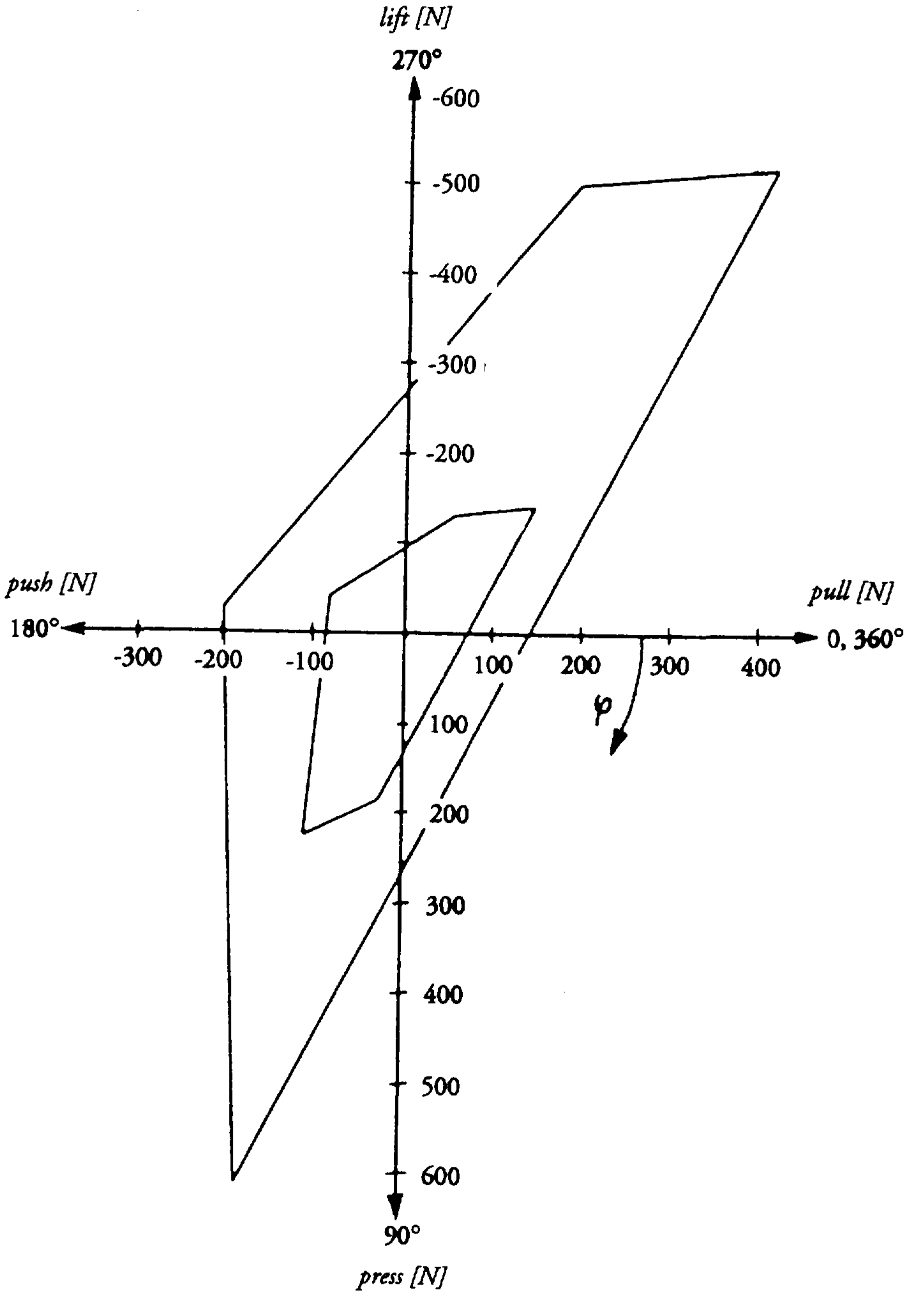
Other characteristics: -





position of the feet [cm]

Results



Push, pull, lift, press and forces in various other directions in the sagittal plane [N]. Range of 21 men. The inner contour represents the minimum maximal force, the outer contour represents the maximum maximal force.

Thompson (1975)

Source Thompson, D., 1975.
Ergonomics data for evaluation and specification of operating devices on components for use by the elderly. Loughborough: Institute for Consumer Ergonomics.

Subjects

Number: 100

Sex: 62 female, 38 male.

Age:

60 - 65 years:	22 female, 13 male;
66 - 70 years:	23 female, 14 male;
71 - 75 years:	17 female, 11 male.

Other characteristics: subjects were selected locally at random from elderly persons within this age range who were living in unassisted occupation of a dwelling. However, preliminary screening eliminated from selection those with any indication of coronary disease.

Method

Direction of force: push, pull, to the left, to the right, lift and press.

Posture: a line was drawn on the floor in line with, and vertically beneath, the handle of the apparatus. The subject's leading foot was positioned on this line to ensure maximum force application. Apart from this positioning, subjects were allowed to adopt whatever stance was natural to them.

Sort of force: maximal static force.

Laterality: the dominant hand.

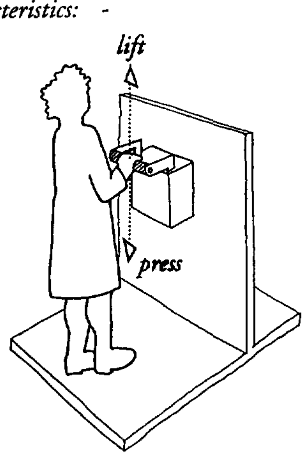
Measurement: subjects were told to exert force as hard as they could until they felt they had reached their maximum, and they were then to release the handle. The highest value of three trials is the value used for computation of the strength data.

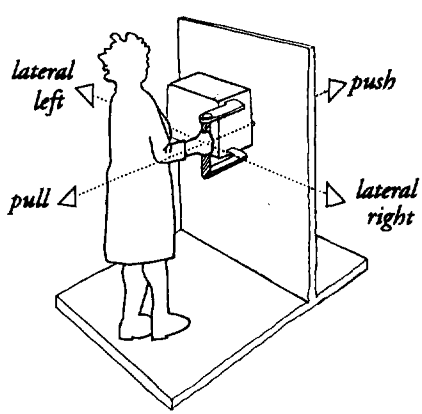
Sort of handle: for push, pull, to the left and to the right: handle in vertical position.
for lift and press: handle in horizontal position.

Size of handle: handle Ø 3.2 cm.

Position of handle: 0.83 m, 1.0 mm, 1.3 m and 1.6 m above the floor.

Other characteristics: -

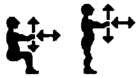




force direction	height [cm]	age [years]	females x̄	females s	females P_5	females range	males x̄	males s	males P_5	males range
push	83	60 - 65	149.3	54.9	58.9		282.7	122.1	81.9	
		66 - 70	168.9	47.8	90.4		220.3	88.0	75.5	
		71 - 75	147.0	68.4	34.4		204.8	43.0	134.1	
		all	155.9	56.0	63.8	75.7 - 327.7	237.2	94.7	81.4	87.6 - 574.9
	100	60 - 65	159.3	40.7	92.4		282.7	103.6	112.3	
		66 - 70	165.4	35.9	106.3		225.0	76.9	98.5	
		71 - 75	160.6	57.0	66.8		199.3	34.8	142.2	
		all	162.0	43.2	90.9	83.1 - 309.3	237.3	83.1	100.7	92.2 - 540.2
	130	60 - 65	143.0	53.4	55.3		235.8	81.9	101.0	
		66 - 70	142.1	35.4	87.8		202.9	63.8	97.9	
		71 - 75	119.1	32.8	65.2		183.6	34.3	127.2	
		all	136.1	42.4	66.4	61.1 - 299.3	208.6	65.4	101.1	83.1 - 424.4
	160	60 - 65	134.1	44.2	61.3		219.7	75.1	96.1	
		66 - 70	126.9	42.7	56.7		182.3	67.7	70.9	
		71 - 75	117.8	35.2	59.8		170.9	54.1	82.0	
		all	126.9	40.9	59.7	52.0 - 267.4	191.8	79.8	60.5	84.9 - 479.1
pull	83	60 - 65	175.2	62.5	72.4		387.9	144.5	150.2	
		66 - 70	223.8	72.1	105.2		281.4	102.0	113.5	
		71 - 75	185.4	82.6	49.4		284.5	116.1	93.6	
		all	196.0	73.5	75.1	83.0 - 402.8	318.7	127.2	109.4	98.1 - 664.0
	100	60 - 65	197.4	66.0	88.8		378.6	164.0	108.7	
		66 - 70	207.3	56.1	115.0		277.8	92.6	125.4	
		71 - 75	195.3	76.3	69.9		257.8	68.0	146.1	
		all	200.5	64.3	94.9	100.0 - 406.5	306.5	124.1	102.3	102.8 - 785.8
	130	60 - 65	175.5	66.5	66.1		315.0	128.6	103.4	
		66 - 70	181.5	45.2	107.2		253.3	81.9	118.6	
		71 - 75	157.8	54.5	68.0		217.0	33.1	162.6	
		all	172.9	55.5	81.5	80.2 - 389.6	263.9	96.8	104.6	105.7 - 577.3
	160	60 - 65	159.1	54.2	70.0		299.6	132.6	81.4	
		66 - 70	150.2	34.5	93.4		227.1	85.0	87.2	
		71 - 75	145.7	46.5	69.3		210.8	68.3	98.5	
		all	152.2	49.5	70.6	48.1 - 305.6	247.2	103.6	76.8	87.7 - 582.9
lateral, to the left	83	60 - 65	97.9	35.0	40.2		230.6	79.8	99.5	
		66 - 70	101.2	49.8	19.2		158.2	60.7	58.4	
		71 - 75	101.6	44.3	28.7		144.5	58.6	48.2	
		all	100.2	42.6	30.2	27.3 - 225.3	179.0	74.8	56.1	63.8 - 320.0
	100	60 - 65	105.3	35.9	46.3		221.0	85.6	80.1	
		66 - 70	97.9	40.9	30.7		163.3	54.5	73.9	
		71 - 75	98.6	39.0	34.6		143.3	44.7	69.8	
		all	100.8	37.9	38.6	34.0 - 215.4	177.3	70.1	61.9	61.9 - 381.2
	130	60 - 65	105.8	54.5	16.3		159.0	56.3	66.5	
		66 - 70	84.5	22.9	46.9		142.3	45.7	67.1	
		71 - 75	86.6	37.1	25.5		142.1	43.9	70.0	
		all	92.6	40.5	26.0	23.5 - 149.8	147.9	47.8	69.4	55.1 - 245.1
	160	60 - 65	86.5	30.9	35.6		156.8	66.3	47.6	
		66 - 70	80.3	27.7	34.8		125.0	46.2	48.9	
		71 - 75	75.1	33.3	20.2		121.2	54.5	31.6	
		all	81.0	35.2	23.2	24.1 - 234.0	134.8	56.2	42.3	44.0 - 264.3

force direction	height [cm]	age [years]	females x̄	s	P_5	range	males x̄	s	P_5	range
lateral, to the right	83	60-65	60.9	24.3	20.8		156.2	80.3	24.2	
		66-70	59.1	24.0	19.5		104.9	29.4	56.5	
		71-75	60.6	27.7	15.1		75.8	35.0	18.2	
		all	60.1	24.5	19.7	19.2 - 142.3	114.0	55.9	22.0	43.2 - 293.4
	100	60-65	60.5	28.3	14.1		147.5	63.6	43.0	
		66-70	57.2	26.9	13.1		106.2	51.4	21.8	
		71-75	68.0	31.0	17.0		85.0	39.0	20.7	
		all	61.3	28.2	15.1	15.0 - 159.6	114.2	56.8	20.8	23.5 - 255.0
	130	60-65	61.9	26.1	18.9		129.9	45.9	54.4	
		66-70	66.3	23.9	26.9		101.0	34.1	44.8	
		71-75	60.1	21.4	24.9		79.0	35.1	21.2	
		all	63.1	23.6	24.1	21.0 - 120.6	104.6	42.5	34.6	19.8 - 196.8
	160	60-65	62.5	24.3	22.6		133.0	50.5	49.9	
		66-70	61.6	16.4	34.6		98.8	36.5	38.8	
		71-75	54.4	17.3	25.9		76.7	32.9	22.9	
		all	59.9	19.6	27.7	21.6 - 147.6	104.1	45.3	29.5	26.4 - 208.8
press	83	60-65	208.6	81.8	73.9		464.6	143.2	229.1	
		66-70	256.6	90.1	108.4		343.2	142.1	109.8	
		71-75	182.4	54.9	92.0		363.7	129.9	150.0	
		all	219.2	82.8	83.0	80.4 - 531.0	390.6	144.0	153.8	100.9 - 650.5
	100	60-65	140.9	55.9	49.1		379.5	138.9	151.0	
		66-70	172.4	64.4	66.5		287.1	91.2	137.1	
		71-75	121.2	48.4	41.5		261.5	90.3	113.0	
		all	147.2	59.7	49.0	46.4 - 290.9	311.3	116.6	119.4	93.5 - 578.7
	130	60-65	192.5	55.6	101.0		391.2	129.3	178.5	
		66-70	213.3	73.2	92.8		298.6	129.9	84.9	
		71-75	158.7	51.7	73.7		250.3	58.0	154.8	
		all	190.9	64.1	85.5	69.4 - 406.0	316.3	123.4	113.2	133.7 - 596.6
	160	60-65	230.3	58.1	134.8		426.5	132.3	208.9	
		66-70	254.1	69.9	139.1		360.3	109.1	180.9	
		71-75	200.6	48.8	120.4		338.5	80.3	206.3	
		all	231.0	62.8	127.7	108.3 - 448.1	376.6	112.5	119.5	174.5 - 591.1
lift	83	60-65	138.8	62.3	36.3		402.1	201.3	70.9	
		66-70	192.1	87.4	48.4		289.4	161.1	24.5	
		71-75	120.4	47.4	42.5		294.3	138.3	66.7	
		all	153.5	74.4	31.1	47.4 - 405.0	329.4	171.7	47.0	78.6 - 864.0
	100	60-65	107.9	42.9	37.4		320.6	163.3	51.9	
		66-70	134.9	67.1	24.6		244.4	97.4	84.1	
		71-75	100.9	34.6	44.1		194.1	75.1	70.6	
		all	116.1	52.4	29.8	28.2 - 375.6	255.9	117.0	63.5	85.8 - 667.8
	130	60-65	166.7	67.5	55.5		489.3	245.6	85.3	
		66-70	206.4	99.5	42.9		348.5	184.7	44.6	
		71-75	136.7	57.6	41.9		233.3	105.2	60.3	
		all	173.2	81.8	38.6	56.4 - 510.6	363.3	186.9	55.9	99.6 - 937.3
	160	60-65	157.9	35.9	98.9		283.0	107.9	105.6	
		66-70	163.0	46.6	86.4		212.6	68.2	100.5	
		71-75	142.0	40.8	75.0		221.0	64.0	115.8	
		all	155.5	41.3	87.4	71.4 - 291.0	239.2	85.7	98.0	119.4 - 476.4

Various forces [N] exerted on a handle at various heights. Averages, standard deviations, ranges and 5th percentiles of 62 elderly women and 38 elderly men.



Rohmert and Hettinger (1963)

Source Rohmert, W. and Hettinger, T., 1963.
Körperkräfte im Bewegungsraum. Berlin: Beuth-Vertrieb, GMBH.

Subjects

Number: 60

Sex: male.

Age: ?

Other characteristics: ?

Method

Direction of force: push, pull, horizontal force inwards and outwards, lift and press.

Posture: some seated, most standing, various arm postures (see table), feet close together, 30 cm apart, or one foot in front of the other.

Sort of force: maximal static force.

Laterality: one-handed.

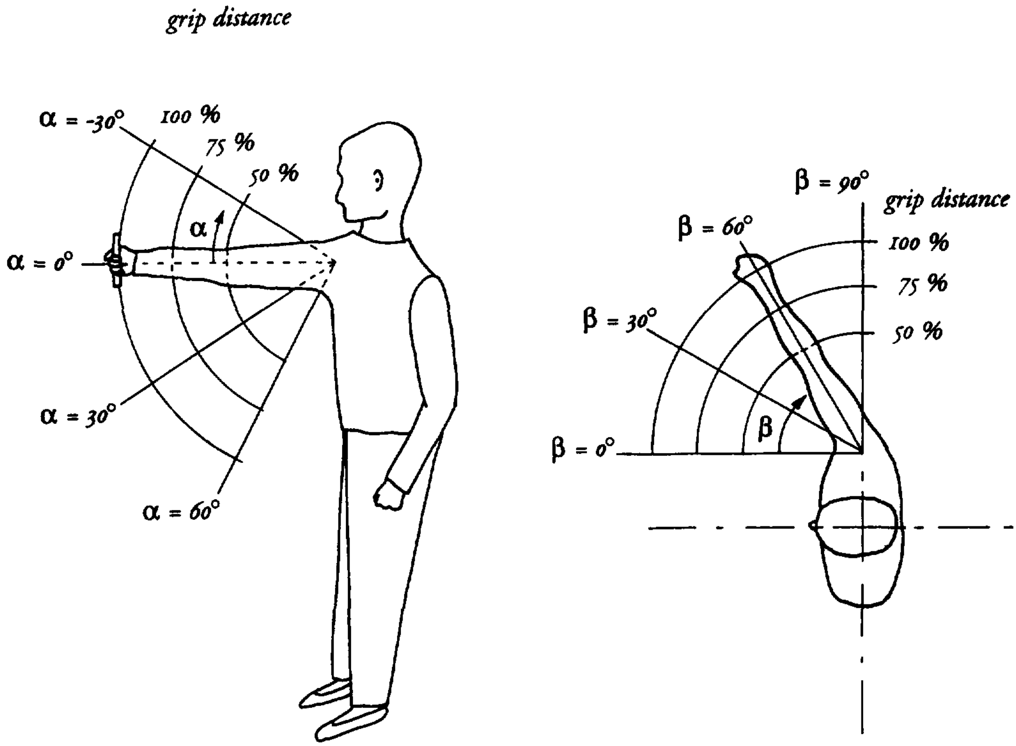
Measurement: ?

Sort of handle: see figure: cylindrical?

Size of handle: ?

Position of handle: at 50, 75 and 100 % of grip distance and various arm angles (see figure and table).

Other characteristics: -



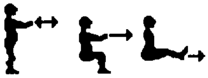
Results

angle α	arm position distance [% of arm reach]	angle β	push $\bar{x}$	pull $\bar{x}$	inwards $\bar{x}$	outwards $\bar{x}$
0°	100%	0°	191	141	74	66
		45°	194	146	75	67
		90°	167	150	67	56
	75%	15°	168	141	82	74
	50%	15°	148	141	101	83

Push, pull, force to the inside and to the outside [N], sitting with back support and feet resting on the floor.

foot posture	angle α	arm position distance [% of arm reach]	angle β	push $\bar{x}$	pull $\bar{x}$	lift $\bar{x}$	press $\bar{x}$	inwards $\bar{x}$	outwards $\bar{x}$
feet 30 cm apart	0°	100%	0°	133	113	103	163	77	75
			30°	154	128	95	151	74	74
			60°	168	149			72	74
			90°	172	155			69	71
		75%	30°	129	111	115	224	95	77
			60°	160	147	162	273	85	74
		50%	30°	111	111	159	265	98	80
			60°	140	146	186	294	87	74
	30°	100%	0°	125	102				
			30°	144	123	122	199	81	80
			60°	158	146			75	74
		75%	0°	108	92				
			30°	118	111	119	259	92	83
			60°	136	129	157	293	87	77
		50%	0°	89	88				
			30°	105	112	131	270	101	89
			60°	110	124	166	307	91	83
	-30°	100%	0°	119	128				
			30°	132	152	132	153	84	83
			60°	149	175			79	79
		75%	0°	127	121				
			30°	142	142	157	178	100	94
			60°	160	164	206	197	93	88
		50%	0°	119	110				
			30°	137	133	187	204	111	97
			60°	151	160	211	234	101	90
	-60°	100%	0°	118	133				
			30°	128	152	189	175	100	98
			60°	143	174			95	90
		75%	0°	138	134				
			30°	153	146	204	176	120	106
			60°	166	172	260	208	111	100
		50%	0°	127	114				
			30°	145	134	206	158	123	110
			60°	160	163	229	175	111	101
feet close together	0°	100%	90°	100	121			43	43
one foot in front of the other,									
same side foot forward	0°	100%	90°	176	149			54	57
other side foot forward	0°	100%	90°	175	140			55	48

Various forces [N] in various standing postures, averages of 60 men.

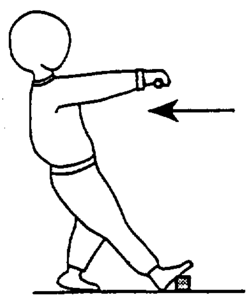


Van de Kerk & Voorbij (1993)

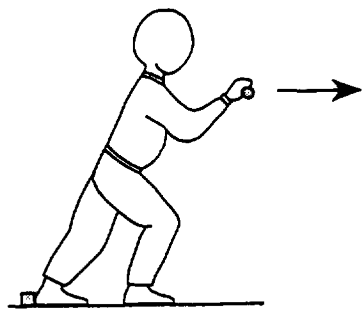
Source: Van de Kerk, B. and Voorbij, L. 1993.
Hoe sterk zijn kinderen? Onderzoek naar krachten van kinderen. Internal report.
Delft: Faculty of Industrial Design Engineering.

Subjects
Number: total 203
Sex: 95 girls and 108 boys.
Age: 4 to 12 years.
Other characteristics: -

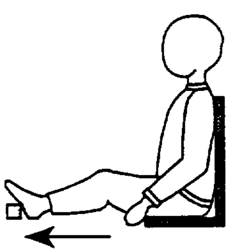
Method
Direction of force: push and pull.
Posture: standing and sitting, see figures.
Sort of force: maximal static peak force.
Laterality: two-handed.
Measurement: sudden peak force was measured. The children were encouraged during the measurements.
Sort of handle: a cylindrical bar.
Size of handle: Ø 3 cm.
Position of handle: see figures.
Other characteristics: -



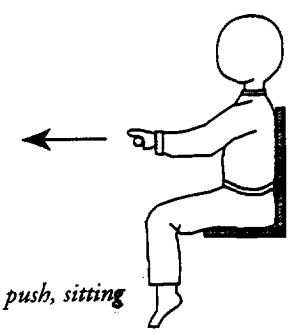
pull, standing



push, standing



push with legs



push, sitting

Results

force and posture	age [years]	girls n	girls x̄	girls s	girls range	boys n	boys x̄	boys s	boys range
a) push, standing	4	9	119.5	27.5	85.0 - 161.5	11	148.4	42.3	63.5 - 223.5
	5	16	151.1	37.8	79.0 - 216.5	19	191.3	37.4	130.5 - 258.0
	6	8	183.9	36.3	117.5 - 237.5	5	195.2	35.8	151.0 - 243.0
	7	13	274.5	52.5	218.5 - 361.0	12	273.8	35.6	226.0 - 331.0
	8	9	265.3	51.1	181.0 - 337.0	15	282.1	47.3	194.5 - 359.5
	9	14	319.0	71.1	197.0 - 500.5	14	365.8	80.9	247.0 - 529.0
	10	5	479.0	67.8	396.0 - 568.5	8	390.7	90.6	262.5 - 576.5
	11	13	386.4	56.1	293.5 - 468.0	10	432.2	154.9	288.0 - 727.0
	12	8	420.4	99.8	321.5 - 615.5	14	539.8	153.2	333.5 - 958.5
b) pull, standing	4	9	144.3	43.2	84.0 - 200.5	11	172.0	43.5	87.0 - 240.5
	5	16	182.2	69.4	99.5 - 371.0	19	217.6	66.1	122.5 - 345.0
	6	8	246.2	96.4	122.5 - 410.5	5	246.8	28.0	220.5 - 290.0
	7	13	351.2	109.5	227.0 - 627.0	12	402.1	101.1	254.0 - 540.0
	8	9	399.7	127.6	221.5 - 598.0	15	399.9	118.4	160.5 - 604.0
	9	14	433.2	118.2	280.5 - 677.5	14	509.8	127.6	285.5 - 788.0
	10	5	538.8	106.1	453.0 - 713.5	8	596.5	173.7	232.5 - 766.0
	11	13	582.0	152.5	315.5 - 820.5	10	622.5	146.0	407.5 - 864.5
	12	8	565.7	160.5	264.0 - 804.5	14	737.7	243.6	356.5 - 1182.0
c) push, sitting	4	9	214.6	78.9	107.5 - 358.0	11	193.1	55.2	110.0 - 263.5
	5	16	220.8	109.8	54.0 - 420.5	19	245.0	86.5	77.0 - 376.5
	6	8	295.8	57.1	180.5 - 350.5	5	299.4	46.7	242.0 - 366.5
	7	13	331.4	99.0	177.5 - 566.5	12	379.0	58.8	263.5 - 465.5
	8	9	416.1	89.7	238.0 - 532.5	15	378.7	72.7	252.0 - 492.5
	9	14	476.9	104.5	288.5 - 671.5	14	502.1	115.3	332.5 - 767.0
	10	5	602.6	84.4	518.5 - 729.5	8	532.0	78.1	401.0 - 625.5
	11	13	490.4	93.9	341.5 - 618.0	10	518.4	119.9	286.5 - 671.0
	12	8	497.9	95.5	363.0 - 651.5	14	673.9	174.6	354.5 - 978.0
d) push with legs	4	9	309.1	145.3	122.5 - 640.5	11	369.9	214.6	151.5 - 925.0
	5	16	408.0	228.5	89.0 - 819.5	19	470.0	287.9	98.0 - 1027.5
	6	8	516.2	257.0	180.0 - 933.0	5	372.2	39.2	325.5 - 425.5
	7	13	600.3	332.5	179.5 - 1234.0	12	718.3	285.8	320.0 - 1098.0
	8	9	793.3	378.2	370.0 - 1527.5	15	660.4	364.6	308.0 - 1828.5
	9	14	997.0	435.7	350.5 - 1843.0	14	1024.0	427.1	461.5 - 1924.5
	10	5	1321.3	383.4	821.0 - 1829.0	8	1206.7	455.9	448.5 - 1745.5
	11	13	808.8	353.7	424.5 - 1420.5	10	1006.8	572.2	360.5 - 1949.5
	12	8	739.6	222.8	391.5 - 1134.0	14	1291.3	515.9	552.0 - 1959.0

Various forces [N], averages of girls and boys between 4 and 12 years old.

Caldwell (1962)

Source Caldwell, L.S., 1962.
Body stabilization and the strength of arm extension.
Human Factors, 4, 125-130.

Subjects

Number: 9

Sex: probably men.

Age: average 24 years, range 22 - 26.

Other characteristics: body height: average 174.6 cm, range 1647.6 - 188.6;
body weight: average 71.7 kg, range 57.6 - 88.4.

Method

Direction of force: push

Posture: sitting, knee angle 140°, with five different elbow angles: 60°, 85°, 110°, 135° and 160°.

Sort of force: maximal static force.

Laterality: probably one (the right) hand.

Measurement: each trial lasted 7 s. The subject was told to push as hard as he could on the handle and to reach maximum output in about 3 s.
The subject was instructed to note his peak output on the meter and to do his best to exceed this on the next trial. The first trial of each pair was used as a 'motivator'. The results presented are based only on the second trials.

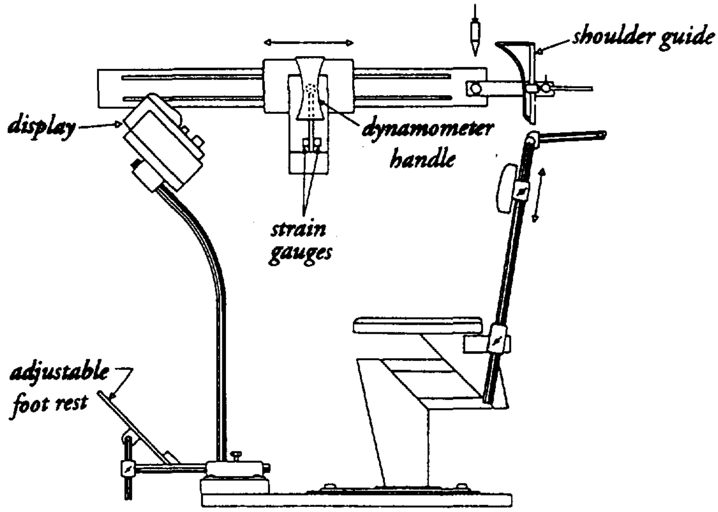
Sort of handle: ? see figure.

Size of handle: ?

Position of handle: at shoulder height, at a horizontal distance changing with the elbow angle (see posture).

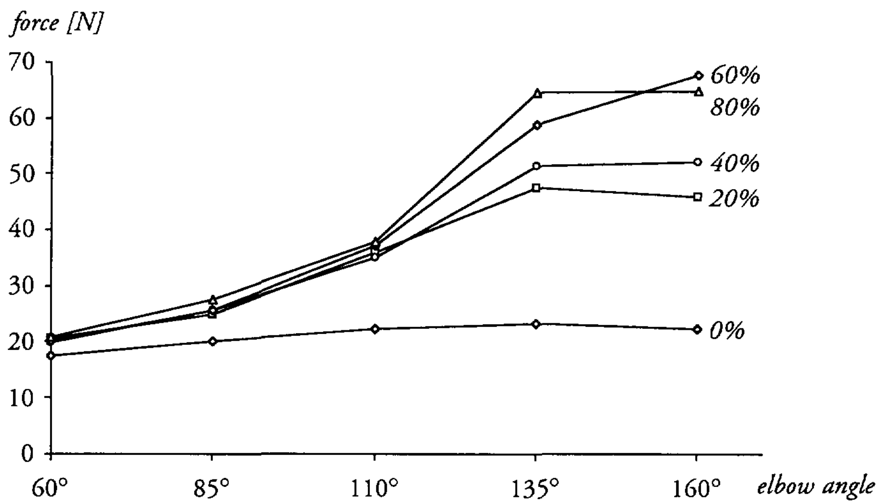
Other characteristics: 5 backrest conditions were included:
- no backrest;
- backrest height 20 % of shoulder height;
- backrest height 40 % of shoulder height;
- backrest height 60 % of shoulder height;
- backrest height 80 % of shoulder height.

A footrest was provided.



Results

backrest height [% of shoulder height]	elbow angle 60° $\bar{x}$	85° $\bar{x}$	110° $\bar{x}$	135° $\bar{x}$	160° $\bar{x}$	all angles $\bar{x}$
0%	17.4	20.1	22.4	23.2	22.2	21.0
20%	20.5	24.8	35.8	47.5	45.7	34.9
40%	19.9	25.5	35.0	51.3	51.9	36.7
60%	20.0	25.7	37.1	58.6	67.6	41.8
80%	20.9	27.5	37.9	64.4	64.8	43.1



Arm extension force [N] at five elbow-angles with different backrest positions. Averages of 9 subjects.

Daams (1994)

Source Daams, B.J., 1994.
Human force exertion in user-product interaction. Physical Ergonomics Series.
Delft: Delftse Universitaire Pers.

Subjects

Number: 24 for maximal force and endurance measurements,
17 for discomfort measurements.

Sex: maximal force and endurance: 12 female, 12 male;
discomfort: 8 female, 9 male.

Age: average 28.2 years (s = 11.2).

Other characteristics: university students and staff.

Method

Direction of force: push.

Posture: maximal force and endurance: sitting and standing, see figures;
discomfort: sitting.

Sort of force: maximal static force, endurance and discomfort of sub-maximal static force.
'discomfort' is measured as the time to the first change of hand when maintaining a sub-maximal push force with one hand.

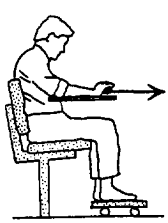
Laterality: maximal force and endurance: non-preferred hand sitting, preferred hand standing;
discomfort: alternating, starting with the preferred hand.

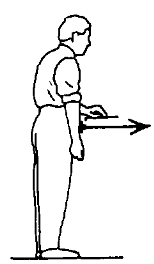
Measurement: duration of maximal force: 2 s build up, 4 s maximal force.
duration of endurance: measurement limit 30 minutes.
duration of discomfort measurements:
- at 80 % of maximal force 69 s;
- at 60 %: 144 s;
- at 40 %: 282 s;
- at 30 %: 474 s;
- at 20 %: 1170 s;
- at 15 %: 1800 s (30 min.).

Sort and size of handle: sitting: a slightly convex doorknob, round, Ø 59 mm. Force is exerted with the hand;
standing: a metal plate covered with soft plastic, size 13.5 * 4 cm. Force is exerted with the distal part of the lower arm.

Position of handle: see figure

Other characteristics: -





	females			males			both		
	$\bar{x}$	s	n	$\bar{x}$	s	n	$\bar{x}$	s	n
sitting, push	176.9	48.5	138	311.1	86.6	161	249.0	98.0	299
standing, push	63.8	13.8	99	114.6	29.7	100	89.3	34.4	199

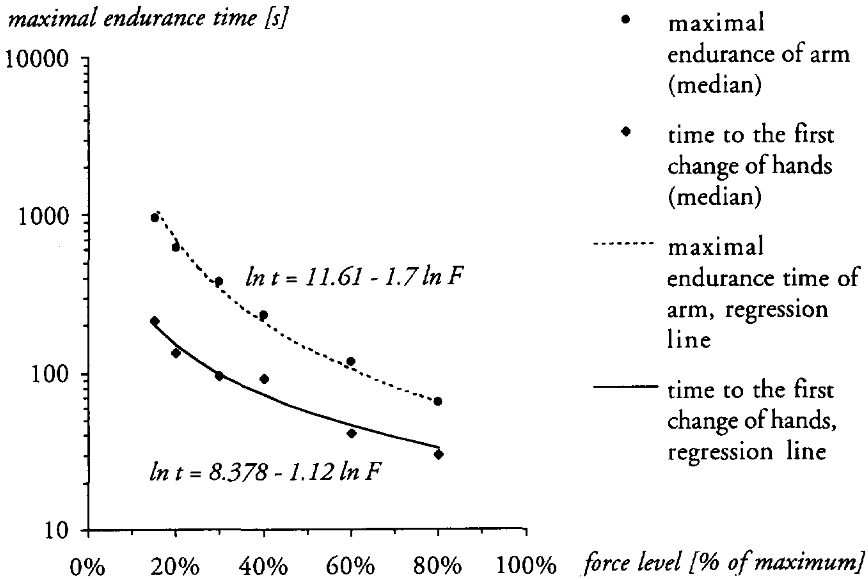
Push [N], ***maximal forces*** *exerted sitting and standing, averages and standard deviations and numbers of measurements of 12 women and 12 men.*

force level	P_{25}	P_{50}	P_{75}	range	$\bar{x}$	s	coeff. of variation	n
women (n=12)								
80%	58.8	75.0	107.0	27 - 166	86.3	37.8	0.44	23
60%	95.0	133.0	172.8	54 - 290	144.7	63.9	0.44	23
40%	150.3	230.0	381.5	95 - 457	258.7	119.9	0.46	23
30%	225.0	353.0	494.0	123 - 1389	426.6	293.8	0.69	22
20%	385.5	485.0	732.3	182 - 1800	652.5	450.3	0.69	19
15%	396.0	701.5	1182.0	313 - 1800	835.8	461.4	0.55	18
men (n=12)								
80%	52.0	58.5	82.5	28 - 76	65.2	23.7	0.36	24
60%	76.5	101.0	135.0	44 - 254	111.2	48.5	0.44	24
40%	162.0	237.5	334.5	93 - 574	254.8	119.4	0.47	24
30%	267.5	389.0	640.8	139 - 1800	557.7	460.0	0.82	23
20%	418.0	729.5	1187.0	253 - 1800	855.1	525.4	0.61	22
15%	785.0	1088.0	1800.0	409 - 1800	1229.0	535.9	0.44	23
women and men (n=24)								
80%	52.0	64.0	90.0	27 - 166	75.5	32.8	0.43	47
60%	85.0	116.0	156.5	44 - 290	127.6	58.4	0.46	47
40%	160.0	230.0	353.0	93 - 574	256.7	118.3	0.46	47
30%	252.8	378.0	609.3	123 - 1800	493.6	389.1	0.79	45
20%	401.3	621.5	915.8	182 - 1800	761.2	496.6	0.65	42
15%	603.3	946.0	1800.0	313 - 1800	1056.4	536.2	0.51	41

Maximal endurance time *[s] per force level. Median, percentiles, range, average, standard deviation, coefficient of variation and number of measurements of 24 subjects.*
The endurance times in the two postures are not significantly different and therefore presented together.

	force level	time [s]	P_{25}	P_{50}	P_{75}	range	$\bar{x}$	s	coeff. of variation
time to the first change of hand [s]	80%	69	22.0	27	38.5	17 - > 69	31.8	14.1	0.44
	60%	144	29.0	41	56.3	14 - 87	45.0	21.4	0.48
	40%	282	58.0	92	107.0	28 - 182	89.1	39.3	0.44
	30%	474	66.8	95	125.3	44 - 344	112.3	72.2	0.64
	20%	1170	109.3	134	212.5	88 - 848	211.2	208.3	0.99
	15%	1800	143.8	212	329.0	90 - 1295	321.9	323.3	1.00
total number of changes (n)	80%	69	1.0	2	2.0	0 - 4	1.71	0.92	0.54
	60%	144	2.0	3	3.3	1 - 5	2.88	1.11	0.39
	40%	282	3.0	4	6.0	1 - 9	4.35	2.09	0.48
	30%	474	3.0	4	7.0	1 - 8	4.82	2.13	0.44
	20%	1170	4.8	9	12.0	1 - 15	7.94	4.28	0.54
	15%	1800	4.8	9	12.3	1 - 19	8.82	4.94	0.56

*The **time to the first change of hand** [s] per force level. Median, percentiles, range, average, standard deviation and coefficient of variation of 17 subjects (8 female, 9 male).*



*Medians and interpolations of **maximal endurance time** and **time to the first change of hand** [s], for arms only.*

Hunsicker and Greey (1957)

Source Morgan, C.T., Cook, J.S., Chapanis, A. and Lund, M.W. (editors), 1963. *Human engineering guide to equipment design.* New York: McGraw-Hill.
VanCott, H.P. and Kinkade, R.G. (editors), 1972. *Human engineering guide to equipment design.* Washington: USGPO.

Original source: Hunsicker and Greey, 1957.

Subjects

Number: 30

Sex: male.

Age: ?

Other characteristics: college students.

Method

Direction of force: push, pull, to the left and to the right (all horizontal), up and down (both vertical).

Posture: sitting with back and feet supported, see figure. Hand pronated and supinated.

Sort of force: static maximal force.

Laterality: left and right hand separate.

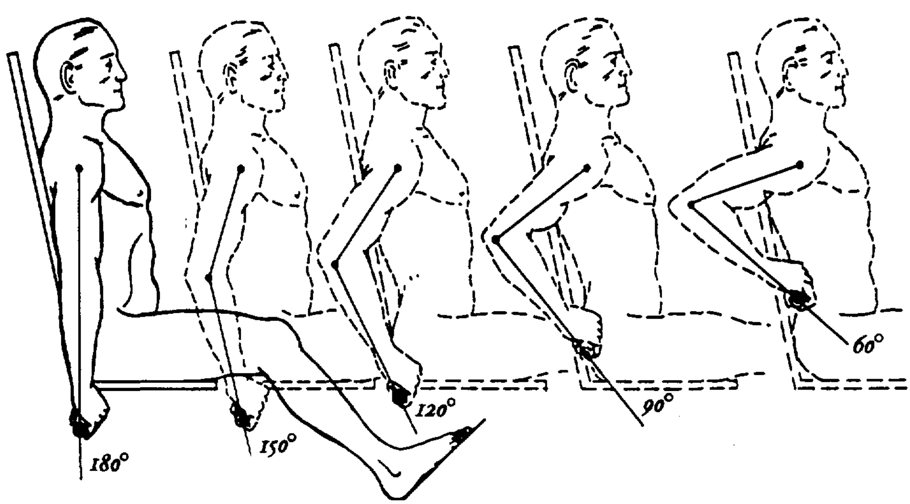
Measurement: ?

Sort of handle: 'a horizontal handgrip'.

Size of handle: ?

Position of handle: see figure and table.

Other characteristics: handgrip was oriented in a vertical lateral plane passing through the subject's external canthus (outside corner of the eye). Subjects wore no restraint harness.



Results

direction of force	elbow angle	left hand P5	left hand P50	left hand P95	left hand s	right hand P5	right hand P50	right hand P95	right hand s
push	60°	147	382	613	156	178	418	693	160
	90°	120	267	413	124	111	289	445	107
	120°	76	191	316	76	102	204	311	67
	150°	67	164	307	80	80	178	293	80
	180°	53	142	262	58	76	142	262	53
pull	60°	89	173	284	80	58	164	222	71
	90°	76	164	289	80	62	142	240	58
	120°	53	133	249	62	58	116	191	44
	150°	67	142	231	58	53	129	213	44
	180°	71	151	271	67	49	124	213	53
to the left	60°	89	187	293	67	84	182	320	84
	90°	76	169	267	53	53	138	284	67
	120°	76	151	236	36	40	116	236	58
	150°	76	138	240	49	40	93	173	49
	180°	67	124	182	36	44	84	151	31
to the right	60°	80	160	227	67	71	213	324	80
	90°	49	120	240	49	71	173	262	67
	120°	44	98	173	44	67	151	209	49
	150°	40	102	236	71	80	142	200	31
	180°	44	89	218	58	71	138	253	58
lift	60°	98	253	445	98	102	218	351	89
	90°	164	342	547	107	124	307	498	129
	120°	200	405	645	133	182	405	613	133
	150°	258	445	707	142	191	440	733	169
	180°	209	449	760	49	156	422	693	156
press	60°	80	329	618	156	102	360	702	156
	90°	102	333	605	151	98	369	631	156
	120°	129	333	658	178	164	409	716	156
	150°	173	351	605	124	178	400	685	151
	180°	151	338	613	138	182	387	636	138

Various forces [N] exerted on a ***horizontal*** *handgrip with the hand* ***pronated*** *(the palm of the hand downwards). Averages, percentiles and standard deviations of 30 seated males.*

direction of force	elbow angle	left hand P5	P50	P95	s	right hand P5	P50	P95	s
push	60°	156	396	782	187	151	427	765	173
	90°	111	262	462	120	111	289	520	107
	120°	67	178	356	80	89	191	316	76
	150°	58	169	307	133	76	160	262	62
	180°	62	133	209	44	53	142	258	67
pull	60°	102	240	387	102	71	227	413	111
	90°	58	187	302	93	58	191	329	84
	120°	62	178	293	80	49	178	280	76
	150°	71	178	276	67	49	164	293	76
	180°	76	178	311	80	67	173	324	84
to the left	60°	71	169	284	53	80	196	324	84
	90°	53	142	204	53	80	173	320	107
	120°	62	138	244	58	76	151	284	67
	150°	53	142	276	67	67	142	267	62
	180°	53	129	191	40	62	129	213	53
to the right	60°	76	187	360	89	58	160	311	76
	90°	71	147	231	53	58	138	213	53
	120°	62	124	200	36	53	133	204	49
	150°	53	116	191	44	53	138	231	62
	180°	36	120	196	44	44	124	196	44
lift	60°	89	218	396	98	76	200	347	98
	90°	107	333	582	129	93	280	476	120
	120°	169	418	676	147	182	391	636	147
	150°	196	462	729	133	164	458	716	178
	180°	213	493	769	178	227	502	733	151
press	60°	89	258	613	182	89	262	587	156
	90°	102	356	711	191	76	356	636	164
	120°	156	373	605	147	129	409	658	58
	150°	191	373	605	129	164	413	667	156
	180°	160	347	551	124	196	387	600	142

*Various forces [N] exerted on a **horizontal** handgrip with the hand **supinated** (the palm of the hand upwards). Averages, percentiles and standard deviations of 30 seated males.*

Hunsicker (1955)

Source Morgan, C.T., Cook, J.S., Chapanis, A. and Lund, M.W. (editors), 1963.
Human engineering guide to equipment design. New York: McGraw-Hill.
VanCott, H.P. and Kinkade, R.G. (editors), 1972.
Human engineering guide to equipment design. Washington: USGPO.

Original source: Hunsicker, 1955.

Subjects

Number: 55

Sex: male.

Age: ?

Other characteristics: college students.

Method

Direction of force: push, pull, to the left and to the right (all horizontal), up and down (both vertical).

Posture: sitting with vertical back support and feet supported, see figure.

Sort of force: static maximal force.

Laterality: left and right hand separate.

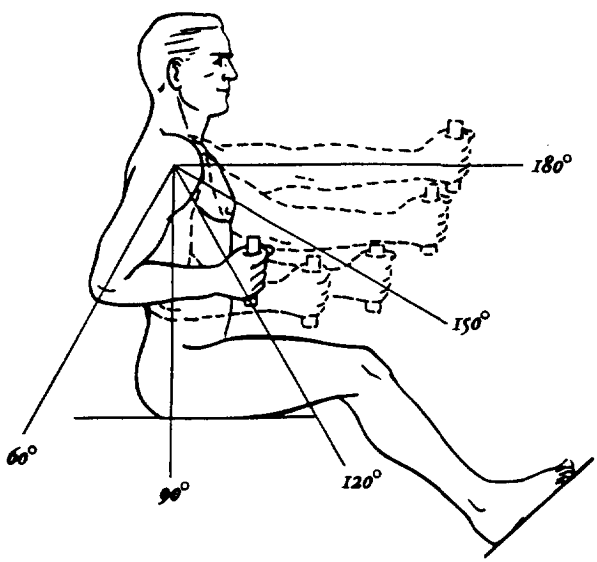
Measurement: ?

Sort of handle: 'a vertical handgrip'.

Size of handle: ?

Position of handle: see figure and table.

Other characteristics: subjects wore no restraint harness.



Results

direction of force	elbow angle	left hand P_5	left hand P_{50}	left hand P_{95}	left hand s	right hand P_5	right hand P_{50}	right hand P_{95}	right hand s
push	60°	98	356	729	138	151	409	667	169
	90°	98	369	765	156	160	387	685	147
	120°	116	440	800	187	160		765	191
	150°	133	493	853	213	187	547	862	200
	180°	187	560	871	209	222	613	933	218
pull	60°	116	284	489	102	107	280	329	98
	90°	142	356	542	124	164	391	600	133
	120°	151	418	676	151	187	462	685	138
	150°	187	498	747	164	249	542	840	160
	180°	222	520	765	164	231	538	760	164
to the left	60°	53	142	276	76	89	231	387	84
	90°	44	147	320	84	80	222	431	102
	120°	44	133	302	80	98	236	445	116
	150°	36	129	293	89	89	240	462	111
	180°	36	133	284	89	89	222	462	116
to the right	60°	76	222	369	93	76	187	365	89
	90°	71	213	387	98	71	164	302	80
	120°	89	200	396	93	67	138	276	76
	150°	67	209	502	120	67	147	284	80
	180°	80	191	409	98	62	156	276	107
lift	60°	67	196	365	80	89	218	365	80
	90°	76	231	445	98	89	249	471	98
	120°	76	240	453	111	107	267	551	107
	150°	67	231	489	120	80	293	525	124
	180°	40	182	369	102	62	191	391	98
press	60°	80	204	338	80	89	227	396	93
	90°	93	218	409	89	116	240	391	89
	120°	93	227	453	102	116	258	436	102
	150°	80	182	329	71	89	209	356	80
	180°	58	156	320	67	76	182	365	80

*Various forces [N] exerted on a **vertical** handgrip. Averages, percentiles and standard deviations for 55 seated males.*

Laubach (1978)

Source Laubach, L.L. 1978.
Human muscular strength. Chapter 7 in *Anthropometric Source Book. Volume 1: Anthropometry for Designers.* NASA reference publication 1024.

Subjects

Number: 55

Sex: male.

Age: average 21.3 years (s = 3.2).

Other characteristics: body weight average 75.1 kg (s = 14.0), body height average 176.9 cm (s = 5.6)

Method

Direction of force: push (horizontal).

Posture: sitting, with back support, see tables.

Sort of force: probably static maximal force.

Laterality: right hand.

Measurement: according to Caldwell et al. (1974) (≈ 1 s built-up, 4 s maximal force, B.D.), the score is the peak force exerted.

Sort of handle: knurled aluminium cylinder.

Size of handle: Ø 3.8 cm, length 12 cm.

Position of handle: the orientation of the handles was always vertical and the requested direction of the exertion was in a horizontal plane in the forward direction.The position of the handle, relative to the Seat Reference Point, is indicated in the tables. The Seat Reference Point is the point of intersection of the seat pan with the midline of the seat back.

Other characteristics: seat back angles of 13°, 25° and 65°. The feet are supported. The free hand is not allowed to grasp the chair during force exertion.

Results

seat back angle	location of the handle: above SRP* [cm]	forward of SRP* [cm]	left/right of SRP* [cm]	push: x̄	s	P_5	P_{95}
65°	38	15	51 right	272.4	91.1	153.9	426.3
	38	15	38 right	362.6	110.7	191.1	339.1
	31	15	25 left	487.1	149.0	204.8	708.5
	51	30	0	351.8	98.0	203.8	527.2
	31	13	64 right	228.3	81.3	115.6	385.1
	64	5	64 right	241.1	74.5	139.2	483.1
	64	28	25 right	534.1	149.0	322.4	804.6
	64	28	0	483.1	123.5	297.9	651.7
	64	20	13 left	604.7	160.7	345.9	870.2
	76	3	25 left	488.0	177.4	236.2	825.2
	76	18	0	559.6	156.8	297.9	798.7
	76	20	13 right	625.2	160.7	373.4	860.4
	76	8	51 right	320.5	97.0	180.3	488.0
	89	3	0	394.0	155.8	175.4	683.1
	89	3	25 right	495.9	179.3	253.8	793.8
25°	38	38	25 left	348.9	100.9	188.2	523.3
	38	43	0	307.7	94.1	172.5	478.2
	38	41	25 right	353.8	106.8	212.7	583.1
	31	20	64 right	229.3	68.6	127.4	356.7
	31	38	38 right	408.7	124.5	244.0	647.8
	31	43	13 right	464.5	133.3	269.5	691.9
	31	46	25 left	473.3	133.3	282.2	704.6
	64	25	38 left	390.0	106.8	242.1	598.8
	64	56	13 left	537.0	137.2	324.4	799.7
	64	56	0	484.1	108.8	319.5	649.7
	64	51	25 right	600.7	157.8	342.0	850.6
	64	38	51 right	399.8	116.6	231.3	590.9
	76	25	64 right	288.1	80.4	165.6	429.2
	76	46	38 right	584.1	175.4	364.6	884.0
	76	48	0	628.2	148.0	361.6	859.5
	76	43	25 left	695.8	182.3	416.5	1000.6
	89	46	13 left	698.7	213.6	339.1	1081.9
	89	48	0	682.1	176.4	389.1	984.9
	89	51	25 right	735.0	187.2	435.1	1054.5
	89	41	51 right	492.0	172.5	253.8	816.3
	102	5	64 right	225.4	56.8	147.0	330.3
	102	41	13 right	648.8	204.8	353.8	958.4
	102	38	0	518.4	161.7	304.8	836.9
	102	23	25 left	400.8	105.8	247.0	598.8

Push [N] exerted sitting with various seat back angles. Average, standard deviation and percentiles of 55 males.

** SRP = Seat Reference Point, point of intersection of the seat pan with the midline of the seat back.*

	location of the handle			push			
seat back angle	above SRP* [cm]	forward of SRP* [cm]	left/right of SRP* [cm]	$\bar{x}$	s	P_5	P_{95}
25°	114	13	13 left	298.9	101.9	158.8	480.2
	114	25	25 right	452.8	132.3	241.1	676.2
	114	20	38 right	394.9	110.7	227.4	588.0
13°	38	46	25 left	330.3	81.3	192.1	459.6
	38	48	0	307.7	85.3	185.2	465.5
	38	48	13 right	345.9	102.9	211.7	550.8
	38	41	38 right	300.9	76.4	178.4	433.2
	38	30	51 right	247.9	66.6	147.0	365.5
	51	41	51 right	314.6	82.3	197.0	473.3
	51	51	25 right	422.4	107.8	267.5	623.3
	51	51	13 right	417.5	112.7	249.9	621.3
	51	53	0	357.7	100.0	218.5	556.6
	51	51	13 left	434.1	110.7	244.0	605.6
	64	58	25 left	590.0	148.0	336.1	817.3
	64	69	0	475.3	109.8	277.3	609.6
	64	58	38 right	534.1	158.8	307.7	846.7
	64	38	64 right	289.1	86.2	179.3	459.6
	76	53	51 right	453.7	146.0	227.4	723.2
	76	64	25 right	668.4	178.4	366.5	975.1
	76	64	0	588.0	139.2	335.2	800.7
	76	58	13 left	641.9	160.7	389.1	931.0
	76	25	38 left	363.6	92.1	229.3	528.2
	89	46	25 left	511.6	148.0	283.2	763.4
	89	61	0	662.5	163.7	399.8	936.9
	89	61	13 right	724.2	178.4	474.3	1038.8
	89	56	38 right	651.7	192.1	325.4	984.9
	89	8	76 right	166.6	46.1	101.9	256.8
	102	25	64 right	256.8	70.6	151.9	388.1
	102	53	25 right	707.6	189.1	430.2	1039.8
	102	51	0	505.7	149.9	307.7	781.1
	102	48	13 left	514.5	171.5	290.1	834.0
	114	30	13 left	295.0	90.2	158.8	454.7
	114	38	0	314.6	92.1	186.2	496.9
	114	20	51 right	278.3	63.7	193.1	395.9
	127	36	13 right	378.3	92.1	191.1	502.7
	127	33	0	306.7	95.1	183.3	491.0
	127	25	25 left	318.5	82.3	201.9	470.4

continued

Morgan et al. (1963)

Source Morgan, C.T., Cook, J.S., Chapanis, A. and Lund, M.W. (editors), 1963. *Human engineering guide to equipment design.* New York: Mc Graw-Hill.
VanCott, H.P. and Kinkade, R.G. (editors), 1972. *Human engineering guide to equipment design.* Washington: USGPO.

Original source: unpublished data of the Aerospace Medical Research Laboratories.

Subjects

Number: 15 (two-handed measurements) and 48 (one-handed measurements).

Sex: male.

Age: ?

Other characteristics: air force personnel.

Method

Direction of force: push, pull, to the left and to the right.

Posture: sitting, see figures.

Sort of force: static maximal force.

Laterality: right hand and both hands.

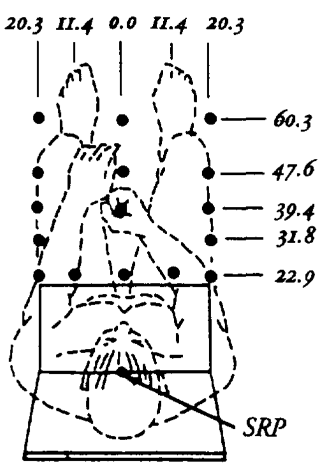
Measurement: ?

Sort of handle: a) 'an aircraft control wheel' and
b) 'an aircraft control stick'.

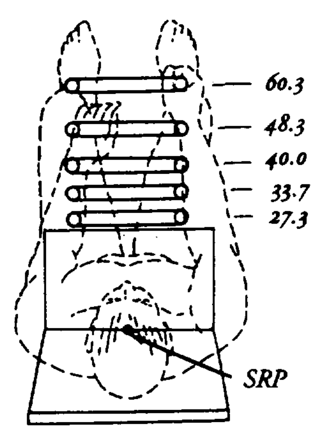
Size of handle: ?

Position of handle: see figure and table.
a) stick is grasped 34 cm above the Seat Reference Point.
b) wheel grips are 46 cm above the Seat Reference Point and 38 cm apart.
The Seat Reference Point is the point of intersection of the seat pan with the midline of the seat back.

Other characteristics: -



a) aircraft control stick



b) aircraft control wheel

Results

location of the handle forward of SRP* [cm]	distance from mid-plane of body [cm]	right hand P5	right hand P50	right hand P95	both hands P50	right hand P5	right hand P50	right hand P95	both hands P50
			push				**pull**		
22.9	0.0	116	204	298	440	151	253	382	471
	11.4 left	80	147	240	391	124	200	293	471
	20.3 left	53	129	196	342	116	178	298	413
	11.4 right	151	258	365	440	173	276	391	471
	20.3 right	164	289	422	440	173	258	382	471
31.8	20.3 left	80	160	302	489	147	236	342	533
	20.3 right	191	329	453	489	218	356	480	533
39.4	0.0	191	382	711	733	240	369	502	649
	20.3 left	102	267	525	538	173	284	436	591
	20.3 right	236	445	729	636	244	396	529	649
47.6	0.0	284	551	787	685	249	382	565	711
	20.3 left	160	320	507	538	200	329	480	649
	20.3 right	311	556	880	685	258	440	560	711
60.3	0.0	240	471	627	489	276	453	613	769
	20.3 left	129	284	462	391	227	400	573	769
	20.3 right	249	445	653	440	258	458	591	769
			to the left				**to the right**		
22.9	0.0	133	209	293		102	169	218	
	11.4 left	138	218	298		138	213	284	
	20.3 left	107	196	289		151	244	329	
	11.4 right	116	204	347		67	120	227	
	20.3 right	116	196	320		53	98	191	
31.8	20.3 left	102	196	311		138	213	311	
	20.3 right	98	173	262		71	107	204	
39.4	0.0	107	169	231		89	124	173	
	20.3 left	89	156	258		111	191	280	
	20.3 right	107	178	311		58	98	218	
47.6	0.0	36	142	236		67	111	156	
	20.3 left	71	133	249		98	160	271	
	20.3 right	98	173	311		62	107	222	
60.3	0.0	62	129	204		58	89	133	
	20.3 left	49	93	218		84	138	213	
	20.3 right	89	164	293		53	98	227	

a) Various forces [N] exerted on an aircraft control ***stick.*** *Percentiles of male airforce personnel.*

** The Seat Reference Point is the point of intersection of the seat pan with the midline of the seat back.*

location of the handle									
forward of SRP* [cm]	control position	right hand			both hands	right hand			both hands
		P_5	P_{50}	P_{95}	P_{50}	P_5	P_{50}	P_{95}	P_{50}
		push				**pull**			
27.3	0°	231	382	600	653	196	293	453	560
	45° left	213	373	662	653	178	298	493	560
	90° left	142	298	556	458	102	244	485	436
	45° right	178	298	569	653	173	298	431	560
	90° right	84	231	498	391	80	191	387	436
33.7	90° left	142	240	413	391	147	298	533	498
	90° right	111	227	369	391	138	267	453	498
40.0	0°	271	400	689	787	293	418	645	685
	90° left	142	262	618	525	187	316	640	622
	90° right	142	236	453	587	218	356	578	622
48.3	0°	284	538	1 045	1 178	324	471	751	871
	90° left	164	391	760	720	267	391	565	685
	90° right	147	298	622	720	271	418	662	747
60.3	0°	467	760	1 076	1 178	342	556	809	1 040
	90° left	365	582	938	787	324	520	720	809
	90° right	218	520	876	849	329	489	827	871
		to the left				**to the right**			
27.3	0°	116	204	391	409	89	213	427	405
	45° left	93	240	547	453	107	307	538	587
	90° left	102	209	405	453	120	262	449	449
	45° right	138	240	533	591	107	227	525	493
	90° right	93	187	462	542	67	240	498	538
33.7	90° left	116	196	382	453	93	231	436	493
	90° right	111	200	440	542	84	227	493	449
40.0	0°	120	204	498	453	120	262	431	449
	90° left	120	191	365	365	84	236	427	449
	90° right	129	222	382	498	89	204	405	405
48.3	0°	111	196	422	453	133	280	462	449
	90° left	98	191	338	365	120	204	418	449
	90° right	147	231	462	542	98	182	387	360
60.3	0°	89	173	382	409	156	267	436	449
	90° left	93	169	324	316	116	187	365	405
	90° right	116	244	485	453	98	178	302	316

b) Various forces [N] exerted on an aircraft control ***wheel****. Percentiles of male airforce personnel.*

** The Seat Reference Point is the point of intersection of the seat pan with the midline of the seat back.*

Frank et al. (1985)

Source Frank, P., Han, F. and Spangenberg, S., 1985.
Krachtuitoefening bij kinderen in een Vliegende Hollander. Internal report no. 66. Delft: Department of Product and Systems Ergonomics, Faculty of Industrial Design Engineering.

Subjects

Number: 59

Sex: youngest group: 13 girls, 18 boys;
oldest group: 14 girls, 14 boys.

Age: youngest group: 5.5 to 8.5 years;
oldest group: 10 to 13 years.

Other characteristics: length and length/weight ratio are sufficiently representative for Dutch children.

body height,	youngest group:	average 125.6 cm (s = 6.7);
	oldest group:	average 149.1 cm (s = 8.5);
body weight,	youngest group:	average 24.6 kg (s = 3.9);
	oldest group:	average 39.1 kg (s = 8.1).

distance of back to feet when the knees are at an angle of 110°:

	youngest group:	average 59.1 cm (s = 6.1);
	oldest group:	average 76.9 cm (s = 7.4).

Method

Direction of force: push and pull.

Posture: sitting in an experimental situation similar to a *'Vliegende Hollander'* (Flying Dutchman, children's vehicle propelled by pushing and pulling with arms and upper body), see figures.
Two different postures: with knees at an angle of 110° and at an angle of 160°. Apart from this, the posture was free.

Sort of force: maximal static force.

Laterality: both hands.

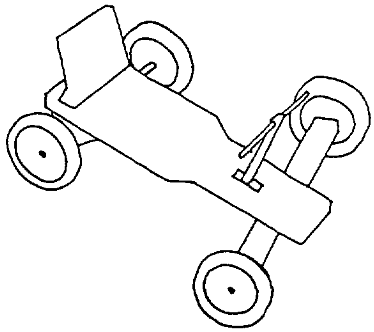
Measurement: ?

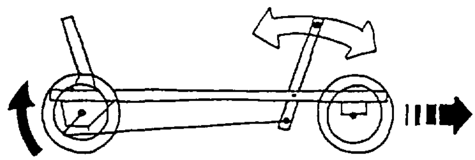
Sort of handle: a cylindrical bar.

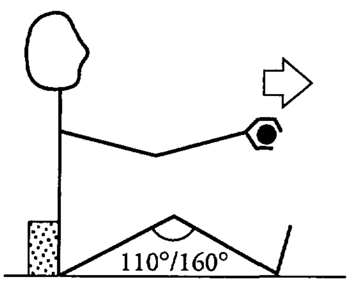
Size of handle: ?

Position of handle: see figure, height not known.

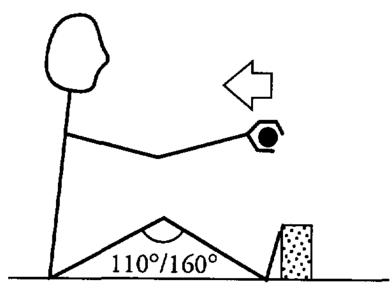
Other characteristics: a foot support was provided, to push against.







posture during push

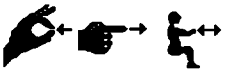


posture during pull

Results

age	n	force	$\bar{x}$	s	P_5	P_{95}
5.5 – 8.5 years	31	push	151.9	33.7	96.3	207.6
		pull (knee 110°)	333.9	103.3	163.4	504.4
		pull (knee 160°)	373.4	82.1	237.9	508.9
10 – 13 years	28	push	230.5	57.2	136.1	324.9
		pull (knee 110°)	573.9	159.1	311.3	836.4
		pull (knee 160°)	603.6	133.8	382.8	824.4

Push and pull [N], average, standard deviation and percentiles of children.



Steenbekkers (1993)

Source Steenbekkers, L.P.A, 1993.
Child development, design implications and accident prevention. Physical Ergonomics Series. Delft: Delftse Universitaire Pers.

Subjects

Number: 782

Sex: 392 girls, 390 boys.

Age: 4 to 13 years.

Other characteristics: Dutch children, selected to be representative for the Netherlands.

Method

Direction of force: push and pull with hand and fingers.

Posture: sitting before the measuring device, which is in front of the forearm. The forearm is horizontal and in a sagittal plane. Upper arm and forearm are at an angle of about 150°. The legs hang down freely or are positioned forward.
a) pulling with the hand: the bar is placed vertically, its axis between middle finger and ring finger.
b) pulling with thumb and forefinger: the finger is placed on top of a round knob, the thumb is on the bottom of the knob. The other fingers are flexed into a fist.
c) pushing with the hand: force is exerted with the palm of the hand;
d) pushing with the forefinger: the finger is placed in the middle of a round concave knob. The other fingers and the thumb are flexed into a fist.

Sort of force: maximal static force.

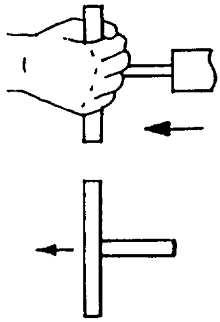
Laterality: preferred and non-preferred hand (they are not significantly different and therefore represented in one table).

Measurement: duration 3 s.

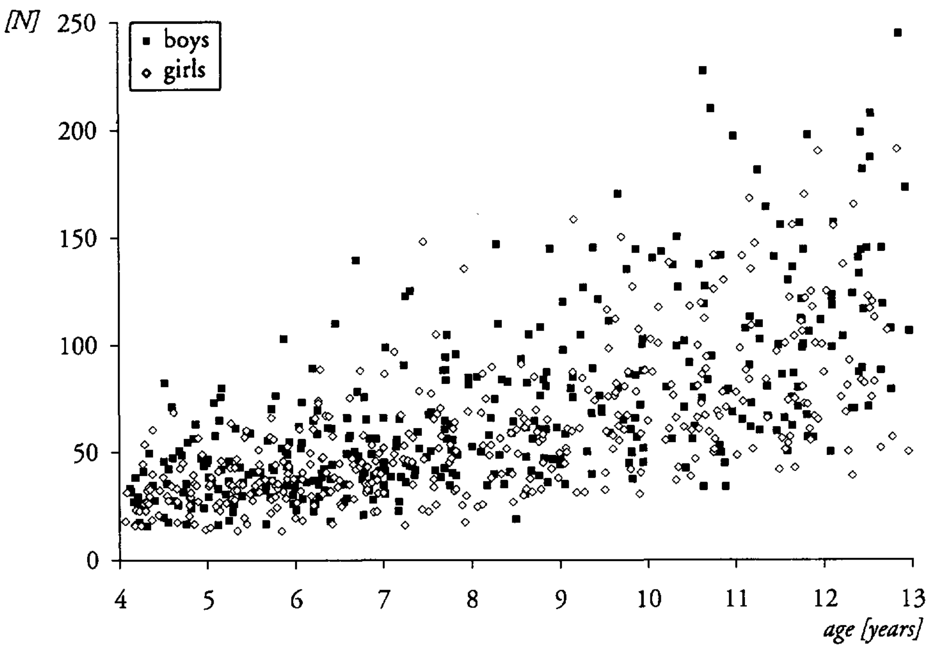
Sort and size of handle: a) vertical bar, Ø 1.1 cm;
b) round concave knob, Ø 2 cm;
c) round convex knob, Ø 4 cm;
d) round concave knob, Ø 2 cm.

Position of handle: mounted on a table.

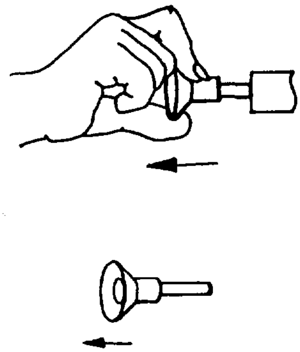
Other characteristics: -



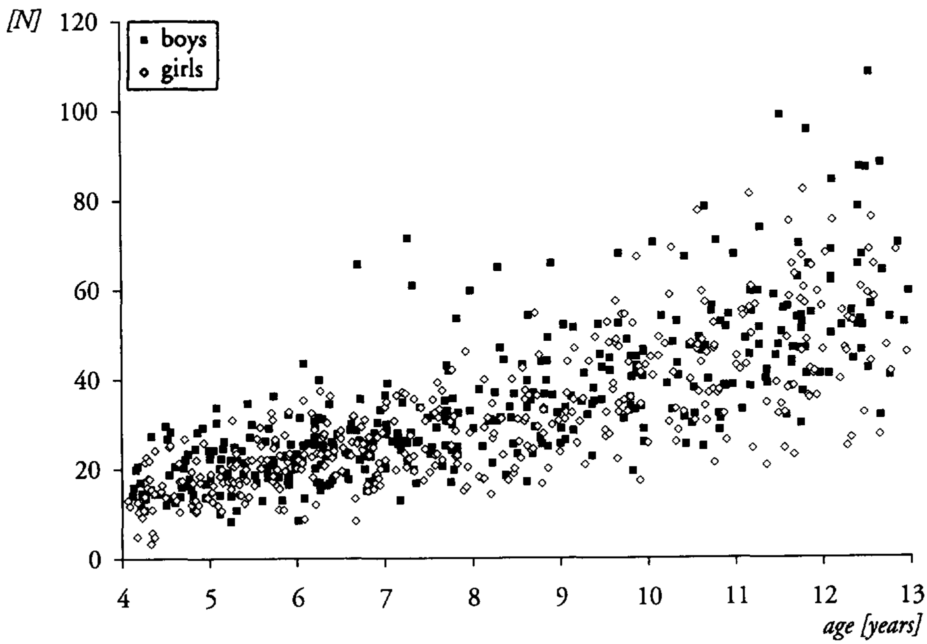
age [years]	girls n	girls $\bar{x}$	girls s	girls P_3	girls P_{97}	boys n	boys $\bar{x}$	boys s	boys P_3	boys P_{97}	all $\bar{x}$	all s
4.0 – 4.9	46	31.2	12.5	15.9	60.6	41	36.9	15.1	16.9	71.4	33.9	14.0
5.0 – 5.9	59	36.3	12.1	13.7	63.7	53	43.3	17.7	16.9	80.2	39.6	15.3
6.0 – 6.9	57	44.0	16.4	18.6	88.3	59	48.1	21.7	21.0	110.3	46.1	19.3
7.0 – 7.9	42	55.0	28.5	17.6	135.7	50	59.0	24.5	27.0	122.9	57.2	26.3
8.0 – 8.9	40	53.8	17.7	25.9	90.1	41	66.3	28.6	30.6	145.1	60.1	24.5
9.0 – 9.9	42	72.2	29.8	31.4	150.6	41	81.3	32.9	37.8	145.6	76.7	31.5
10.0 – 10.9	39	80.6	28.5	38.9	138.6	35	99.7	49.7	34.3	210.2	89.7	40.8
11.0 – 11.9	44	93.5	36.8	42.9	170.3	40	100.6	37.2	57.0	181.5	96.9	36.9
12.0 – 12.9	23	97.8	40.0	39.2	191.2	30	127.0	45.9	50.2	244.9	114.3	45.5



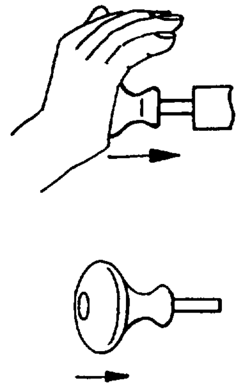
a) Pull [N] with one hand. Averages, standard deviations and percentiles of girls and boys.



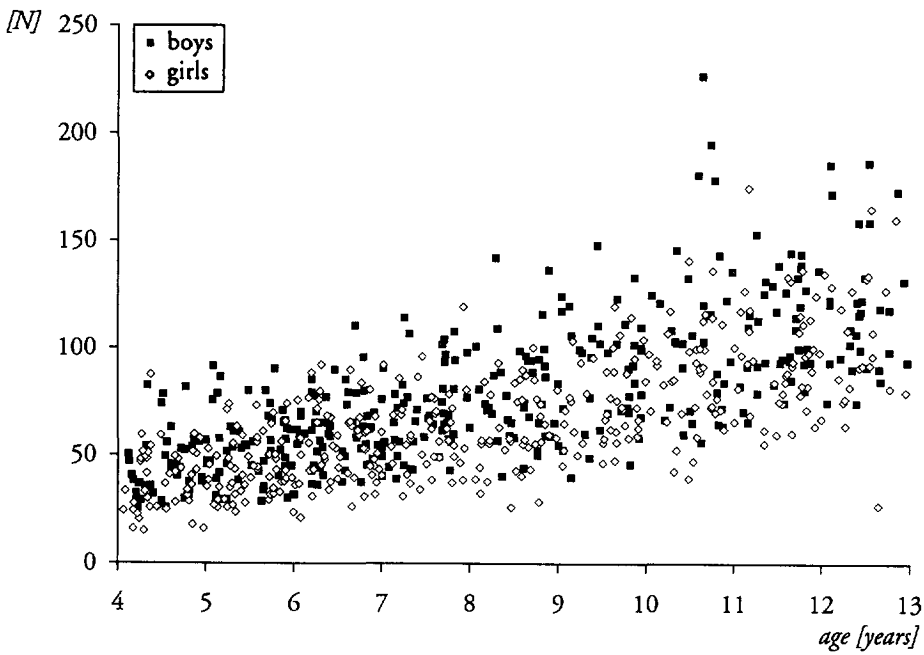
age [years]	girls n	girls $\bar{x}$	girls s	girls P_3	girls P_{97}	boys n	boys $\bar{x}$	boys s	boys P_3	boys P_{97}	all $\bar{x}$	all s
4.0– 4.9	46	15.3	5.7	4.8	25.9	41	18.3	5.5	11.4	29.3	16.7	5.8
5.0– 5.9	59	20.0	5.3	10.9	32.6	53	21.6	6.0	10.1	34.7	20.7	5.7
6.0– 6.9	57	23.7	6.4	8.8	36.3	59	25.3	8.5	13.5	43.6	24.5	7.5
7.0– 7.9	42	27.7	7.6	15.9	42.1	50	30.5	11.2	16.8	61.0	29.2	9.8
8.0– 8.9	40	28.9	8.7	16.6	45.3	41	34.7	10.9	18.5	64.9	31.8	10.2
9.0– 9.9	42	38.7	10.8	20.9	57.4	41	39.0	9.6	22.8	52.3	38.9	10.2
10.0–10.9	39	42.0	11.8	25.9	69.2	35	45.7	13.9	25.4	70.8	43.7	12.9
11.0–11.9	44	48.1	14.9	23.0	81.2	40	51.3	14.5	31.8	95.5	49.6	14.7
12.0–12.9	23	51.4	15.2	24.8	75.9	30	60.9	17.2	31.7	108.2	56.8	16.9



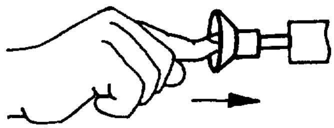
b) Pull [N] with thumb and forefinger. Average, standards deviations and percentiles of girls and boys.

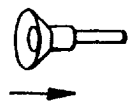


age [years]	girls n	girls x̄	girls s	girls P_3	girls P_{97}	boys n	boys x̄	boys s	boys P_3	boys P_{97}	all x̄	all s
4.0 – 4.9	46	38.7	15.0	16.1	60.0	41	45.9	15.0	25.7	81.7	42.1	15.3
5.0 – 5.9	59	44.4	13.8	23.8	73.9	53	54.2	16.6	28.8	90.4	49.0	15.9
6.0 – 6.9	57	55.0	16.9	26.3	90.1	59	61.9	15.6	36.5	95.7	58.5	16.6
7.0 – 7.9	42	60.9	18.9	34.3	96.2	50	69.7	19.6	40.4	108.0	65.6	19.7
8.0 – 8.9	40	62.4	18.8	28.6	93.2	41	79.4	22.5	44.3	136.9	71.0	22.3
9.0 – 9.9	42	74.5	19.3	46.6	114.9	41	88.6	25.6	46.2	133.6	81.5	23.6
10.0 – 10.9	39	86.4	23.6	42.8	136.7	35	108.9	40.6	59.9	195.5	97.0	34.4
11.0 – 11.9	44	94.3	24.8	59.9	137.0	40	108.5	23.3	70.6	144.9	101.1	25.0
12.0 – 12.9	23	104.0	32.5	27.0	165.5	30	118.9	31.7	74.8	186.9	112.5	32.6

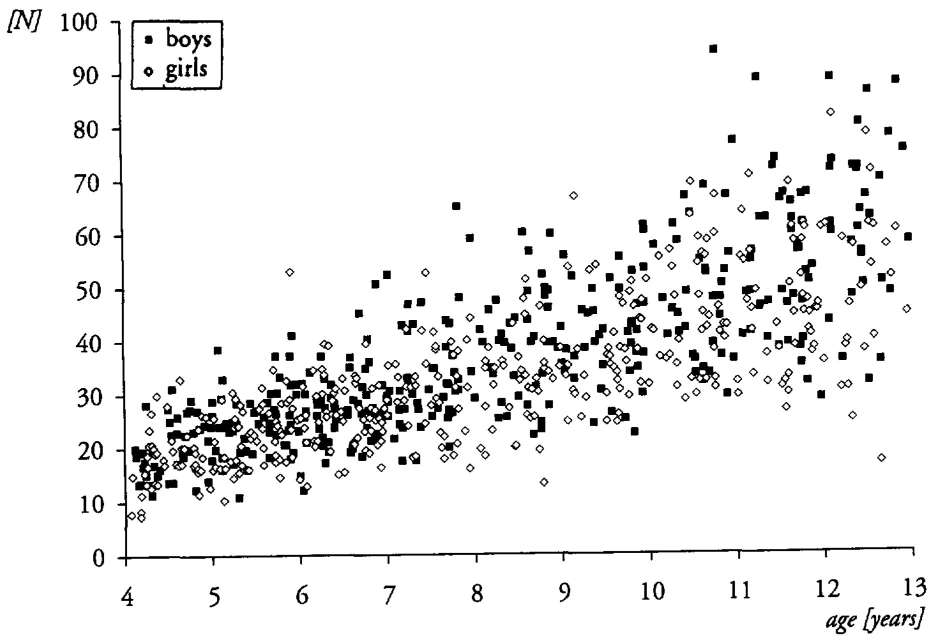


c) Push [N] with one hand. Averages, standard deviations and percentiles of girls and boys.





age [years]	girls n	girls x̄	girls s	girls P_3	girls P_{97}	boys n	boys x̄	boys s	boys P_3	boys P_{97}	all x̄	all s
4.0 – 4.9	46	18.3	5.5	7.8	29.9	41	20.0	5.3	12.3	29.0	19.1	5.4
5.0 – 5.9	59	22.8	6.7	14.2	34.7	53	25.2	6.1	16.0	38.6	24.0	6.5
6.0 – 6.9	57	26.3	6.0	15.0	39.4	59	27.5	6.8	14.8	45.2	26.9	6.5
7.0 – 7.9	42	30.8	8.4	17.9	44.2	50	33.1	9.9	17.6	59.0	32.1	9.3
8.0 – 8.9	40	32.3	8.4	18.4	47.6	41	39.1	9.8	23.2	59.7	35.7	9.7
9.0 – 9.9	42	38.1	9.7	24.6	53.9	41	41.2	9.6	24.3	60.4	39.6	9.7
10.0 – 10.9	39	44.7	11.0	29.7	66.7	35	49.4	14.0	32.1	76.8	46.9	12.7
11.0 – 11.9	44	45.7	11.3	29.5	69.1	40	52.8	12.7	31.9	73.5	49.1	12.5
12.0 – 12.9	23	50.1	16.4	16.9	81.6	30	62.3	15.1	31.9	88.4	57.0	16.7



d) Push [N] with forefinger. Averages, standard deviations and percentiles of girls and boys.

Fothergill et al. (1992)

Source Fothergill, D.M., Grieve, D.W. and Pheasant, S.T., 1992.
The influence of some handle designs and handle height on the strength of the horizontal pulling action. *Ergonomics*, 35 (2), 203-212.

Subjects

Number: 30

Sex: 16 female, 14 male.

Age: average 30.0 (s = 8.2).

Other characteristics: volunteer staff and students.
body height: average 170.4 cm (s = 9.6);
body weight: average 67.5 kg (s = 9.4).

Method

Direction of force: pull.

Posture: standing. The type of grip on each handle and the posture adopted were freely chosen, provided that 1) only the dominant hand was used on the handle/bar; 2) only the feet made contact with the floor; and 3) the leading foot was not placed in front of the handle.

Sort of force: maximal static force.

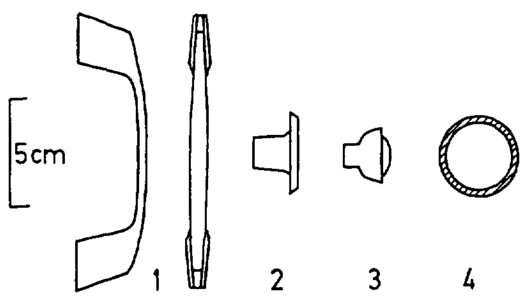
Laterality: the dominant hand.

Measurement: subjects were instructed to exert a steady maximal pull on each handle for 5 s, in a direction as close to the horizontal plane as possible. For each measurement, peak force was determined and steady pull strength was calculated from a 3 s average.

Sort and size of handle: three handles and one bar were used (see figure).

Position of handle: two handle heights: 1.0 m and 1.75 m.

Other characteristics: the floor was covered with a coarse emery paper to prevent slipping. Subjects wore their normal everyday footwear. The majority wore rubber soled shoes or trainers.



Side views of the four handles used in this study (the front view for handle 1 is also shown). Handles 1 and 2 were cast alloy, handle 3 was made of bakelite, and handle 4 was a mild steel bar.

Results

	bar height	handle type	female $\bar{x}$	female s	male $\bar{x}$	male s	both $\bar{x}$	both s
peak pull	1 m	1	276	58	400	125	334	113
		2	186	36	256	86	219	72
		3	112	18	127	27	119	23
		4	282	76	403	114	338	112
	1.75 m	1	164	30	232	58	196	56
		2	122	20	191	46	154	49
		3	100	16	121	28	110	24
		4	178	40	241	61	207	59
steady max. pull	1 m	1	247	51	364	125	302	109
		2	171	45	225	87	197	72
		3	90	21	105	22	97	23
		4	244	62	361	109	299	104
	1.75 m	1	139	28	197	50	166	49
		2	101	21	168	44	133	47
		3	82	17	104	31	93	26
		4	144	25	201	53	171	49

Pull [N] on four different handles at two different heights, defined as 'peak strength' and 'steady maximal strength'. Averages and standard deviations of 30 subjects.

Kanis (1989)

Source Kanis, H., 1989.
Bediening & handikap. Delft: Faculty of Industrial Design Engineering.

Subjects

Number: 34

Sex: 28 female and 6 male.

Age: average 54 years (s = 14.2).

Other characteristics: 28 arthritic subjects (24 women/4 men) and 6 subjects (4 women/2 men) with a muscle disease.

Method

Direction of force: push with thumb and push with forefinger.

Posture: sitting, with the elbow 90° flexed. See figures.

Sort of force: maximal and comfortable static force.'Comfortable' refers to a level of pain or fatigue found acceptable by the subject.

Laterality: preferred hand.

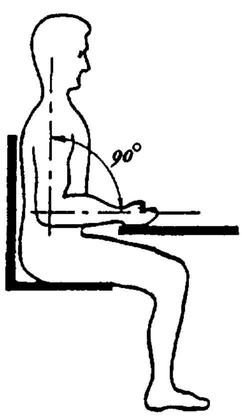
Measurement: subjects were instructed to build up their force gradually and to hold the maximum force for at least a few seconds.

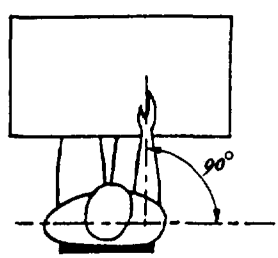
Sort of handle: plastic cylinder.

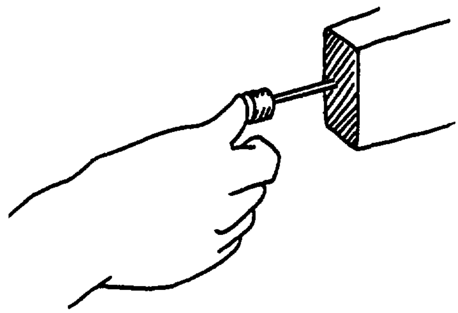
Size of handle: height 15 mm, Ø 20 mm.

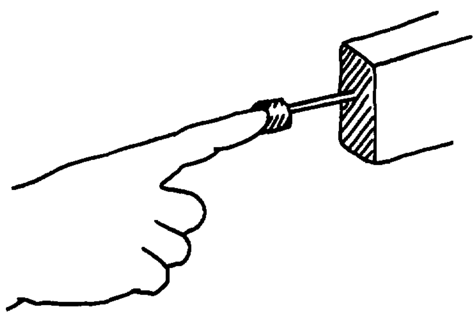
Position of handle: mounted on a table.

Other characteristics: -









Results

grip	force	females $\bar{x}$	females s	males $\bar{x}$	males s	arthritis $\bar{x}$	arthritis s	muscle disease $\bar{x}$	muscle disease s	all $\bar{x}$	all s
thumb	maximal	25.0	16.3	35.8	29.5	28.8	19.2	18.2	18.1	26.9	19.2
forefinger	maximal	17.2	9.9	19.3	15.9	18.8	10.6	12.0	11.9	17.6	11.0
	comfortable	7.6	4.7	9.1	9.5	8.1	5.0	7.1	7.9	7.9	5.6

Push [N] with thumb and forefinger. Averages and standard deviations of 34 impaired subjects.

Schoorlemmer and Kanis (1992)

Source Schoorlemmer, W. and Kanis, H., 1992.
Operation of controls on everyday products. In: *Proceedings of the Human Factors Society 36th Annual Meeting* - 1992 (pp. 509-513). Santa Monica, CA: The Human Factors Society.

Schoorlemmer, W., 1993.
Bediening van knoppen. Internal report. Delft: Faculty of Industrial Design Engineering.

Subjects

Number: 27

Sex: 21 female, 6 male

Age: average 49.4 years (s = 17.4)

Other characteristics: average body height 165 cm (s = 12), average body weight 67 kg (s = 12).
12 healthy subjects, 5 spastics, 4 visually impaired, 3 blind subjects, 3 subjects with Parkinson's disease.

Method

Direction of force: push with the thumb.

Posture: sitting, with the elbow 90° flexed (see figures) and in free posture.

Sort of force: maximal and comfortable static force. 'Comfortable' refers to a level of pain or fatigue found acceptable by the subject.

Laterality: left- and right hand (averaged in the table).

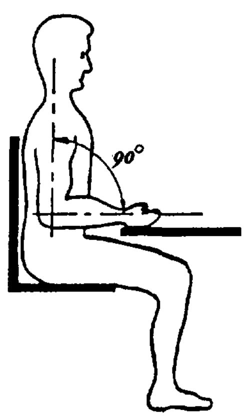
Measurement: subjects were instructed to build up their force gradually and to hold the maximum for at least a few seconds.

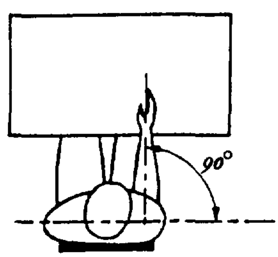
Sort of handle: plastic cylinder.

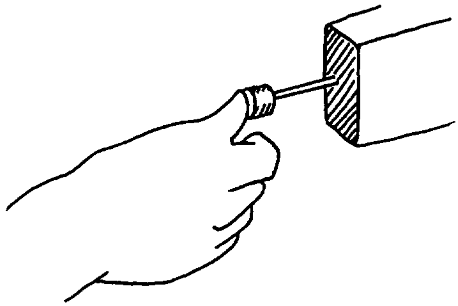
Size of handle: height 15 mm, Ø 20 mm.

Position of handle: mounted on a table.

Other characteristics: -







force	posture	females n = 21 x̄	s	males n = 6 x̄	s	healthy, blind & visually impaired n = 19 x̄	s	spastics n = 5 x̄	s	Parkinson's desease n = 3 x̄	s	all n = 27 x̄	s
max.	standard	64.1	32.4	81.3	26.7	76.2	31.3	54.3	25.9	38.1	18.5	67.9	35.6
	free	68.5	36.1	86.9	43.0	79.1	39.0	67.2	34.7	40.8	19.1	72.6	37.7
comf.	standard	31.8	15.4	22.4	16.6	33.0	16.5	19.0	9.1	26.9	15.1	29.7	15.8

Push [N] with the thumb. Averages and standard deviations of 12 healthy and 15 impaired subjects.

Torque

Introduction

Various sorts of torque. Torque can be exerted in various ways. The orientation of the lid/knob/handle is important, but also its shape. With a circular knob, the torque force cannot exceed the tangential force caused by the friction between hand and knob (which increases with increasing grip force). A small grip force thus limits the maximal exertion of torque. It is easier to operate a torque device which enables the hand to exert torque without the exertion of much grip force, like a T-bar or a lever with paddle. Torque knobs with levers, or handles, are therefore recommended for products that require much force and in designs for weak persons.

Products. Some investigators used 'real products' to measure the torque exerted. Berns (1981) and Daams (1994) used aluminium replicas of jam jars. Imrhan and Loo (1988) used glass jars with circular screw-type container lids. Bordett et al. (1988) used various faucet handles. Adams and Peterson (1988) used electrical connectors. Putto (1988) measured torque on light bulbs. Mital and Sanghavi (1986) and Mital (1986) used various hand tools, including wrenches and screwdrivers. Pheasant (1983) used screwdriver-like handles.

Maximal and comfortable torque. All measured torques are static. Most are maximal, but Berns (1981), Kanis (1989) and Schoorlemmer and Kanis (1992) measured comfortable torque. Putto (1988) investigated the actual torque exerted when screwing in light bulbs, the maximal torque exerted when screwing real bulbs out and the maximal torque exerted on dummy bulbs.

Clockwise and counter-clockwise. Kanis (1989), Schoorlemmer and Kanis (1992) and Steenbekkers (1993) investigated both torque directions and came to the conclusion that the exerted moments were not significantly different. So they presented their results in one table. Mital (1986) measured clockwise torque only. Berns (1981), Daams (1993) and Imrhan and Loo (1988) measured counter-clockwise torque only. Bordett et al. (1988), Adams and Peterson (1988), Thompson (1975) and Rohmert and Hettinger (1963) give both values in a table. From the reports of Swain et al. (1977), Pheasant (1983) and Mital and Sanghavi (1986), it is not clear what the measured torque direction is.

Fingers. In general, torque is exerted with the whole hand, certainly when large lids or knobs are involved. With smaller knobs, either the whole hand can be used, or just the fingers. Adams and Peterson (1988) define and measure both fingertip grasp and full wraparound grasp. Kanis (1989) and Schoorlemmer and Kanis (1992) use a lateral grip. The subjects of Steenbekkers (1993) exert torque both with the whole hand and with forefinger and thumb only.

Laterality. Nearly all forces are exerted with one hand, although in the case of the jam jar of Daams (1994), in free posture the subjects could use both hands. Probably the same applies to the jam jar of Berns (1981).

Sex. The torque exerted by women was investigated by Bordett et al. (1988). The torque exerted by men was investigated by Swain et al. (1970). All other researchers measured both sexes.

Children. Steenbekkers (1993) measured torque exerted by Dutch girls and boys between 4 and 13 years of age.

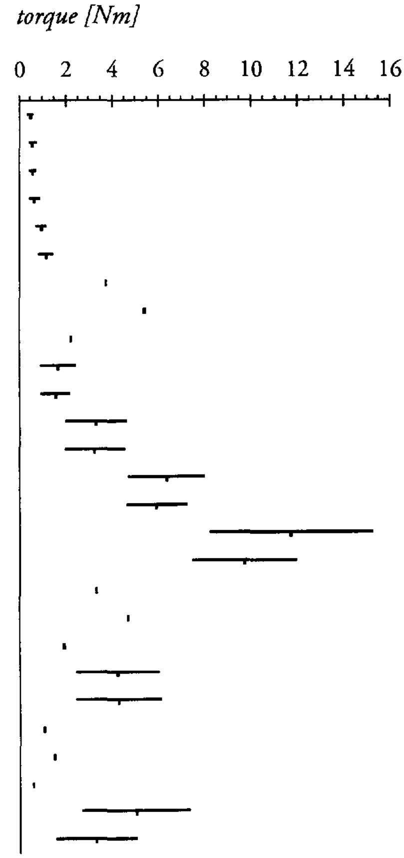
Elderly. The following investigators measured torque exerted by elderly subjects. Berns (1981) had subjects aged from 20 to over 71. Imrhan and Loo (1988) investigated elderly people aged between 60 and 97 years. Bordett et al. (1988) looked into the capacities of females aged between 60 and 90. The age of the subjects of Thompson (1975) ranged from 60 to 75 years.

Disabled. Berns (1981) and Schoorlemmer and Kanis (1992) measured torque of both healthy persons and various disabled subjects. Kanis (1989) investigated torque exerted by arthritic persons and persons with muscle diseases. All measured female and male subjects.

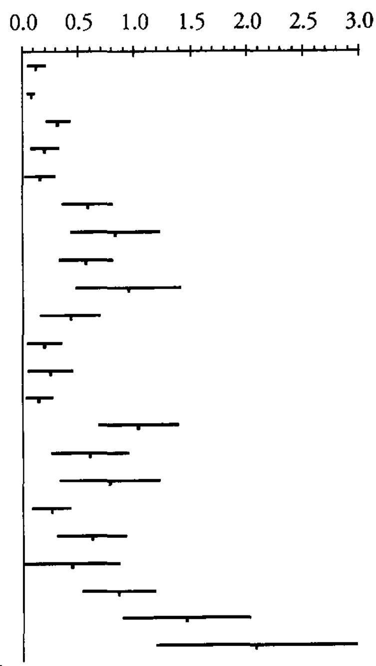
Summary. Part of the collected data is summarized, as far as possible, in the following tables. Torques around a horizontal axis and a vertical axis are summarized in different tables. Only torque on circular knobs or lids is included, because the moment arm of torque on handles cannot be determined exactly. Average values are included, and standard deviations. A selection is made of the values of some authors. Of the values of Steenbekkers, for example, the results of three age groups were selected. For more detailed information, the relevant tables should be studied.

Left out. Not included, because of lack of information on subjects and/or measuring method, are: Brooks et al. (1974), Burandt (1978), Pheasant and O'Neill (1975), Woodson (1981), two tables gathered by Damon et al. (1969) and a collection of torque data summarized by Laubach (1978). Data from Wang and Strasser (1993) are not included because the average moments (and standard deviations), exerted by the subjects on various screwdrivers, can not easily and unambiguously be deducted from the graphs (which show the moments expressed as % of the maximal force per subject). Not included either are Fähnrich et al. (1983) and Denkert et al. (1984), whose reports on various forces, including torque, were too extensive.

diameter	study	subjects
Ø 10 mm	Swain et al. (1970)	young men with gloves
		young men with bare hands
Ø 13 mm		young men with gloves
		young men with bare hands
Ø 19 mm		young men with gloves
		young men with bare hands
Ø 28 mm	Berns (1981)	women, 20 - 71+
		men, 61 - 71 +
		disabled, 20 - 71+
Ø 31 mm	Imrhan and Loo (1988)	elderly, 60 - 97, rough lid
		elderly, 60 - 97, smooth lid
Ø 55 mm		elderly, 60 - 97, rough lid
		elderly, 60 - 97, smooth lid
Ø 66 mm	Daams (1994)	young women, jar fixed
		young women, jar free
		young men, jar fixed
		young men, jar free
Ø 73 mm	Berns (1981)	women, 20 - 71+
		men, 61 - 71 +
		disabled, 20 - 71+
Ø 74 mm	Imrhan and Loo (1988)	elderly, 60 - 97, rough lid
		elderly, 60 - 97, smooth lid
Ø 85 mm	Berns (1981)	women, 20 - 71+
		men, 61 - 71 +
		disabled, 20 - 71+
Ø 113 mm	Imrhan and Loo (1988)	elderly, 60 - 97, rough lid
		elderly, 60 - 97, smooth lid



Ø 13 mm	Kanis (1989)	arthritic, maximal force
		muscle disease, maximal force
	Schoorlemmer and Kanis (1992)	healthy, maximal force
		spastics, maximal force
		parkinson, maximal force
Ø 28 mm	Thompson (1981)	females, 60-75 yrs., clockwise
		males, 60-75 yrs., clockwise
		females, 60-75 yrs., counter-clockwise
		males, 60-75 yrs., counter-clockwise
Ø 40 mm	Kanis (1989)	arthritic, maximal force
		arthritic, comfortable force
		muscle disease, maximal force
		muscle disease, comfortable force
	Schoorlemmer and Kanis (1992)	healthy, maximal force
		healthy, comfortable force
		spastics, maximal force
		spastics, comfortable force
		parkinson, maximal force
		parkinson, comfortable force
	Steenbekkers (1993)	girls and boys, 4-5 years
		girls and boys, 8-9 years
		girls and boys, 12-13 years



Daams (1994)

Source Daams, B.J., 1994.
Human force exertion in user-product interaction. Physical Ergonomics Series. Delft: Delftse Universitaire Pers.

Subjects

Number: 22

Sex: 10 female, 12 male.

Age: 8 young women and 9 young men, average 22 years. 2 women and 3 men were older.

Other characteristics: healthy students and staff of Delft University.

Method

Direction of force: torque, counter-clockwise.

Posture: standing in free posture (see figure), a) torque on a fixed jar;
b) torque on a freely movable jar.

Sort of force: maximal static force.

Laterality: one-handed on the fixed jar, two-handed on the freely movable jar.

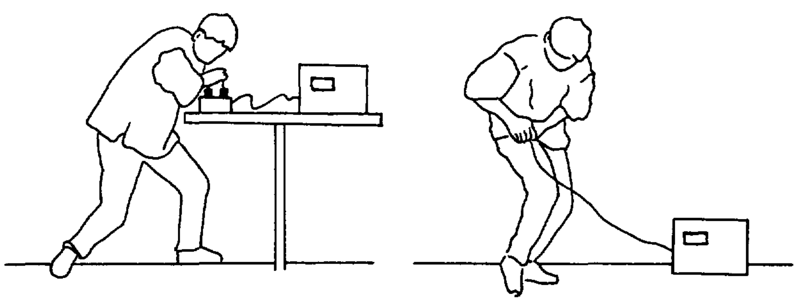
Measurement: duration 6 s, measure is the average of the last four seconds. The score is the average of two trials.

Sort of handle: jam jar shaped with built-in force transducer, material aluminium, weight 650 gr.

Size of the handle: lid Ø 66 mm, jar Ø 75 mm, jar height 113.5 mm.

Position of handle: fixed jar: lid fixed at 0.95 m from the floor.
freely movable jar: not fixed.

Other characteristics: non-slip plastic material was placed between hand and jar if maximal torque could otherwise not be obtained.



a) torque on a fixed jar *b) torque on a freely movable jar.*

Results

posture	females $\bar{x}$	females s	males $\bar{x}$	males s	both $\bar{x}$	both s
free, jar fixed at 0.95 m	6.36	1.61	11.70	3.45	9.27	3.84
free, jar not fixed	5.91	1.26	9.67	2.20	7.96	2.62

Torque [Nm] on a jam jar, exerted in two postures. Averages and standard deviations of 10 women and 10 men.

Berns (1981)

Source Berns, T., 1981.
The handling of consumer packaging. *Applied Ergonomics,* 12 (3), 153-161.

Subjects

Number: 198

Sex: 144 female, 54 male.

Age: 20 - 40 years: 31 females;
41 - 50 years: 30 females;
51 - 60 years: 28 females;
61 - 70 years: 23 females, 31 males;
71+ years: 28 females, 23 males.

Other characteristics: 111 healthy subjects, 87 disabled subjects. More specific: rheumatic illnesses: 30; multiple sclerosis: 10; Parkinson's disease: 10; cerebral palsy: 7; one-hand function hemiplegics: 20; and one-hand function amputation: 10.

Method

Direction of force: counter-clockwise torque.

Posture: healthy subjects: standing at a work bench of 85 cm height.
disabled subjects: not known.

Sort of force: maximal and comfortable static force. Comfortable force is 'such that one should not feel pain'.

Laterality: probably both hands are used.

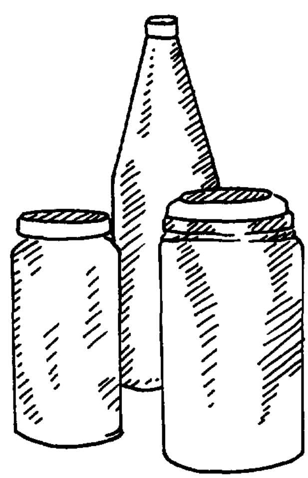
Measurement: ?

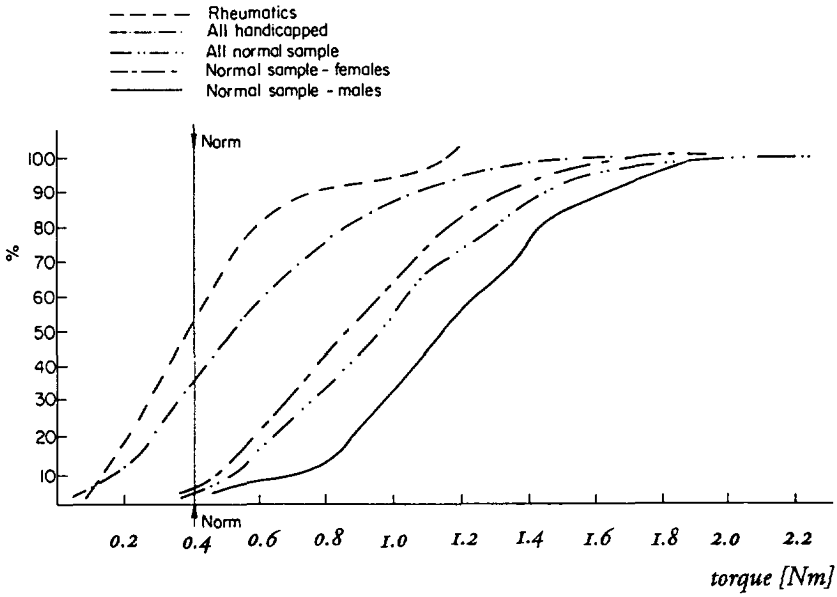
Sort of handle: a litre bottle and two jars, all made of aluminium. The jars had grooved lids.

Size of handle: bottle lid Ø 28 mm, jar lids Ø 73 mm and Ø 85 mm.

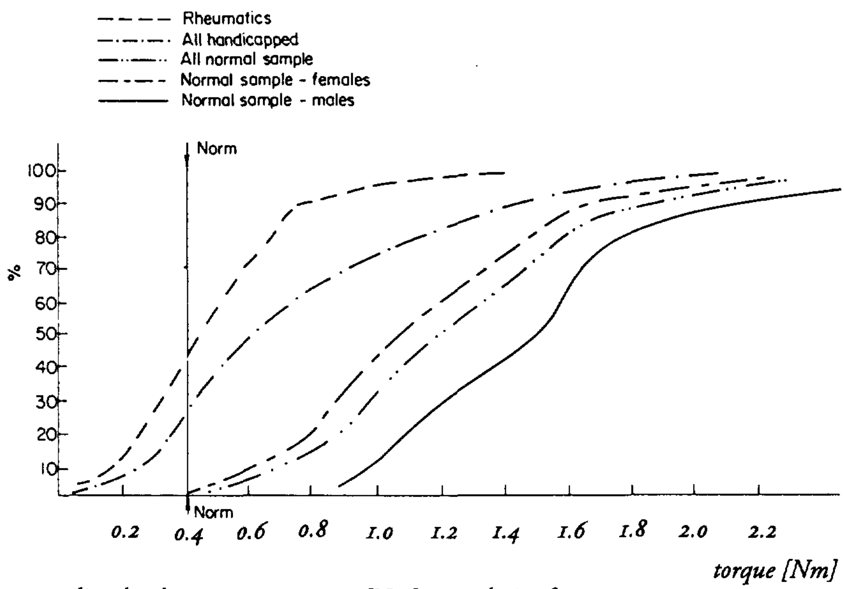
Position of handle: the bottle and jars appeared to be freely movable.

Other characteristics: -

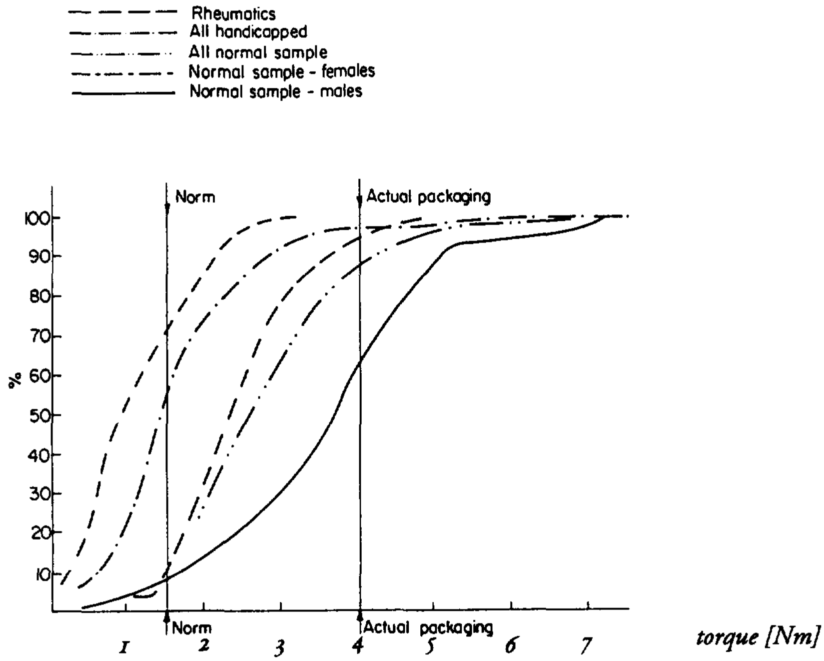




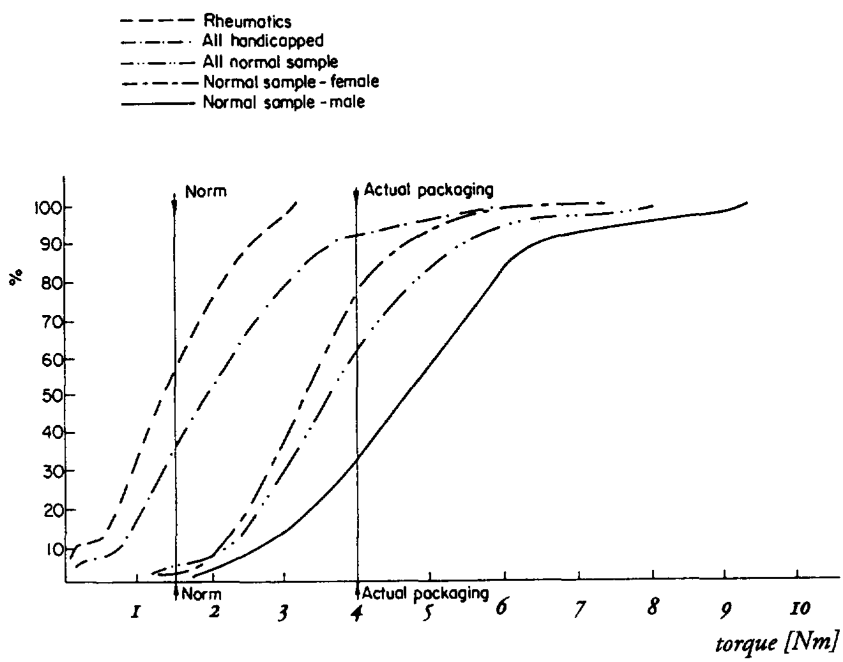
1 litre bottle, comfortable torque [Nm], cumulative frequency curves.



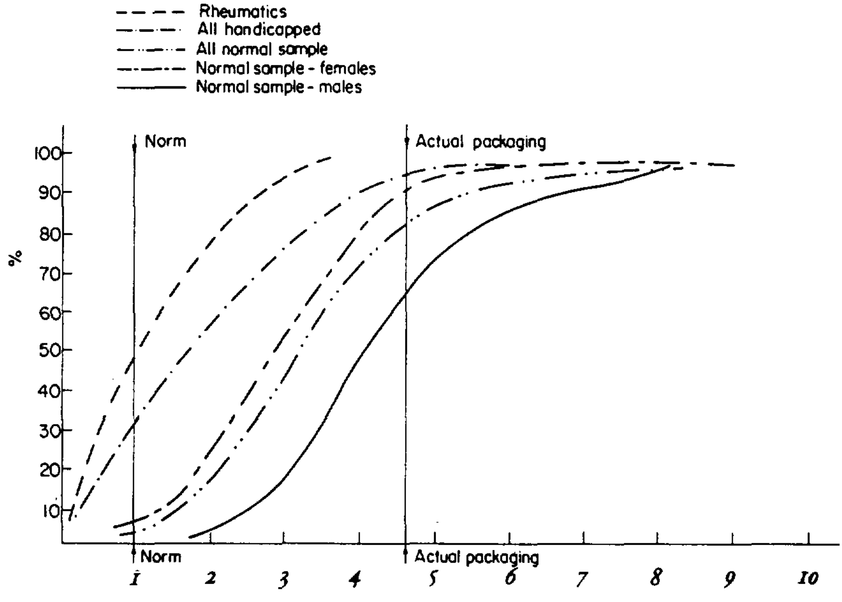
1 litre bottle, maximum torque [Nm], cumulative frequency curves.



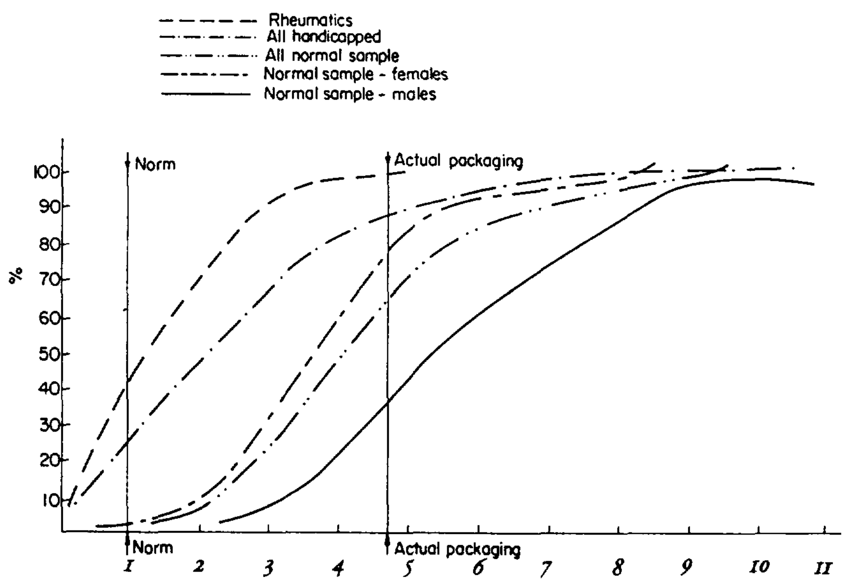
Small jar, grooved lid, comfortable torque [Nm], cumulative frequency curves.



Small jar, grooved lid, maximum torque [Nm], cumulative frequency curves.



Large jar, grooved lid, comfortable torque [Nm], cumulative frequency curves.



Large jar, grooved lid, maximum torque [Nm], cumulative frequency curves.

Imrhan and Loo (1988)

Source Imrhan, S.N. and Loo, C.H., 1988.
Modelling wrist-twisting strength of the elderly.
Ergonomics, 31 (12), 1807-1819.

Subjects

Number: 42

Sex: 26 female, 16 male.

Age: female: 60 to 87 years, male: 60 to 97 years.

Other characteristics: All subjects were recruited from one nursing home and 2 lunch centres for the elderly.

Method

Direction of force: torque, counter-clockwise.

Posture: standing in front of the tester and grabbing the container lid with the preferred hand. The tester handle (on the side) was held firmly with the other hand to stabilize the system. Subjects had to flex their body at the trunk to accomplish this. Four subjects sat, at their request, while being tested.

Sort of force: maximal static force.

Laterality: preferred hand.

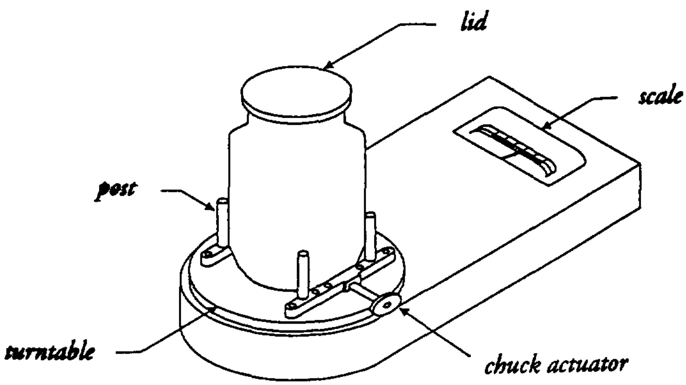
Measurement: gradually build up the effort and try to hold for at least 2 seconds. The score was the peak torque.

Sort of handle: glass jars with circular screw-type container lids

Size of handle: lids Ø 31 mm, Ø 55 mm, Ø 74 mm and Ø 113 mm.

Position of handle: jar clamped on a table, 83 cm high.

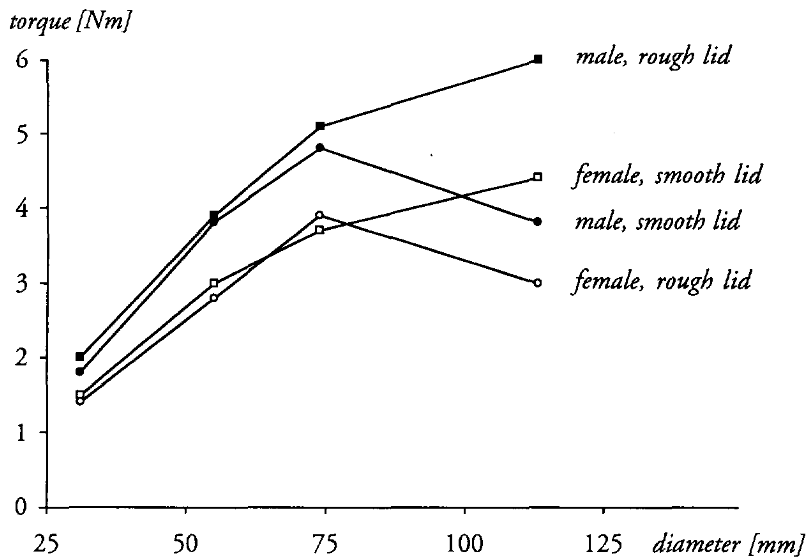
Other characteristics: rough and smooth lids were used.



Apparatus arrangement for measuring wrist-twisting strength. The jar is placed upright on the turntable of an Owen-Illinois torque tester. It is clamped firmly in place by four posts by tightening a chuck actuator. The turntable rotates with the applied torque (on the lid) which is then read from the scale.

Results

diameter [mm]	torque rough lids $\bar{x}$	s	torque smooth lids $\bar{x}$	s
31	1.66	0.70	1.53	0.60
55	3.30	1.27	3.25	1.25
74	4.20	1.73	4.26	1.80
113	5.01	2.29	3.29	1.71



Torque [Nm] exerted on smooth and rough container lids, averages and standard deviations of 42 elderly people.

Bordett et al. (1988)

Source Bordett, H.M., Koppa, R J. and Congelton, J.J., 1988.
Torque required from elderly females to operate faucet handles of various shapes. *Human Factors,* 30 (3), 339-346.

Subjects

Number: 23

Sex: female.

Age: ranging from 65 to 90 years.

Other characteristics: residents of retirement homes in Texas. All of the subjects appeared to have some form of osteoarthritis in their hands and several had moderate curvature of the spine.

Method

Direction of force: torque, clockwise and counter-clockwise.

Posture: 11 subjects sitting, 12 subjects standing.

Sort of force: comfortable static force.

Laterality: left hand and right hand separately.

Measurement: duration unknown. Each condition was measured twice and averaged.

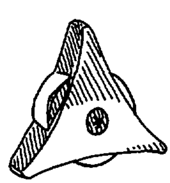
Sort of handle: seven different types of faucet handles, see figure:

1) tripoint
2) lever & lip
3) cross
4) small paddle
5) lever
6) multipoint
7) large paddle

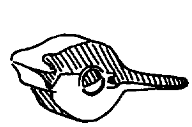
Size of handle: ?

Position of handle: mounted, with the axis vertically, on a torque meter that was clamped to a table 0.76 m high at a point 0.53 m from the forward edge.

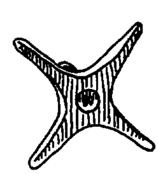
Other characteristics: asymmetrical handles (no. 2, 4, 5 and 7) were positioned so that the handle extension faced the subject's right when right-hand torque (clockwise and counter-clockwise) was being measured and the subject's left when left-hand torque (clockwise and counter-clockwise) was being measured.
The subjects were allowed to lean on the table surface, as they might in their kitchen or bath.



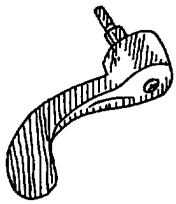
1. tripoint



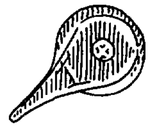
2. lever



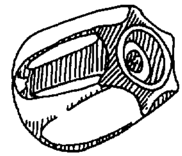
3. cross



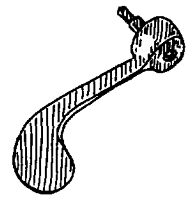
4. small paddle



5. lever



6. multipoint



7. large paddle

Results

handle	hand	direction	sitting $\bar{x}$	sitting s	standing $\bar{x}$	standing s
1 tripoint	right	clockwise	3.73	1.51	4.90	1.20
		counter-clockwise	3.67	2.18	4.72	1.04
	left	clockwise	3.63	1.79	4.46	1.43
		counter-clockwise	3.22	1.32	4.15	1.15
2 lever & lip	right	clockwise	3.19	1.32	4.24	1.03
		counter-clockwise	3.45	1.84	4.55	1.25
	left	clockwise	3.19	1.46	4.69	1.71
		counter-clockwise	3.34	1.66	3.81	0.97
3 cross	right	clockwise	4.15	1.57	5.46	1.07
		counter-clockwise	3.23	1.15	4.77	1.06
	left	clockwise	3.48	1.63	4.18	1.10
		counter-clockwise	3.50	1.53	4.33	1.48
4 small paddle	right	clockwise	6.56	2.27	7.41	1.60
		counter-clockwise	4.39	1.66	6.60	1.67
	left	clockwise	4.52	2.12	6.94	2.00
		counter-clockwise	6.26	2.68	6.89	2.43
5 lever	right	clockwise	3.47	1.37	4.54	1.33
		counter-clockwise	3.08	1.13	3.89	1.24
	left	clockwise	3.04	1.54	3.90	1.36
		counter-clockwise	3.28	1.11	3.64	1.11
6 multipoint	right	clockwise	2.82	1.37	3.67	0.89
		counter-clockwise	2.78	1.34	3.78	1.14
	left	clockwise	2.70	1.08	3.37	0.98
		counter-clockwise	2.75	1.34	3.50	1.34
7 large paddle	right	clockwise	9.45	4.00	10.04	2.64
		counter-clockwise	5.68	2.23	8.17	1.89
	left	clockwise	7.07	3.88	9.69	3.52
		counter-clockwise	8.30	3.31	9.58	2.28

Torque [Nm] exerted on faucet handles, averages and standard deviations of 23 elderly females.

Swain et al. (1970)

Source Swain, A.D., Shelton, G.C. and Rigby, L.V., 1970.
Maximum torque for small knobs operated with and without gloves.
Ergonomics, 13 (2), 201-208.

Subjects

Number: 120

Sex: male.

Age:

civilians:	average 31.4	range 22 - 40 years;
military, army:	average 27.2	range 21 - 38 years;
military, navy:	average 27.4	range 23 - 32 years.

Other characteristics: 96 civilians, 12 army, 12 navy.

Method

Direction of force: torque.

Posture: standing. The steadying hand was always placed on top of the measuring apparatus. The subjects were required to stand approximately in front of the device, to keep both feet on the floor and not to move the device.

Sort of force: maximal static force.

Laterality: preferred hand.

Measurement: the subjects were instructed to get a firm grip and give the knob a single, hard twist, and then stop.

Sort of handle: small knob.

Size of handle: knob Ø 9.5 mm, 12.7 mm and Ø 19.1 mm.

Position of handle: about 81 cm above the floor.
Two orientations were used:
1) control panel facing the subject;
2) the edge of the control panel toward the subject so that the knob was on his right.

Other characteristics: bare hands and gloves were used.
To avoid the effects of sweaty hands, paper towels were provided and subjects were instructed to wipe their finger tips before each trial.

Results

knob		mil. under 29 n = 16 x̄	s	mil. over 29 n = 8 x̄	s	civ. under 29 n = 31 x̄	s	civ. over 29 n = 65 x̄	s	all x̄	s
	age [years]	24.50	2.16	32.62	2.88	25.26	1.97	34.32	2.88		
9.5 mm	with gloves										
	front	44.66	10.39	47.94	7.03	41.98	8.28	46.82	7.88	45.35	8.48
	side	46.08	11.89	49.54	11.68	46.19	11.06	47.82	8.48	47.28	9.82
	bare hand										
	front	49.23	8.94	47.06	13.06	51.42	13.64	54.94	12.92	52.75	12.80
	side	52.56	11.98	58.87	11.02	52.36	12.21	56.78	12.87	55.21	12.54
12.7 mm	with gloves										
	front	57.00	10.82	60.02	11.42	56.00	10.28	58.02	10.48	57.50	10.46
	side	58.73	9.52	62.15	9.49	57.26	13.64	61.06	11.39	59.84	11.68
	bare hand										
	front	59.66	14.54	62.15	14.77	62.48	13.38	68.41	15.60	65.29	15.09
	side	63.00	15.21	64.46	18.33	61.66	14.00	69.74	16.35	66.40	16.00
19.1 mm	with gloves										
	front	92.69	23.94	97.75	15.85	88.97	14.89	93.57	16.39	92.54	17.13
	side	95.22	19.85	84.96	14.21	92.08	18.32	95.06	17.63	93.64	17.90
	bare hand										
	front	105.17	21.81	104.33	22.00	103.82	25.05	117.89	27.04	111.65	26.20
	side	112.31	27.37	105.75	32.01	109.41	26.72	118.27	25.88	114.35	26.74

*Torque [**Nmm**] exerted on knobs, with bare hand and gloves, averages and standard deviations of males.*

Mital (1986)

Source Mital, A., 1986.
Effect of body posture and common hand tools on peak torque exertion capabilities. *Applied Ergonomics*, 17 (2), 87-96.

Subjects

Number: 50

Sex: 14 female, 36 male.

Age: average females 23.3 years (s = 2.0);
males 22.4 years (s = 0.9).

Other characteristics: the subjects are civilians in good health.
body height, average: females 165.3 cm (s = 6.1);
males 177.2 cm (s = 6.2).
body weight, average: females 58.6 kg (s = 9.4);
males 74.0 kg (s = 7.9).

Method

Direction of force: torque, clockwise.

Posture: standing, kneeling, squatting and lying in 21 different postures (see figures).

Sort of force: maximal static force.

Laterality: probably up to the subject (free posture).

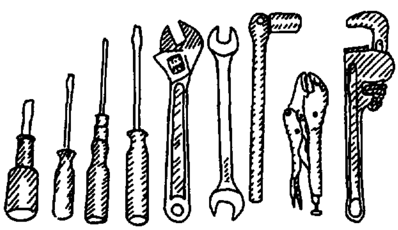
Measurement: subjects were asked to build up to the maximum torque slowly, without jerking, over a 3 s period and then hold it at the maximum value for about 1 s.

Sort and size of handle: nine different hand tools (see figure):

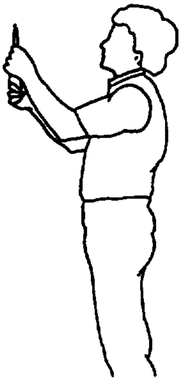
1. short screwdriver	Ø 3.5 * 15.5 cm long;
2. medium screwdriver	Ø 2.3 * 18 cm long;
3. long screwdriver	Ø 2.8 * 24 cm long;
4. longest screwdriver	Ø 3.0 * 25.3 cm long;
5. crescent wrench	26 cm lever arm * 2.2 cm opening;
6. spanner wrench	23 cm lever arm * 2.2 cm opening;
7. socket wrench	23 cm lever arm * 1.75 cm opening;
8. vice grip	17 cm lever arm * 1.75 cm opening;
9. pipe wrench	24 cm lever arm * 2.5 cm opening.

Position of handle: various orientations and heights, see figures.

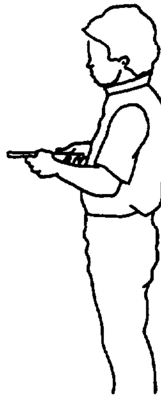
Other characteristics: during the experiment, subjects wore comfortable work clothes.



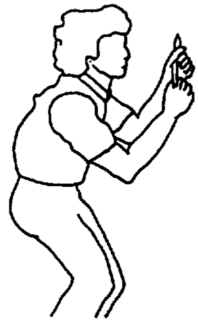
tools 1 (extreme left) to 9 (extreme right).



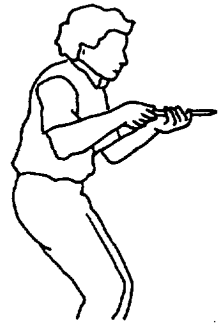
1 *Standing, tool axis vertical (upward)*



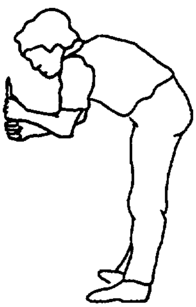
2 *Standing, tool axis horizontal (outward)*



3 *Standing, knees bent, back supported, tool axis vertical (upward)*

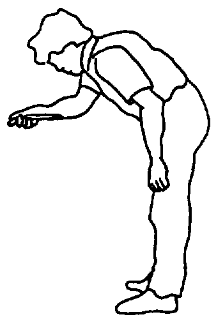


4 *Standing, knees bent, back supported, tool axis horizontal (outward)*



5 *Standing, bent at the waist, tool axis vertical (upward)*

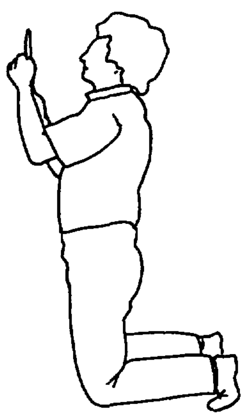
6 *Standing bent at the waist, tool axis horizontal (outward)*



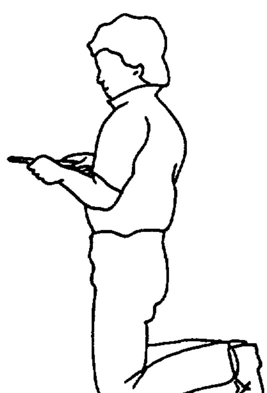
7 *Standing, bent at the waist, tool axis horizontal (inward)*

8 *Kneeling, on one knee, tool axis vertical (upward)*

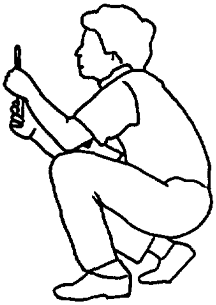
9 *Kneeling, on one knee, tool axis horizontal (outward)*



10 *Kneeling, both knees, tool axis vertical (upward)*



11 *Kneeling, both knees, tool axis horizontal (outward)*

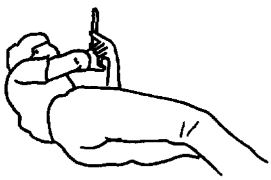


12 *Squat, tool axis vertical (upward)*

13 *Squat, tool axis horizontal (outward) and between knees and shoulder*

14 *Squat, tool axis horizontal (outward) and between knees and ankles*

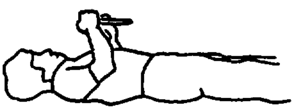
15 *Squat, tool axis vertical (downward),* ***work*** *surface-floor*



16 *Lying on the side, tool axis vertical (upward)*

17 *Lying on the side, tool axis horizontal (outward)*

18 *Lying on the back, tool axis vertical (outward)*



19 *Lying on the back, tool axis horizontal (parallel to the body)(work-piece remote from the subject)*

20 *Lying on the stomach, tool axis vertical (upward)*

21 *Lying on the stomach, tool axis horizontal (outward)*

Results

tool	females			males		
	$\bar{x}$	s	range	$\bar{x}$	s	range
1. short screwdriver	3.27	1.23	0.90 - 7.35	4.48	1.68	1.13 - 11.53
2. medium screwdriver	1.65	0.66	0.56 - 3.39	2.35	0.98	0.68 - 7.35
3. long screwdriver	2.19	0.84	0.45 - 5.31	3.20	1.18	0.45 - 8.82
4. longest screwdriver	2.96	1.31	0.68 - 9.50	4.12	1.58	1.02 - 10.86
5. crescent wrench	20.05	7.76	1.58 - 46.03	30.30	12.01	8.25 - 83.80
6. spanner wrench	20.39	8.24	5.65 - 60.61	33.58	12.54	3.17 - 84.70
7. socket wrench	24.33	9.43	7.01 - 55.41	40.06	13.61	10.86 - 93.07
8. vice grip	16.46	5.66	4.64 - 33.59	25.34	7.97	7.58 - 56.32
9. pipe wrench	24.14	10.18	6.00 - 76.00	39.57	13.92	11.76 - 91.71

Torque [Nm] on various hand tools averaged over 21 postures. Averages, standard deviations and ranges of 14 females and 36 males.

posture	short screwdriver x̄	s	range	medium screwdriver x̄	s	range	long screwdriver x̄	s	range	longest screwdriver x̄	s	range
female												
1	3.61	1.60	1.13 - 7.12	1.91	0.75	0.79 - 3.39	2.45	1.19	0.56 - 4.41	3.29	1.54	0.79 - 6.78
2	3.08	1.12	1.02 - 5.54	1.69	0.68	0.90 - 2.94	2.29	0.89	0.79 - 3.73	2.75	1.26	0.68 - 4.97
3	3.69	1.45	1.02 - 6.11	1.75	0.92	0.56 - 3.39	2.49	1.23	0.79 - 5.31	3.58	1.70	1.58 - 7.12
4	3.04	0.96	1.36 - 5.31	1.54	0.56	0.50 - 2.60	2.16	0.78	1.02 - 4.07	2.85	1.11	0.90 - 5.20
5	3.56	1.46	0.90 - 6.33	1.82	0.82	0.79 - 2.94	2.26	1.11	0.45 - 4.52	3.18	1.73	0.68 - 6.22
6	2.97	1.18	1.13 - 5.09	1.43	0.50	0.56 - 2.37	1.85	0.65	0.56 - 2.94	2.50	0.80	1.02 - 4.07
7	3.40	1.07	1.81 - 5.20	1.62	0.60	0.68 - 2.94	2.09	0.63	0.68 - 3.17	2.77	1.05	1.13 - 4.52
8,10	3.91	1.48	1.81 - 7.35	1.79	0.72	0.79 - 3.17	2.46	0.76	1.24 - 4.18	3.44	1.84	1.47 - 9.50
9,11	3.36	0.94	2.03 - 5.65	1.62	0.53	0.79 - 2.71	2.13	0.60	1.47 - 3.50	2.81	0.97	1.13 - 5.43
12	3.78	1.47	1.58 - 6.33	1.74	0.81	0.56 - 3.17	2.25	1.03	0.56 - 4.41	3.13	1.58	1.02 - 7.01
13	3.06	0.92	2.03 - 5.54	1.58	0.52	0.90 - 2.60	2.21	0.61	1.36 - 3.39	2.80	0.94	1.47 - 4.64
14	3.22	1.11	1.58 - 5.77	1.72	0.73	0.79 - 3.28	2.42	0.50	1.81 - 3.39	3.25	0.99	1.81 - 5.09
15	3.43	1.53	1.24 - 6.67	1.95	0.74	1.02 - 3.17	2.45	1.08	0.79 - 4.52	3.44	1.62	1.02 - 6.56
16	2.75	0.99	1.58 - 4.75	1.44	0.62	0.68 - 2.60	1.99	0.78	0.79 - 3.62	2.69	1.09	1.24 - 4.86
17	2.96	1.03	1.13 - 4.64	1.40	0.43	0.79 - 2.26	1.82	0.88	0.79 - 4.41	2.46	0.95	1.36 - 4.75
18,21	2.68	0.85	1.24 - 4.64	1.54	0.63	0.68 - 2.71	1.90	0.70	0.79 - 4.07	2.54	0.95	1.13 - 4.97
19	3.09	1.18	1.47 - 5.54	1.73	0.68	0.79 - 2.94	2.13	0.78	0.45 - 3.62	2.98	1.28	1.47 - 5.88
20	3.05	1.17	0.90 - 5.09	1.49	0.64	0.56 - 2.60	2.06	0.86	0.68 - 3.62	2.80	1.46	1.24 - 7.12
male												
1	4.60	1.32	2.26 - 7.58	2.54	0.90	1.24 - 5.20	3.36	1.15	1.36 - 6.33	4.28	1.39	2.49 - 8.37
2	4.42	1.53	1.13 - 9.05	2.16	1.04	0.90 - 6.78	2.92	1.09	1.13 - 6.11	3.85	1.27	1.70 - 7.80
3,4	4.42	1.42	1.47 - 9.16	2.36	0.94	0.90 - 6.67	3.21	1.01	1.58 - 6.33	4.09	1.43	1.47 - 8.82
5	5.03	1.68	2.60 - 9.27	2.64	0.91	1.24 - 4.86	3.48	1.17	1.47 - 5.99	4.62	1.68	1.70 - 8.93
6,7	4.35	1.70	1.47 - 10.63	2.27	0.94	0.90 - 6.56	2.98	0.96	1.36 - 6.11	3.83	1.47	1.47 - 8.59
8	5.04	1.72	2.03 - 9.84	2.57	1.13	1.13 - 7.35	3.36	1.01	1.70 - 5.54	4.44	1.39	2.37 - 8.14
9,10,11	4.65	1.71	1.81 - 11.42	2.38	0.90	0.79 - 4.86	3.20	1.26	1.36 - 7.69	4.21	1.66	1.81 - 9.84
12	5.13	1.77	2.49 - 11.53	2.52	0.88	1.36 - 4.52	3.52	1.21	1.70 - 6.22	4.37	1.44	2.15 - 8.37
13, 14, 15	4.41	1.63	1.24 - 9.61	2.37	0.85	0.68 - 4.52	3.22	1.24	1.13 - 8.82	4.08	1.53	1.47 - 10.18
16	4.48	1.74	2.15 - 9.61	2.40	0.93	0.79 - 4.41	3.36	1.22	1.36 - 6.56	4.21	1.68	1.24 - 9.50
17	3.75	1.70	1.47 - 8.71	1.98	0.76	0.79 - 4.41	2.82	1.21	0.45 - 7.35	3.40	1.51	1.02 - 9.16
18,21	4.18	1.67	1.13 - 9.61	2.14	0.84	0.68 - 4.41	3.11	1.27	1.02 - 7.92	4.02	1.83	1.47 - 10.29
19	4.46	1.79	2.03 - 9.05	2.55	1.02	1.13 - 5.88	3.39	1.31	1.36 - 7.35	4.45	2.05	1.81 - 10.86
20	4.19	1.63	1.70 - 8.14	2.28	0.87	1.02 - 3.96	3.12	1.17	1.24 - 6.33	4.04	1.43	1.81 - 8.37

Torque [Nm] on various hand tools and in various postures (see figures). Averages, standard deviations and ranges of 14 females and 36 males.

crescent wrench			spanner wrench			socket wrench			vice grip			pipe wrench		
$\bar{x}$	s	range	$\bar{x}$	s	range	$\bar{x}$	s	range	$\bar{x}$	s	range	$\bar{x}$	s	range
16.36	6.78	6.11 - 31.44	15.28	6.06	5.65 - 27.71	18.85	6.49	7.01 - 28.50	14.27	5.00	6.44 - 26.12	17.73	5.78	6.67 - 32.34
24.71	9.17	11.76 - 40.82	24.78	8.33	9.50 - 37.43	31.13	11.15	11.08 - 52.58	19.23	6.66	6.67 - 33.59	31.04	14.04	13.23 - 60.61
19.41	7.88	7.92 - 38.22	19.97	8.15	9.84 - 32.12	22.88	8.04	8.59 - 35.51	16.99	6.16	7.01 - 32.79	23.61	8.06	12.89 - 40.71
23.67	8.37	10.63 - 38.45	23.37	8.02	9.39 - 35.06	28.25	11.09	11.19 - 50.89	18.47	6.42	6.67 - 31.78	29.33	11.79	12.66 - 53.15
18.99	7.37	8.82 - 32.12	20.02	7.92	10.40 - 37.32	23.32	7.03	13.23 - 38.22	16.40	5.49	9.05 - 31.89	20.73	7.90	8.37 - 34.49
22.04	6.47	14.02 - 38.45	23.62	7.76	10.74 - 36.53	27.96	9.33	17.52 - 46.03	18.27	6.13	9.61 - 31.10	28.36	9.93	17.98 - 45.80
23.44	9.63	9.27 - 45.91	25.00	11.00	11.08 - 52.58	29.31	10.21	15.83 - 49.30	18.06	5.30	11.42 - 32.45	30.29	12.98	17.75 - 63.33
20.55	7.62	8.82 - 38.45	18.33	7.92	6.56 - 34.38	23.91	9.68	10.97 - 43.88	16.34	5.87	6.22 - 28.72	22.11	7.78	9.61 - 41.95
22.39	7.55	11.76 - 38.67	24.73	10.35	7.69 - 60.61	27.04	10.00	12.66 - 55.41	16.29	4.87	7.58 - 27.82	28.88	13.55	1.42 - 75.99
17.93	8.51	7.80 - 36.07	16.98	7.98	6.56 - 30.87	22.30	8.62	10.74 - 36.53	15.85	6.64	6.67 - 28.50	19.90	7.22	9.61 - 32.45
20.20	6.05	10.97 - 34.26	21.04	5.97	10.86 - 29.40	26.15	9.68	12.78 - 45.12	16.11	4.16	9.27 - 22.84	25.85	8.71	13.23 - 42.29
21.91	7.83	12.44 - 39.58	23.42	6.64	12.10 - 32.79	28.39	9.61	15.04 - 50.89	18.92	6.04	9.50 - 32.23	28.46	9.24	14.25 - 40.71
20.64	10.35	6.33 - 46.03	16.99	6.55	6.78 - 29.40	20.62	9.19	7.69 - 40.71	15.88	5.96	8.02 - 30.31	22.85	7.80	11.42 - 37.54
15.73	6.43	4.30 - 32.91	15.39	6.63	6.22 - 28.50	18.96	7.71	8.14 - 35.40	14.31	5.94	4.64 - 27.82	16.59	5.81	6.00 - 29.18
17.92	5.51	9.16 - 29.74	18.50	5.41	8.82 - 25.56	22.24	9.36	11.19 - 41.39	15.06	3.58	7.92 - 22.16	22.98	10.24	11.76 - 52.13
16.94	6.00	8.93 - 32.23	17.50	6.20	9.05 - 40.26	20.74	6.50	11.76 - 38.11	14.67	5.17	7.12 - 29.29	20.21	6.31	10.06 - 37.66
19.26	7.33	10.86 - 35.06	23.51	8.45	12.89 - 42.18	25.87	10.56	13.34 - 47.83	15.63	6.33	7.69 - 33.25	25.54	8.83	15.15 - 40.60
18.92	7.74	1.58 - 34.04	18.98	6.83	9.84 - 32.46	21.32	7.59	12.44 - 38.45	17.54	5.72	7.69 - 28.38	21.35	8.68	11.45 - 40.37
29.03	8.71	12.78 - 46.60	31.94	10.37	17.75 - 60.05	40.05	14.35	20.35 - 93.07	24.54	7.50	13.91 - 45.01	37.40	14.06	17.98 - 69.09
34.88	15.25	11.08 - 80.86	37.66	15.41	3.17 - 79.61	43.52	15.57	15.72 - 81.42	27.54	9.42	7.57 - 46.14	46.79	16.16	20.13 - 88.09
30.39	12.00	11.08 - 72.37	35.36	12.30	12.89 - 80.29	41.95	12.83	16.17 - 79.16	27.21	8.28	14.13 - 56.32	42.36	13.29	14.02 - 80.40
29.80	11.55	11.99 - 65.93	34.04	10.47	15.60 - 59.60	41.50	14.57	18.43 - 80.40	25.07	7.79	11.19 - 43.42	39.73	11.88	21.15 - 70.45
32.91	13.72	8.82 - 83.80	37.91	15.05	5.65 - 84.70	42.71	14.34	19.56 - 81.08	26.65	7.94	11.19 - 44.44	44.99	14.26	15.17 - 87.08
33.19	12.54	11.89 - 73.51	33.97	10.92	17.53 - 79.50	41.82	14.43	19.34 - 92.05	25.14	6.64	12.89 - 38.00	38.51	13.03	21.03 - 91.15
32.17	12.82	9.05 - 81.53	35.24	12.97	6.33 - 84.25	43.66	13.69	14.02 - 92.05	27.01	7.77	9.27 - 48.74	41.76	14.08	14.02 - 91.71
32.60	12.54	13.23 - 78.03	33.74	12.82	15.72 - 82.78	42.91	14.39	22.39 - 92.50	24.91	7.29	8.82 - 41.84	39.05	13.67	16.28 - 88.77
29.72	11.50	8.25 - 76.33	32.91	12.06	12.78 - 77.58	39.29	13.14	10.80 - 78.36	29.94	8.06	11.42 - 53.49	39.80	14.53	13.34 - 85.94
26.96	9.91	15.60 - 55.41	30.25	10.93	16.17 - 60.27	37.10	15.88	14.36 - 87.64	22.39	7.69	8.37 - 43.42	33.33	14.03	13.79 - 86.06
24.27	9.57	9.95 - 51.91	26.54	8.86	11.65 - 50.32	32.06	8.45	14.59 - 51.23	22.70	7.82	9.84 - 46.25	32.13	10.73	11.76 - 55.30
26.74	9.25	11.65 - 51.68	29.52	9.64	13.00 - 56.43	35.33	10.88	15.72 - 71.70	23.24	7.78	10.18 - 45.12	33.34	10.54	13.68 - 75.31
30.37	11.51	10.86 - 65.36	35.86	14.16	15.15 - 74.41	40.44	12.13	17.98 - 72.04	25.90	8.49	11.31 - 54.05	40.28	14.16	18.77 - 85.49
29.96	11.04	12.33 - 61.07	31.18	11.57	14.36 - 67.62	36.01	12.42	17.53 - 83.68	23.76	6.94	10.97 - 43.88	37.64	11.95	15.15 - 70.68

Mital and Sanghavi (1986)

Source Mital, A, and Sanghavi, N., 1986.
Comparison of maximum volitional torque exertion capabilities of males and females using common hand tools. *Human Factors,* 28 (3), 283-294.

Subjects

Number: 55

Sex: 25 female, 30 male.

Age: females average 21.6 years (s = 2.5), males average 22.7 years (s = 1.2).

Other characteristics: average body weight: females 62.2 kg (s = 15.0), males 78.8 kg (s = 10.2).
average body height: females 160.8 cm (s = 6.2), males 178.4 (s = 7.2).

Method

Direction of force: torque.

Posture: standing and sitting posture, see also 'position of handle'.

Sort of force: maximal static force.

Laterality: probably one handed (the preferred hand).

Measurement: subjects were asked to build up slowly to the maximum torque over a 3 s period and to hold the maximum value for about one second. This maximum torque was measured.

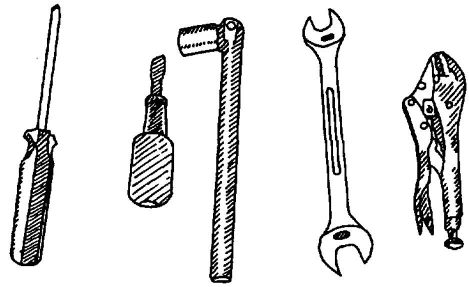
Sort and size of handle: five common hand tools (see figures):
- long screwdriver (Ø 2.9 * 15.2 cm);
- short screwdriver (Ø 3.7 * 5.1 cm);
- socket wrench (Ø 1.7 * 24.1 cm);
- spanner (2.2 * 25.4 cm);
- vise grip (2.2 * 19 cm).

Position of handle: three different reach distances per posture:
- standing: 33cm, 45.7 cm and 58.4 cm measured horizontally from the ankles;
- sitting: 45.7 cm,58.4 cm and 71,1 cm measured horizontally from the seat reference point.

three different heights (which had very little effect on the resulting torque, so that they are not separately mentioned in the table):
- eye level
- elbow height
- shoulder height

and also at six tool orientations, given by the angle of the arm relative to the mid-sagittal plane (these, too , had very little effect on the resulting torque, so that they are not separately mentioned in the table): - 75° (= on the weaker hand side), -45°, -15°, 15°, 45° and 75°.

Other characteristics: -

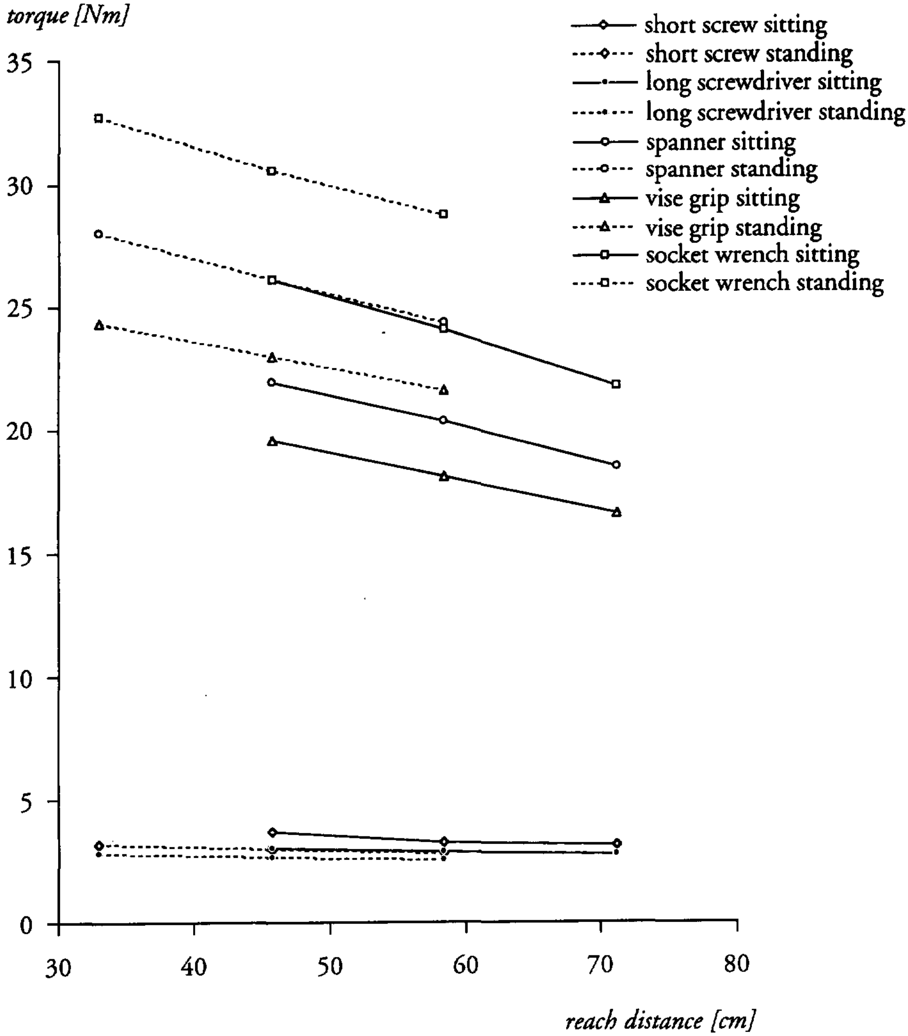


Nonpowered handtools used in the study.

Results

tool	posture	reach [cm]	female $\bar{x}$	female s	male $\bar{x}$	male s
short screwdriver	sitting	45.7	3.6	0.9	3.7	1.5
		58.4	3.1	1.0	3.4	1.5
		71.1	3.0	1.0	3.2	1.4
	standing	33.0	2.9	0.8	3.4	1.1
		45.7	2.7	0.8	3.2	1.1
		58.4	2.5	0.9	3.0	1.1
long screwdriver	sitting	45.7	2.8	0.9	3.2	1.4
		58.4	2.7	0.9	3.0	1.3
		71.1	2.6	0.9	2.8	1.2
	standing	33.0	2.5	0.8	3.2	1.0
		45.7	2.4	0.8	2.9	1.0
		58.4	2.3	0.7	2.8	1.0
spanner	sitting	45.7	16.6	5.6	27.2	10.2
		58.4	15.5	5.0	25.2	9.5
		71.1	14.2	4.7	22.7	8.4
	standing	33.0	23.0	7.7	32.9	12.6
		45.7	20.8	7.1	31.4	12.0
		58.4	19.4	6.6	29.2	11.1
vise grip	sitting	45.7	15.2	5.2	23.9	8.3
		58.4	13.8	4.3	22.3	7.6
		71.1	12.6	3.9	20.6	7.3
	standing	33.0	20.0	7.0	28.6	10.0
		45.7	18.8	6.8	27.0	9.7
		58.4	17.4	5.8	25.8	9.4
socket wrench	sitting	45.7	19.7	6.0	32.4	11.9
		58.4	17.9	5.2	30.2	11.1
		71.1	16.3	4.4	27.2	9.5
	standing	33.0	26.0	8.7	39.5	13.3
		45.7	23.9	7.6	37.1	12.6
		58.4	22.1	7.0	35.3	12.2

Torque [Nm] exerted with hand tools. Averages and standard deviations of 25 females and 30 males.



Torque [Nm] exerted standing and sitting with various hand tools at various reach distances. Averages of females and males.

Pheasant (1983)

Source Pheasant, S.T., 1983.
Sex differences in strength - some observations on their variability.
Applied Ergonomics, 14 (3), 205-211.

Subjects

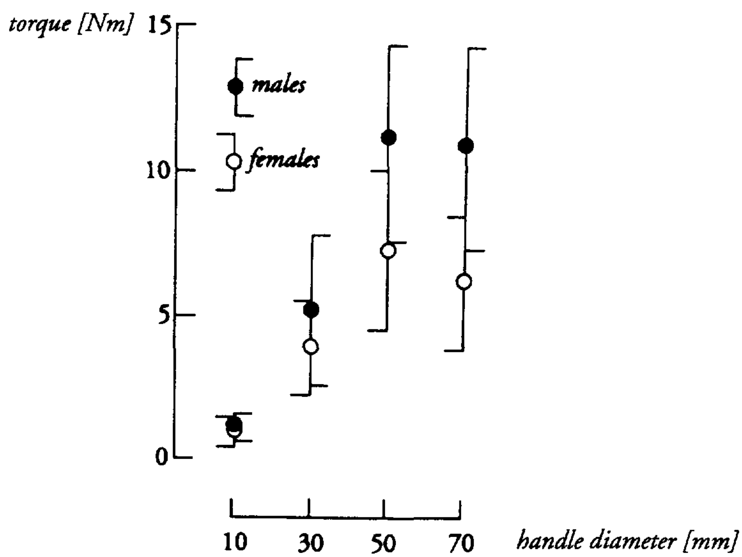
Number: 44
Sex: 22 female and 22 male.
Age: young.
Other characteristics: medical students.

average body height:	females 166.1 cm	males 177.9 cm;
average body weight:	females 59 kg	males 68 kg;
average hand length:	females 17.7 cm	males 19.3 cm;
average grip circumference:	females 16.3 cm	males 17.5 cm.

Method

Direction of force: torque.
Posture: ?
Sort of force: maximal static force.
Laterality: probably one hand.
Measurement: ?
Sort of handle: 4 cylindrical steel handles with a knurled surface
Size of handle: Ø 10 mm, Ø 30 mm, Ø 50 mm and Ø 70 mm.
Position of handle: ?
Other characteristics: ?

Results



Torque [Nm] on handles with various diameters.
Averages and ± 1.65 * standard deviation of 22 women and 22 men.

Thompson (1975)

Source Thompson, D., 1975.
Ergonomics data for evaluation and specification of operating devices on components for use by the elderly. Loughborough: Institute for Consumer Ergonomics.

Subjects

Number: 38

Sex: 23 female, 15 male.

Age: 60 - 75 years.

Other characteristics: subjects were selected locally at random from elderly persons within this age range who were living in unassisted occupation of a dwelling. However, preliminary screening eliminated from selection those with any indication of coronary disease.

Method

Direction of force: a) torque, clockwise and counter-clockwise;
b) torque on door/window handles.

Posture: a line was drawn on the floor in line with, and vertically beneath, the handle of the apparatus. The subject's leading foot was positioned on this line to ensure maximum force application. Apart from this positioning, subjects were allowed to adopt whatever stance was natural to them.

Sort of force: maximal static force.

Laterality: the dominant hand.

Measurement: subjects were told to exert force as hard as they could until they felt they had reached their maximum, and they were then to release the handle. The highest value of three trials is the value used for computation of the strength data.

Sort and size of handle: a1) circular knob, Ø 2.8 cm; a2) square knob, 3.1 * 2.5 cm.
b1) handle, oval diameter; length 11 cm; b2) handle, square diameter, length 12 cm.

Position of handle: 1 m above the floor.

Other characteristics: -

Results

	force	female				male			
handle	direction*	$\bar{x}$	s	range	P_5	$\bar{x}$	s	range	P_5
circular knob									
circular knob	cw	0.58	0.22	1.27 - 0.23	0.21	0.83	0.39	1.66 - 0.33	0.19
	ccw	0.56	0.23	1.60 - 0.28	0.18	0.94	0.46	2.02 - 0.31	0.19
square knob	cw	0.69	0.21	1.04 - 0.19	0.35	1.04	0.36	1.70 - 0.57	0.44
	ccw	0.78	0.20	1.24 - 0.35	0.45	1.12	0.46	2.01 - 0.40	0.36
handle									
oval diameter	push	16.84	5.74	28.83 - 10.12	7.40	24.35	4.70	28.93 - 10.81	16.61
	pull	11.29	3.60	18.42 - 6.94	5.36	15.98	4.67	21.55 - 7.34	8.29
square diameter	push	10.73	4.13	23.83 - 6.47	3.94	16.67	5.92	28.72 - 9.04	6.94
	pull	9.51	3.30	18.78 - 6.12	4.08	15.74	3.77	20.76 - 7.79	9.53

Torque [Nm] exerted on two different knobs and two different handles. Averages, standard deviations, ranges and 5th percentiles of 38 elderly people.
** clockwise and counter-clockwise.*

Adams and Peterson (1988)

Source Adams, S.K. and Peterson, P.J., 1988.
Maximum voluntary hand grip torque for circular electrical connectors.
Human Factors, 30 (6), 733-745.

Subjects

Number: 31

Sex: 11 female, 20 male.

Age: females 19 to 40 years, males 18 to 32 years. Average for all is 23 years.

Other characteristics: civilians, selected to represent Air Force maintenance personnel in terms of standardized height-weight classifications so that approximately 90 % of the Air Force maintenance population could be represented in the study. Only right-handed subjects were used.

Method

Direction of force: torque, clockwise and counter-clockwise.

Posture: standing, with two different hand postures: fingertip grasp and full wraparound grasp (see figure b) and three different handle orientations (see figure c).

Sort of force: maximum static force.

Laterality: right hand.

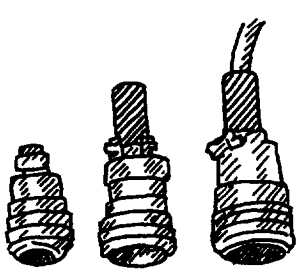
Measurement: duration 3 s.

Sort of handle: three sizes of electrical connectors, see figure a).

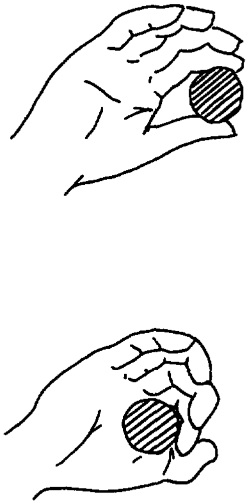
Size of handle: Ø 2.3 mm, Ø 3.8 mm and Ø 5.1 mm.

Position of handle: Three different orientations relative to the subject: frontal, sagittal (right side) and reverse frontal (facing away from the subjecs) planes of rotation. See figure c. Two different heights: at 60 % and 85 % of the subject's maximum reach height (connector height had little effect on torque strength. Only the results of 60 % of maximal reach height are given in the article).

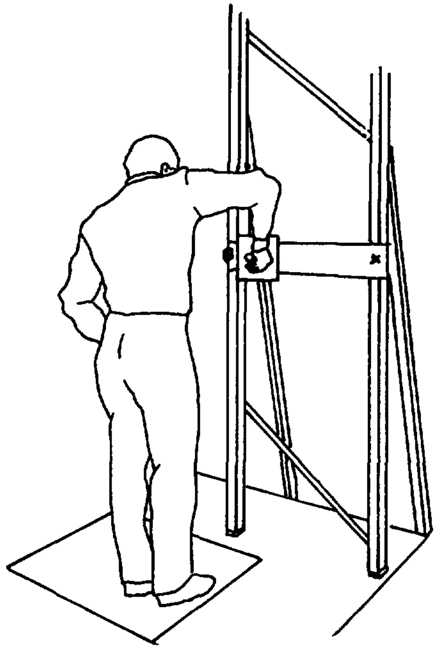
Other characteristics: three 'glove conditions' were used: no glove, a work glove (two layers: an inner wool liner and an outer layer of sewn leather) and chemical defense gloves (three layers: an inner cotton layer, a smooth rubber layer with a sleeve that covered the lower forearm, and an outer layer of sewn leather). These gloves were available in three sizes.



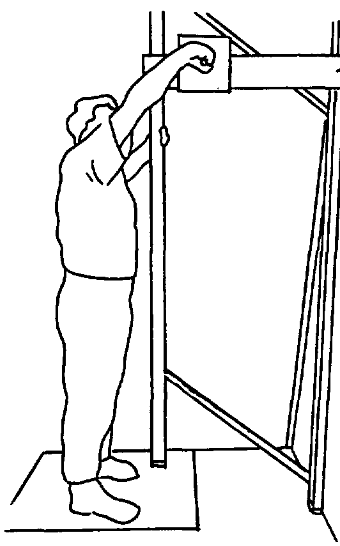
a) Typical circular electrical connectors



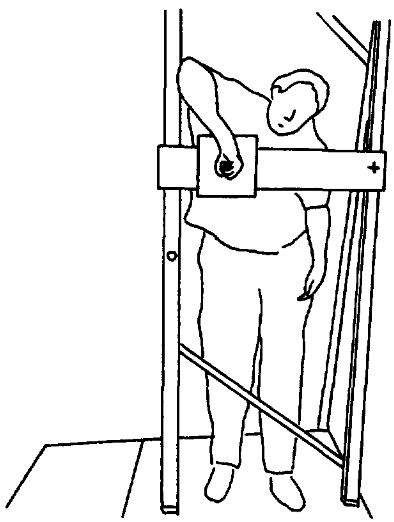
b) fingertip grasp (top) and full wraparound grasp (bottom) using the medium-sized connector.



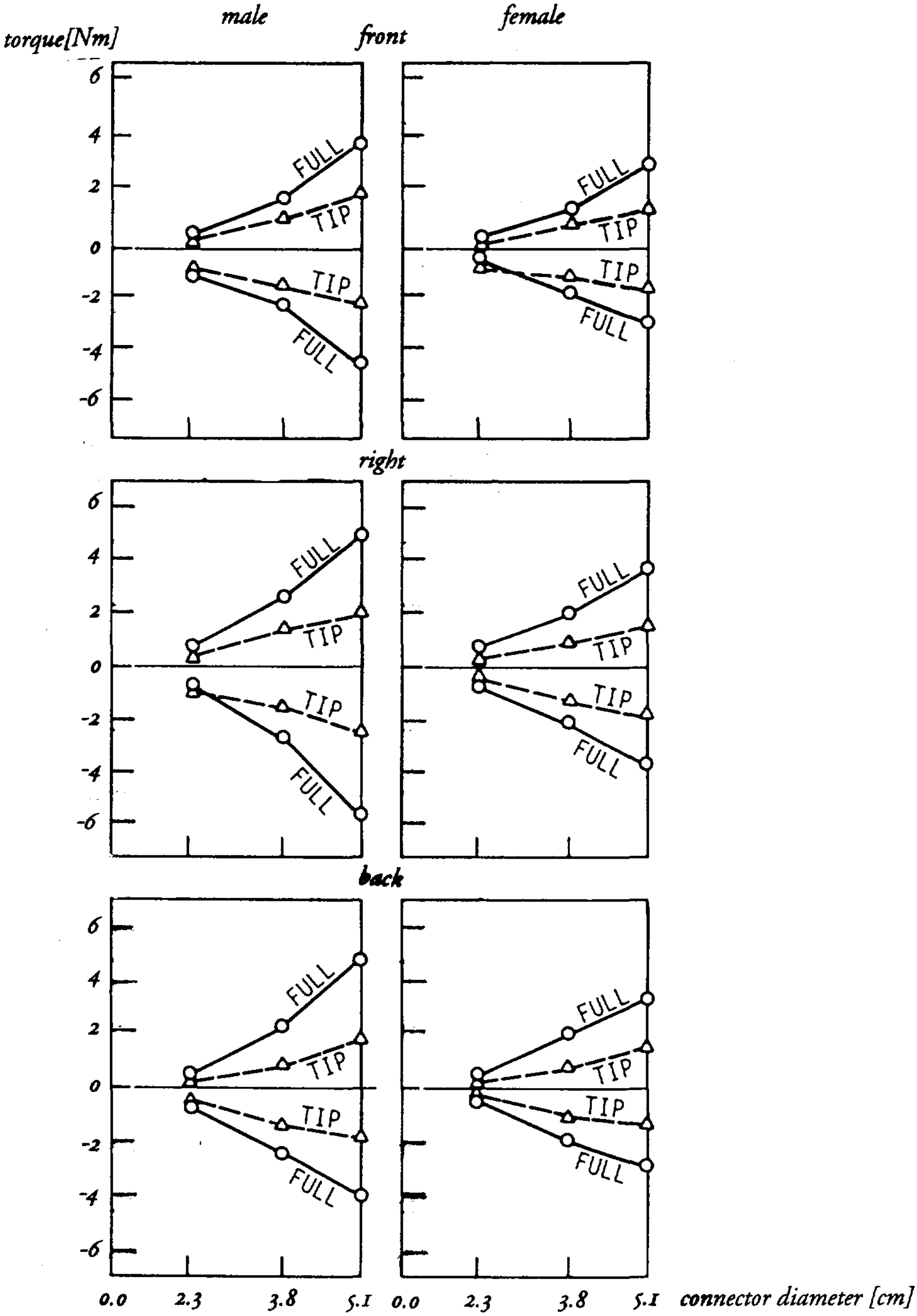
c) Connector in front position.



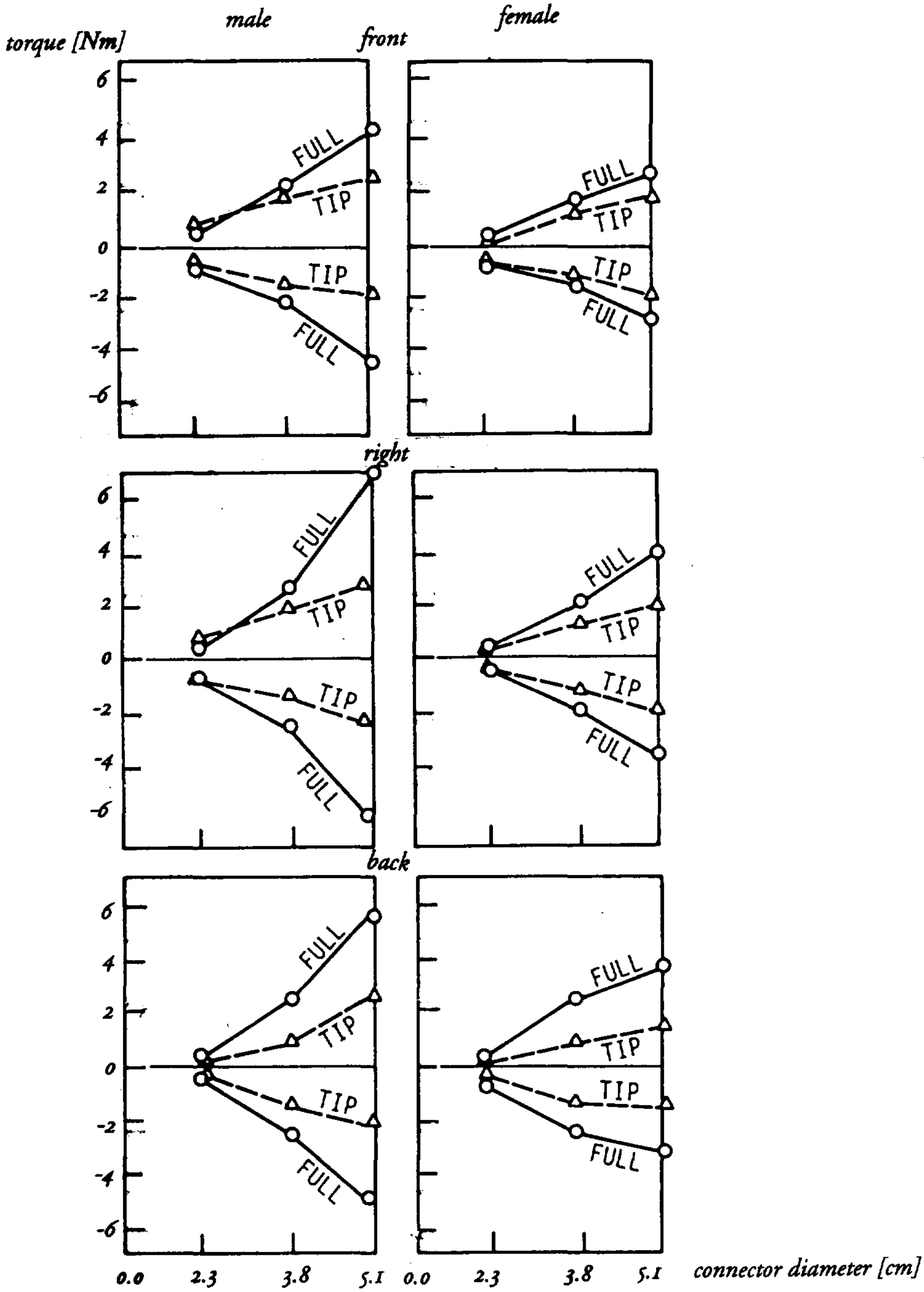
d) Connector in sagittal (right side) position and at 85 % of maximum reach height. Results with connectors at 60 % and 85 % of reach height are similar, only one table is given.



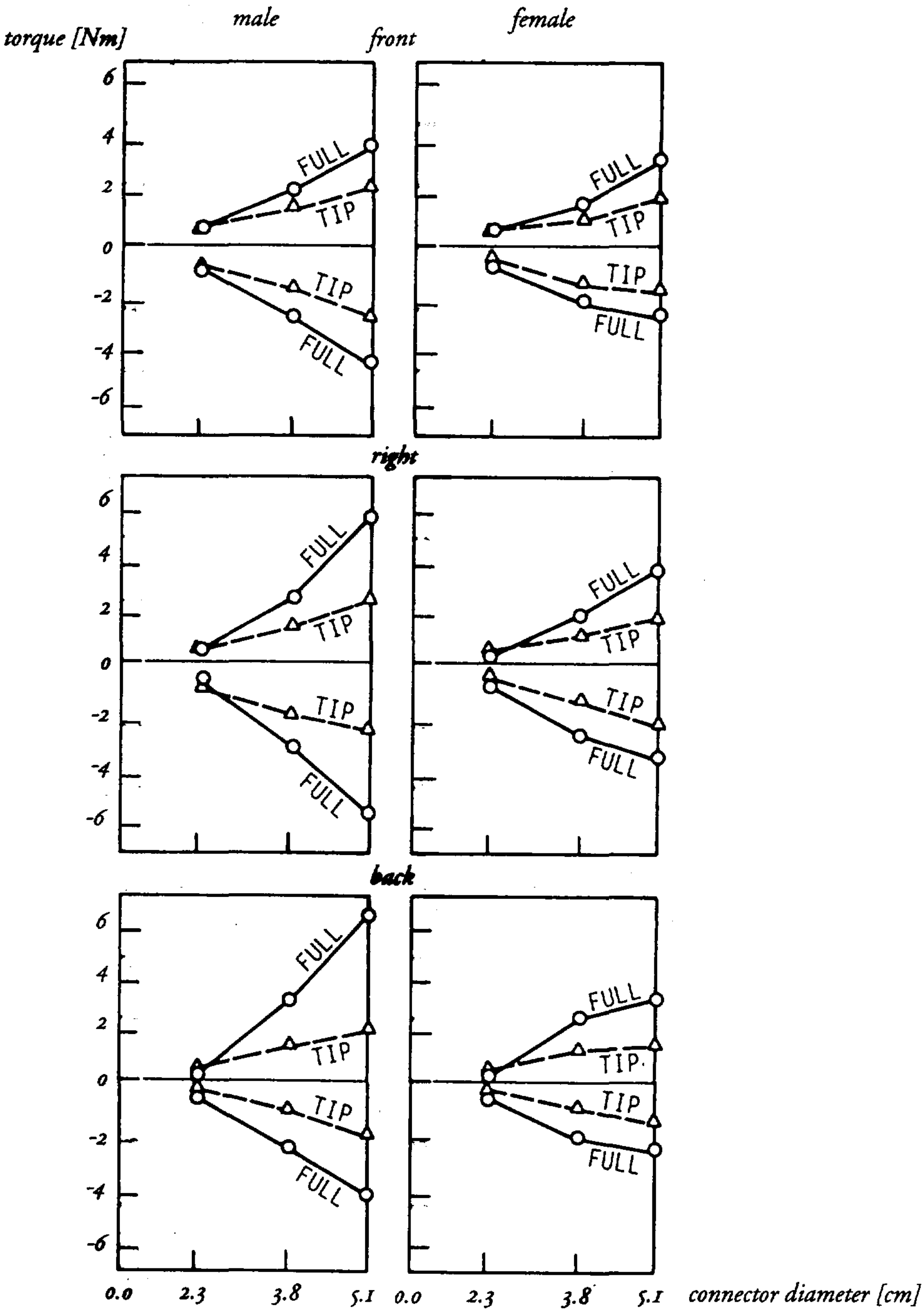
e) Connector in reverse frontal (back) position.



Torque [Nm], averages exerted in various postures ***without glove***
by 11 females and 20 males.



*Torque [Nm], averages exerted in various postures with **work glove** by 11 females and 20 males.*



Torque [Nm], averages exerted in various postures with ***chemical defense glove*** ***by 11 females and 20 males.***

Kanis (1989)

Source Kanis, H., 1989.
Bediening & handikap. Delft: Faculty of Industrial Design Engineering.

Subjects

Number: 34

Sex: 28 female and 6 male.

Age: average 54 years (s = 14.2).

Other characteristics: 28 arthritic subjects (24 women, 4 men) and 6 subjects (4 women, 2 men) with a muscle disease.

Method

Direction of force: torque, averaged for clockwise and counter-clockwise together.

Posture: sitting, with the elbow 90° flexed. Lateral grip. See figures.

Sort of force: maximal and comfortable static force. 'Comfortable' refers to a level of pain or fatigue found acceptable by the subject.

Laterality: left hand, right hand and preferred hand.

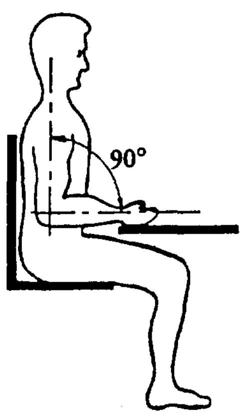
Measurement: subjects were instructed to build up their force gradually and to hold the maximum for at least a few seconds.

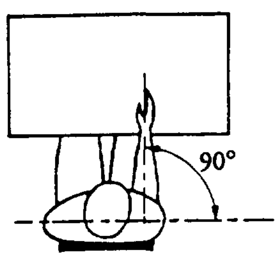
Sort of handle: two aluminium cylinders with anti-slip texture.

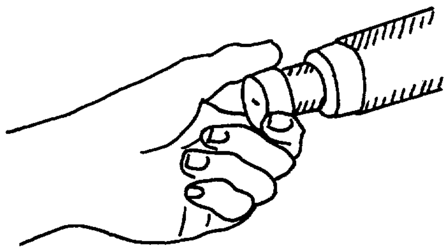
Size of handle: height 15 mm, Ø 13 mm and Ø 40 mm.

Position of handle: mounted on a table.

Other characteristics: -







Results

handle diameter [mm]	force	hand	females $\bar{x}$	females s	males $\bar{x}$	males s	arthritis $\bar{x}$	arthritis s	muscle desease $\bar{x}$	muscle desease s	all $\bar{x}$	all s
40	maximal	left	0.35	0.18	0.45	0.40	0.40	0.23	0.24	0.18	0.37	0.23
		right	0.36	0.19	0.59	0.54	0.44	0.29	0.24	0.20	0.40	0.29
	comfortable	preferred	0.17	0.10	0.26	0.28	0.19	0.15	0.14	0.11	0.18	0.15
13	maximal	preferred	0.10	0.04	0.15	0.12	0.12	0.07	0.07	0.03	0.11	0.07

Torque [Nm] exerted with lateral grip. Averages and standard deviations of 34 impaired subjects.

Schoorlemmer and Kanis (1992)

Source Schoorlemmer, W., 1993.
Bediening van knoppen. Internal report. Delft: Faculty of Industrial Design Engineering.

Schoorlemmer, W. and Kanis, H., 1992.
Operation of controls on everyday products. In: *Proceedings of the Human Factors 36th Annual Meeting - 1992*
(pp. 509 - 513). Santa Monica, CA: The Human Factors Society.

Subjects

Number: 27

Sex: 21 female, 6 male.

Age: average 49.4 years (s = 17.4).

Other characteristics: average body height 165 cm (s = 12), average body weight 67 kg (s = 12).
12 healthy subjects, 5 spastics, 4 visually impaired, 3 blind subjects, 3 subjects with Parkinson's disease.

Method

Direction of force: torque, clockwise and counter-clockwise (they are not significantly different and thus represented in one table).

Posture: sitting, with the elbow 90° flexed (see figures) and in free posture. Lateral grip.

Sort of force: maximal and comfortable static force. 'Comfortable' refers to a level of pain or fatigue found acceptable by the subject.

Laterality: left hand and right hand (averaged in the table).

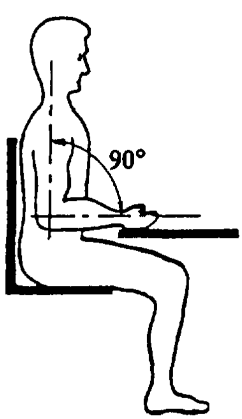
Measurement: subjects were instructed to build up their force gradually and to hold the maximum for at least a few seconds.

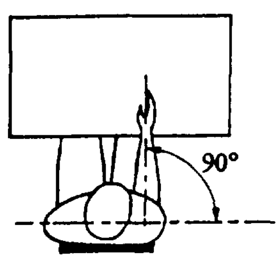
Sort of handle: three handles: two aluminium cylinders with anti-slip texture, one with a rim (see figure).

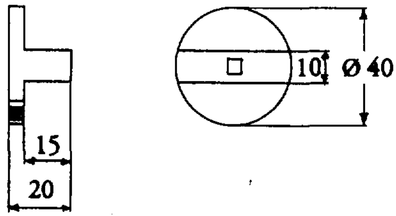
Size of handle: height 15 mm for all, Ø 13 mm and Ø 40 mm (see figure)

Position of handle: mounted on a table.

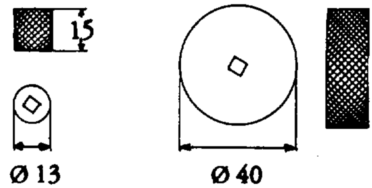
Other characteristics: -



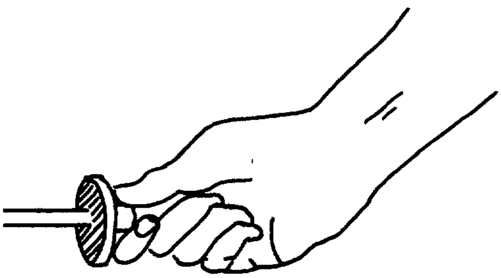




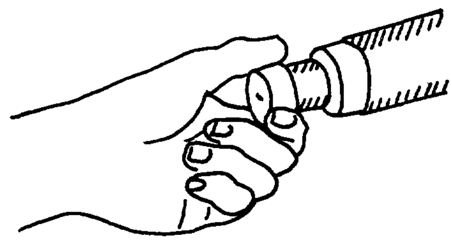
ridged knob



circular knob



Torque with lateral grip on a ridged knob



Torque with lateral grip on a circular knob

Results

force	posture	males n = 6 x̄	s	females n = 21 x̄	s	healthy, blind & visually impaired n = 19 x̄	s	spastics n = 5 x̄	s	Parkinson's disease n = 3 x̄	s	all n = 27 x̄	s
ridged knob													
max.	standard	1.46	0.51	1.14	0.45	1.35	0.42	0.89	0.48	0.85	0.48	1.21	0.47
	free	1.42	0.64	0.94	0.35	1.16	0.45	0.83	0.49	0.69	0.30	1.05	0.46
round knob ø 13 mm													
max.	standard	0.32	0.15	0.26	0.11	0.31	0.10	0.19	0.12	0.15	0.13	0.27	0.12
round knob ø 40 mm													
max.	standard	1.12	0.41	0.85	0.29	1.03	0.29	0.68	0.29	0.51	0.25	0.91	0.34
	free	1.12	0.54	0.92	0.40	1.03	0.40	0.86	0.58	0.71	0.35	0.96	0.43
comf.	standard	0.54	0.38	0.50	0.34	0.59	0.34	0.25	0.16	0.43	0.42	0.51	0.34

Torque [Nm] exerted with lateral grip. Averages and standard deviations of 12 healthy and 15 impaired subjects.

Steenbekkers (1993)

Source Steenbekkers, L.P.A., 1993.
Child development, design implications and accident prevention. Physical Ergonomics Series. Delft: Delftse Universitaire Pers.

Subjects

Number: 782

Sex: 392 girls, 390 boys.

Age: 4 to 13 years.

Other characteristics: Dutch children, selected to be representative for the Netherlands.

Method

Direction of force: torque, clockwise and counter-clockwise (they are not significantly different and thus represented in one table).

Posture: the child sits upright before the measuring device, which is in front of the forearm. The forearm is horizontal and in a sagittal plane. Upper arm and forearm are at an angle of about 150°. The legs hang down freely or are directed forward. (torque of forefinger and thumb: the thumb and fingers are positioned on the knob opposite one another. The other fingers are flexed into a fist.

Sort of force: maximal static force.

Laterality: preferred and non-preferred hand (they are not significantly different and thus represented in one table).

Measurement: duration 3 s.

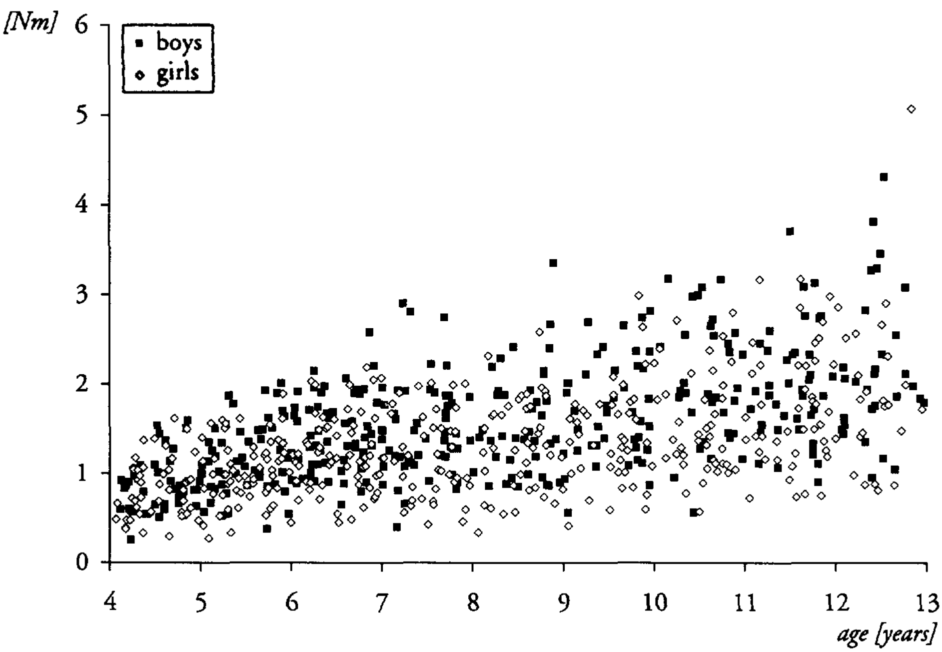
Sort of handle: a) cylindrical knob;
b) star knob (see figure).

Size of handle: a) Ø 4 cm;
b) maximum Ø 2.5 cm.

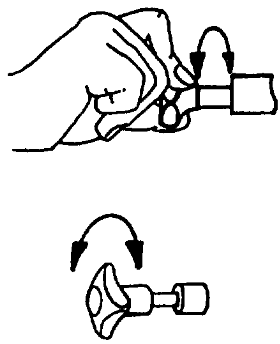
Position of handle: mounted on a table.

Other characteristics: -

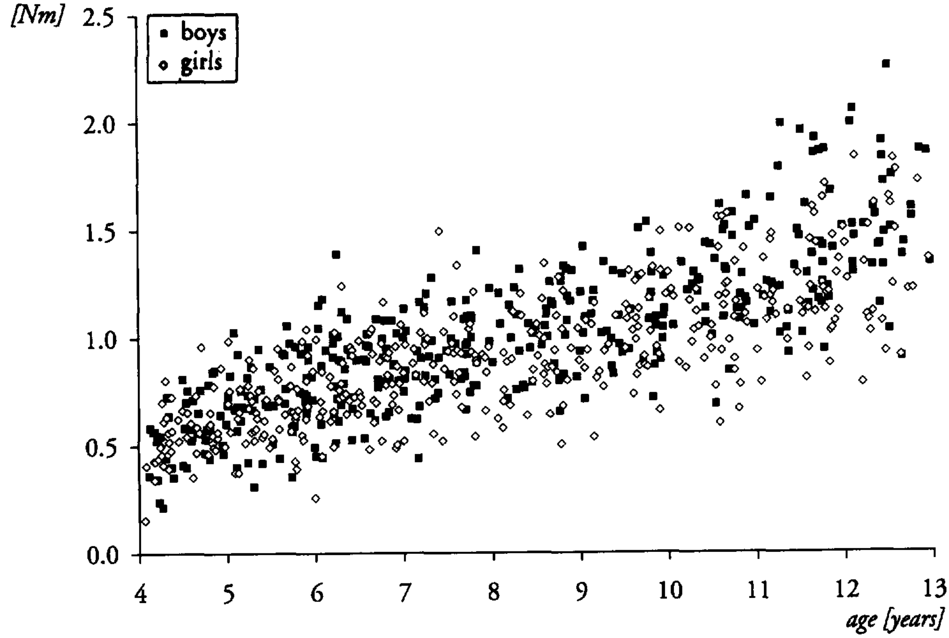
age [years]	girls n	girls x̄	girls s	girls P_3	girls P_{97}	boys n	boys x̄	boys s	boys P_3	boys P_{97}	all x̄	all s
4.0 – 4.9	46	0.83	0.32	0.33	1.50	41	0.88	0.30	0.52	1.54	0.85	0.32
5.0 – 5.9	59	1.02	0.35	0.34	1.61	53	1.16	0.39	0.53	1.93	1.09	0.38
6.0 – 6.9	57	1.23	0.43	0.49	2.08	59	1.43	0.42	0.80	2.21	1.33	0.43
7.0 – 7.9	42	1.20	0.46	0.46	2.01	50	1.50	0.53	0.66	2.81	1.36	0.52
8.0 – 8.9	40	1.33	0.52	0.55	2.32	41	1.56	0.57	0.86	2.68	1.45	0.56
9.0 – 9.9	42	1.45	0.55	0.60	2.64	41	1.74	0.56	0.88	2.75	1.59	0.57
10.0 – 10.9	39	1.54	0.56	0.78	2.72	35	2.07	0.70	0.96	3.18	1.80	0.68
11.0 – 11.9	44	1.74	0.66	0.74	3.18	40	1.98	0.62	1.07	3.14	1.85	0.65
12.0 – 12.9	23	1.94	0.94	0.82	5.08	30	2.18	0.83	0.96	4.33	2.08	0.88



a) Torque [Nm] exerted with one hand. Averages, standard deviations and percentiles for girls and boys.



age	girls					boys					all	
[years]	n	$\bar{x}$	s	P_3	P_{97}	n	$\bar{x}$	s	P_3	P_{97}	$\bar{x}$	s
4.0 – 4.9	46	0.27	0.07	0.17	0.42	41	0.27	0.08	0.12	0.41	0.27	0.07
5.0 – 5.9	59	0.33	0.08	0.18	0.48	53	0.35	0.09	0.17	0.50	0.34	0.08
6.0 – 6.9	57	0.38	0.09	0.23	0.56	59	0.41	0.10	0.22	0.57	0.40	0.09
7.0 – 7.9	42	0.43	0.10	0.25	0.64	50	0.44	0.09	0.30	0.62	0.44	0.09
8.0 – 8.9	40	0.44	0.10	0.28	0.62	41	0.50	0.09	0.35	0.64	0.47	0.10
9.0 – 9.9	42	0.49	0.10	0.32	0.64	41	0.53	0.10	0.35	0.73	0.51	0.10
10.0 – 10.9	39	0.54	0.12	0.32	0.75	35	0.61	0.11	0.41	0.78	0.57	0.12
11.0 – 11.9	44	0.59	0.11	0.39	0.79	40	0.66	0.14	0.46	0.94	0.63	0.13
12.0 – 12.9	23	0.64	0.15	0.38	0.88	30	0.75	0.14	0.44	1.09	0.70	0.16



b) Torque [Nm] exerted with thumb and forefinger. Averages, standard deviations and percentiles of girls and boys.

Putto (1988)

Source Putto, R., 1988.
Hanteren en kracht. Thesis. Delft: Faculty of Industrial Design Engineering.

Subjects

Number: 16

Sex: 2 female, 14 male.

Age: average 41.9 years (s = 10.2), range 23 - 59 years.

Other characteristics: Philips staff. Some had more than average knowledge of light bulbs, but their results did not differ from the others.
body height average 1.79 m (s = 0.10);
body weight average 77.1 kg (s = 1.3);
hand length average 19.2 cm (s = 1.3).

Method

Direction of force: torque, clockwise and counter-clockwise.

Posture: free posture when screwing and unscrewing a light bulb.
When exerting maximal force, the subject's own posture adopted when unscrewing a light bulb was reproduced (i.e. the grip, the orientation relative to the bulb and the arm posture were the same).

Sort of force: a) screwing in a light bulb (actual force, not maximal)
b) unscrewing a real (although fixed) bulb. The exerted force is static and as high as the subjects dare exert.
c) real maximal static torque, unscrewing a dummy bulb.

Laterality: the preferred hand.

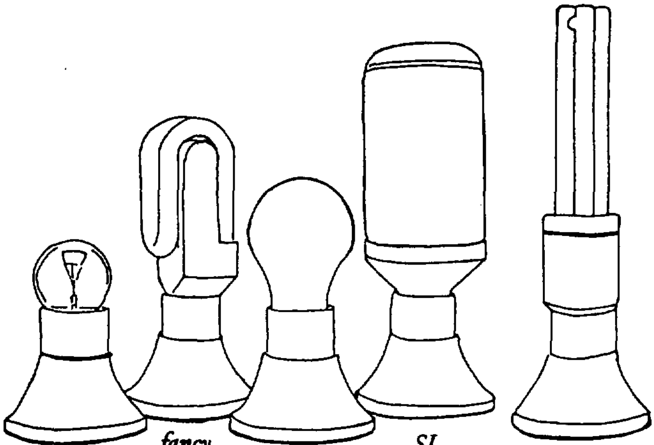
Measurement: a) and b): exerted as in real bulb screwing;
c) for the maximal force, the subjects were instructed to slowly build up their force to a maximum, and to maintain it for a few seconds.

Sort and size of handle: 5 different types of bulbs and 3 different types of dummies were used (see figure):
Bulbs (real)
1. small bulb, Ø 45 mm;
2. standard bulb, Ø 60 mm;
3. PLC-E small energy-saving bulb (square), diagonal cross section 45 mm;
4. fancy bulb (square), diagonal cross-section 55 mm;
5. SL large energy-saving bulb, Ø 70 mm.

Dummies, made of polished PC (Polycarbonate):
similar to the small bulb, Ø 45 mm (no. 1);
similar to the standard bulb, Ø 60 mm (no. 2);
similar to the large energy-saving bulb, Ø 70 mm (no. 5).

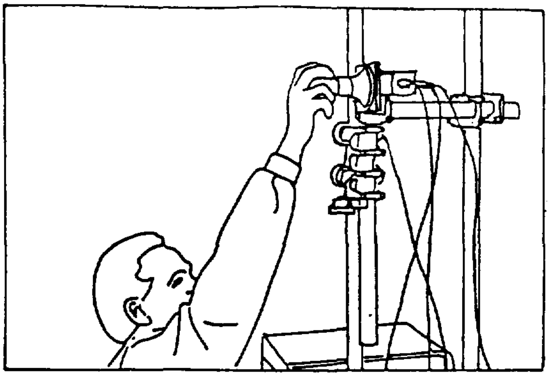
Position of handle: orientation of the bulbs: with the axis around which torque is exerted, horizontal.
Two different heights: chest (heart) height and maximum reach height.

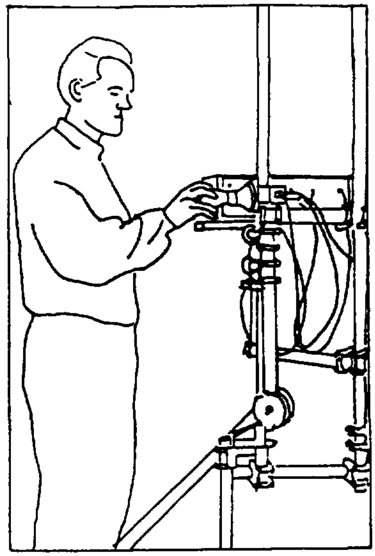
Other characteristics: -

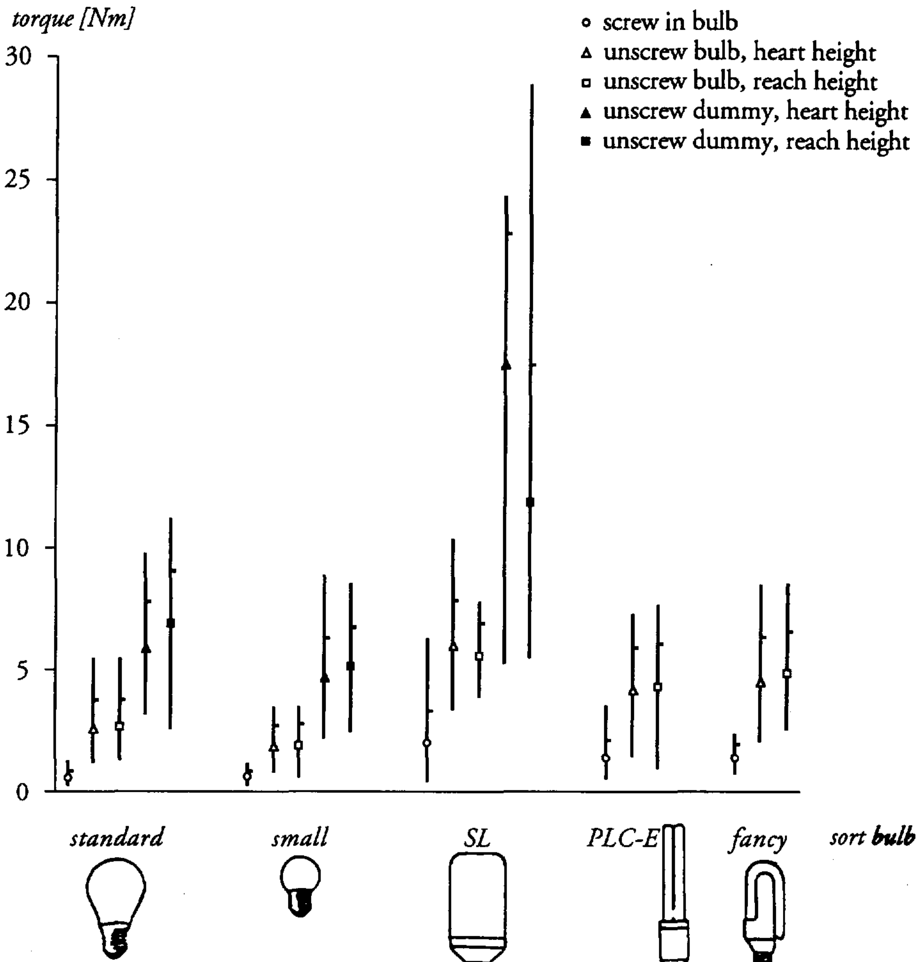


Results Comparing the maximal forces exerted on real bulbs and dummy bulbs, it can be seen that the characteristics of the real bulb limit the maximal force that is exerted.

sort bulb		direction of force	force	bulb height	$\bar{x}$	s	range
standard	real	screw in	actual	heart	0.58	0.26	0.30 - 1.20
		unscrew	maximal	heart	2.61	1.15	1.20 - 5.40
				reach	2.65	1.11	1.30 - 5.40
	dummy	unscrew	maximal	heart	5.89	1.87	3.20 - 9.70
				reach	6.89	2.16	2.60 - 11.10
small	real	screw in	actual	heart	0.60	0.25	0.30 - 1.10
		unscrew	maximal	heart	1.88	0.84	0.83 - 3.40
				reach	1.89	0.84	0.63 - 3.50
	dummy	unscrew	maximal	heart	4.70	1.60	2.20 - 8.80
				reach	5.11	1.63	2.50 - 8.50
SL	real	screw in	actual	heart	2.00	1.32	0.46 - 6.20
		unscrew	maximal	heart	6.03	1.78	3.40 - 10.30
				reach	5.59	1.28	3.90 - 7.70
	dummy	unscrew	maximal	heart	14.47	5.26	5.30 - 24.20
				reach	11.86	5.55	5.50 - 28.80
PLC-E	real	screw in	actual	heart	1.36	0.71	0.53 - 3.50
		unscrew	maximal	heart	4.19	1.72	1.50 - 7.20
	dummy	unscrew	maximal	reach	4.28	1.76	1.00 - 7.60
fancy	real	screw in	actual	heart	1.40	0.52	0.80 - 2.30
		unscrew	maximal	heart	4.53	1.82	2.10 - 8.40
	dummy	unscrew	maximal	reach	4.84	1.71	2.60 - 8.50







Torque [Nm] exerted on real and dummy bulbs. Averages, standard deviations and ranges of 16 subjects.

Rohmert & Hettinger (1963)

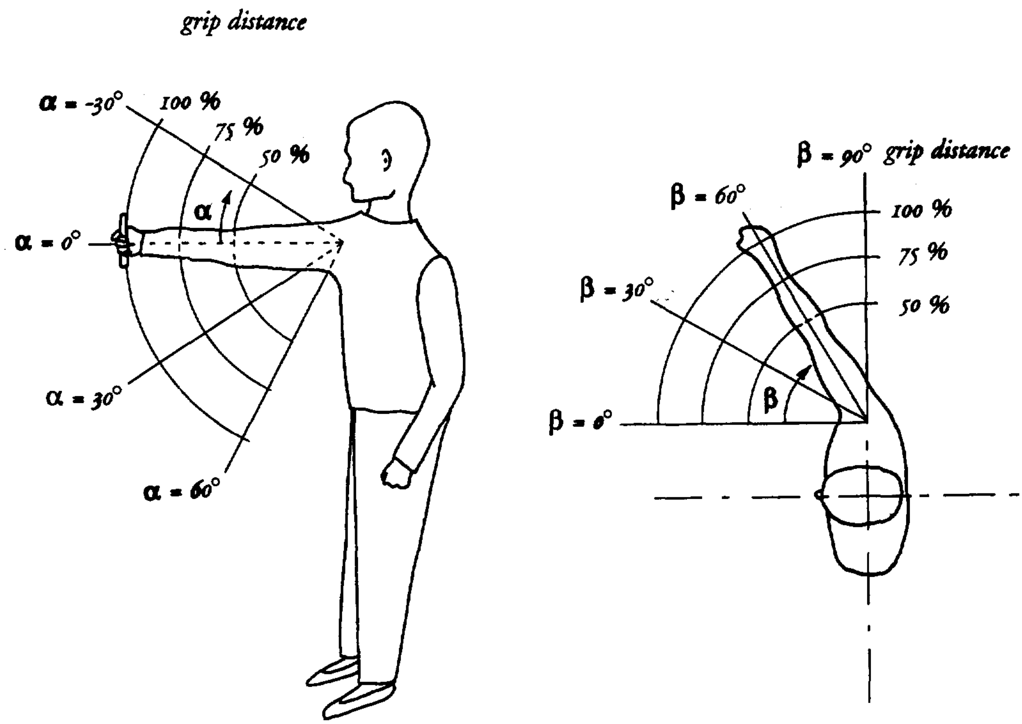
Source: Rohmert, W. and Hettinger, T., 1963.

Subjects:

Number: 60
Sex: male.
Age: ?
Other characteristics: ?

Method

Direction of force: torque, pronation (counter-clockwise) and supination (clockwise).
Posture: standing, with feet 30 cm apart, see figure.
Sort of force: maximal static force.
Laterality: one hand.
Measurement: ?
Sort of handle: see figure: cylindrical?
Size of handle: ?
Position of handle: at 50, 75 and 100 % of grip distance and various angles of the arm.
Other characteristics:



Results

arm position			pronation	supination
angle α	distance [% of arm reach]	angle β	counter-clockwise	clockwise
0°	100%	0	11.8	6.6
		30	12.3	6.7
		60	11.9	6.7
	75%	0	17.5	15.3
		30	17.8	15.0
		60	17.7	15.0
	50%	0	17.9	15.4
		30	17.5	15.3
		60	17.7	15.2
30°	100%	0	11.6	9.8
		30	11.6	9.7
		60	11.2	9.4
	75%	0	15.4	14.7
		30	15.4	15.0
		60	15.2	14.5
	50%	0	16.7	15.2
		30	16.5	15.3
		60	16.1	15.0
-30°	100%	0	13.5	4.9
		30	13.3	5.1
		60	13.0	5.2
	75%	0	17.7	13.0
		30	17.8	13.3
		60	17.9	13.1
	50%	0	18.1	14.3
		30	18.4	14.3
		60	18.3	14.0
-60°	100%	0	15.6	6.6
		30	15.7	6.5
		60	15.5	6.7
	75%	0	18.9	8.9
		30	19.2	9.0
		60	19.2	9.0
	50%	0	19.2	12.6
		30	19.0	12.5
		60	19.0	12.4

Torque [Nm], pronation and supination, with arm straight and bent, feet 30 cm apart and handle vertical. Average of 60 men.

D Correlation coefficient matrix

		1. Sex	2. Age	3. Body height	4. Body weight	5. Shoulder height	6. Elbow height	7. Elbow reach depth	8. Arm reach depth	9. Upper arm length	10. Tense upper arm girth	11. Relaxed upper arm girth	12 Quetelet index	13. Grip force	14. Pull, shoulder height	15. Push, shoulder height	16. Pull, elbow height
antropometry	2. Age	-															
	3. Body height	0.71 (55)	-														
	4. Body weight	0.41 (55)	0.30 (55)	0.60 (55)													
	5. Shoulder height	0.63 (48)	-	0.96 (48)	0.62 (48)												
	6. Elbow height	0.58 (48)	-	0.91 (48)	0.53 (48)	0.96 (48)											
	7. Elbow reach depth	0.67 (31)	-	0.90 (31)	0.52 (31)	0.90 (24)	0.84 (24)										
	8. Arm reach depth	0.62 (31)	-	0.81 (31)	0.53 (31)	0.79 (24)	0.73 (24)	0.87 (31)									
	9. Upper arm length	0.79 (26)	-	0.86 (26)	0.59 (26)	0.87 (19)	0.76 (19)	0.90 (26)	0.85 (26)								
	10. Tense upper arm girth	0.59 (27)	0.37 (27)	0.56 (27)	0.88 (27)	0.63 (20)	0.61 (20)	0.48 (27)	0.51 (27)	0.50 (26)							
	11. Relaxed upper arm girth	0.37 (27)	0.54 (27)	-	0.81 (27)	0.54 (20)	0.55 (20)	-	0.35 (27)	-	0.88 (27)						
	12. Quetelet index	-0.27 (55)	0.39 (55)	-0.32 (55)	0.52 (55)	-0.24 (48)	-0.29 (48)	-0.30 (31)	-	-	0.49 (27)	0.74 (27)					
maximal forces	13. Grip force	0.77 (31)	-	0.73 (31)	0.66 (31)	0.69 (24)	0.62 (24)	0.62 (31)	0.57 (31)	0.72 (26)	0.71 (27)	0.55 (27)	-				
	14. Pull, shoulder height	0.62 (43)	-	0.64 (43)	0.57 (43)	0.65 (43)	0.57 (43)	0.52 (19)	0.39 (19)	0.50 (19)	0.50 (19)	-	-	0.60 (19)			
	15. Push, shoulder height	0.55 (43)	-	0.54 (43)	0.45 (43)	0.51 (43)	0.43 (43)	0.49 (19)	-	0.48 (19)	0.50 (19)	-	-	0.49 (19)	0.77 (43)		
	16. Pull, elbow height	0.63 (43)	-	0.59 (43)	0.47 (43)	0.58 (43)	0.54 (43)	0.48 (19)	-	0.51 (19)	-	-	-	0.51 (19)	0.86 (43)	0.76 (43)	
	17. Push, elbow height	0.56 (43)	-	0.44 (43)	0.41 (43)	0.43 (43)	0.33 (43)	-	-	0.40 (19)	-	-	-	0.44 (19)	0.76 (43)	0.83 (43)	0.80 (43)
	18. Torque on jar (free)	0.72 (19)	-	0.57 (19)	-	0.50 (19)	0.40 (19)	0.55 (19)	0.42 (19)	0.56 (19)	-	-	-	0.48 (19)	0.69 (19)	0.70 (19)	0.92 (19)
	19. Torque on jar (fixed)	0.69 (19)	-	0.56 (19)	-	0.47 (19)	-	0.59 (19)	0.45 (19)	0.63 (19)	-	-	-	0.41 (19)	0.68 (19)	0.70 (19)	0.83 (19)
	20. Moment 1	0.82 (26)	-	0.75 (26)	0.50 (26)	0.74 (19)	0.67 (19)	0.69 (26)	0.58 (26)	0.73 (26)	0.61 (26)	0.36 (26)	-	0.74 (26)	0.66 (19)	0.77 (19)	0.79 (19)
	21. Moment 2	0.80 (26)	-	0.80 (26)	0.69 (26)	0.83 (19)	0.76 (19)	0.71 (26)	0.62 (26)	0.75 (26)	0.79 (26)	0.55 (26)	-	0.88 (26)	0.59 (19)	0.62 (19)	0.53 (19)
	22. Moment 3	0.68 (26)	-	0.75 (26)	0.64 (26)	0.73 (19)	0.68 (19)	0.62 (26)	0.54 (26)	0.70 (26)	0.71 (26)	0.50 (26)	-	0.85 (26)	0.48 (19)	0.54 (19)	-
	23. Moment 4	0.73 (26)	-	0.72 (26)	0.69 (26)	0.70 (19)	0.63 (19)	0.65 (26)	0.53 (26)	0.67 (26)	0.83 (26)	0.56 (26)	-	0.79 (26)	0.55 (19)	0.62 (19)	0.44 (19)
	24. Moment 5	0.63 (26)	-	0.72 (26)	0.72 (26)	0.71 (19)	0.66 (19)	0.63 (26)	0.54 (26)	0.66 (26)	0.76 (26)	0.58 (26)	-	0.85 (26)	0.50 (19)	0.48 (19)	-
	25. Moment 6	0.64 (26)	-	0.81 (26)	0.63 (26)	0.70 (19)	0.64 (19)	0.72 (26)	0.55 (26)	0.72 (26)	0.65 (26)	0.37 (26)	-	0.74 (26)	0.67 (19)	0.76 (19)	0.63 (19)
	26. Moment 7	0.74 (26)	-	0.60 (26)	0.38 (26)	0.59 (19)	0.50 (19)	0.59 (26)	0.46 (26)	0.65 (26)	0.54 (26)	-	-	0.64 (26)	0.67 (19)	0.69 (19)	0.80 (19)
	27. Moment 8	0.76 (26)	-	0.78 (26)	0.67 (26)	0.82 (19)	0.75 (19)	0.77 (26)	0.69 (26)	0.79 (26)	0.68 (26)	0.46 (26)	-	0.83 (26)	0.65 (19)	0.68 (19)	0.68 (19)
	28. Moment 9	0.64 (26)	-	0.76 (26)	0.57 (26)	0.73 (19)	0.68 (19)	0.68 (26)	0.57 (26)	0.78 (26)	0.58 (26)	-	-	0.74 (26)	0.63 (19)	0.78 (19)	0.66 (19)
	29. Moment 10	0.66 (26)	-	0.67 (26)	0.69 (26)	0.66 (19)	0.63 (19)	0.58 (26)	0.51 (26)	0.56 (26)	0.64 (26)	0.46 (26)	-	0.74 (26)	0.41 (19)	0.48 (19)	0.53 (19)
	30 Moment 11	0.65 (26)	-	0.73 (26)	0.71 (26)	0.70 (19)	0.63 (19)	0.66 (26)	0.53 (26)	0.69 (26)	0.77 (26)	0.55 (26)	-	0.83 (26)	0.65 (19)	0.66 (19)	0.57 (19)
	31. Moment 12	0.70 (26)	-	0.71 (26)	0.70 (26)	0.72 (19)	0.65 (19)	0.64 (26)	0.55 (26)	0.69 (26)	0.74 (26)	0.58 (26)	-	0.84 (26)	0.62 (19)	0.67 (19)	0.54 (19)
	32. Moment 13	0.77 (26)	-	0.64 (26)	0.40 (26)	0.61 (19)	0.49 (19)	0.60 (26)	0.44 (26)	0.63 (26)	0.60 (26)	-	-	0.71 (26)	0.77 (19)	0.77 (19)	0.80 (19)
	33. Moment 14	0.82 (26)	-	0.72 (26)	0.53 (26)	0.83 (19)	0.71 (19)	0.73 (26)	0.63 (26)	0.78 (26)	0.65 (26)	0.42 (26)	-	0.70 (26)	0.62 (19)	0.64 (19)	0.70 (19)
	34. Moment 15	0.87 (26)	-	0.82 (26)	0.63 (26)	0.81 (19)	0.70 (19)	0.78 (26)	0.69 (26)	0.81 (26)	0.71 (26)	0.43 (26)	-	0.78 (26)	0.69 (19)	0.74 (19)	0.73 (19)
	35. Moment 16	0.85 (26)	-	0.58 (26)	0.53 (26)	0.60 (19)	0.50 (19)	0.56 (26)	0.52 (26)	0.64 (26)	0.68 (26)	0.48 (26)	-	0.70 (26)	0.48 (19)	0.54 (19)	0.63 (19)
	36. Moment 17	0.86 (26)	-	0.67 (26)	0.59 (26)	0.74 (19)	0.64 (19)	0.62 (26)	0.57 (26)	0.71 (26)	0.77 (26)	0.55 (26)	-	0.77 (26)	0.69 (19)	0.71 (19)	0.65 (19)
	37. Moment 18	0.69 (26)	-	0.52 (26)	0.38 (26)	0.48 (19)	0.40 (19)	0.50 (26)	0.39 (26)	0.53 (26)	0.52 (26)	0.36 (26)	-	0.60 (26)	0.53 (19)	0.58 (19)	0.62 (19)
	38. Arm push	0.73 (24)	-	0.56 (24)	0.59 (24)	0.60 (24)	0.52 (24)	0.50 (24)	0.40 (24)	0.60 (19)	0.72 (20)	0.62 (20)	-	0.75 (24)	0.56 (19)	0.51 (19)	0.51 (19)
	39. Leg flexion	0.79 (24)	-	0.63 (24)	0.56 (24)	0.64 (24)	0.59 (24)	0.54 (24)	0.39 (24)	0.63 (19)	0.72 (20)	0.53 (20)	-	0.78 (24)	0.72 (19)	0.72 (19)	0.66 (19)
	40. Leg extension	0.76 (24)	-	0.67 (24)	0.44 (24)	0.64 (24)	0.56 (24)	0.57 (24)	0.44 (24)	0.61 (19)	0.63 (20)	0.40 (20)	-	0.69 (24)	0.69 (19)	0.74 (19)	0.62 (19)
	41. Arm anteflexion	0.78 (24)	-	0.62 (24)	0.66 (24)	0.64 (24)	0.58 (24)	0.54 (24)	0.37 (24)	0.57 (19)	0.82 (20)	0.65 (20)	-	0.77 (24)	0.69 (19)	0.65 (19)	0.64 (19)

This correlation coefficient matrix includes the variables that resulted from the experiments described in chapter 5 'Experiments'. Only significant correlations are indicated. Underlined values denote correlations which show more generality than specificity (with r ≥ 0.71). The number of subjects is indicated between brackets.

Variable	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
17. Push, elbow height																								
18. Torque on jar (free)	0.74 (19)																							
19. Torque on jar (fixed)	0.75 (19)	0.90 (19)																						
20. Moment 1	0.73 (19)	0.80 (19)	0.70 (19)																					
21. Moment 2	0.54 (19)	0.61 (19)	0.54 (19)	0.86 (26)																				
22. Moment 3	0.44 (19)	0.45 (19)	0.45 (19)	0.74 (26)	0.91 (26)																			
23. Moment 4	0.52 (19)	0.53 (19)	0.53 (19)	0.81 (26)	0.94 (26)	0.89 (26)																		
24. Moment 5	-	0.42 (19)	-	0.70 (26)	0.91 (26)	0.95 (26)	0.91 (26)																	
25. Moment 6	0.57 (19)	0.67 (19)	0.68 (19)	0.79 (26)	0.85 (26)	0.85 (26)	0.86 (26)	0.86 (26)																
26. Moment 7	0.73 (19)	0.79 (19)	0.75 (19)	0.91 (26)	0.75 (26)	0.60 (26)	0.75 (26)	0.58 (26)	0.69 (26)															
27. Moment 8	0.58 (19)	0.73 (19)	0.64 (19)	0.88 (26)	0.91 (26)	0.80 (26)	0.86 (26)	0.83 (26)	0.86 (26)	0.83 (26)														
28. Moment 9	0.67 (19)	0.68 (19)	0.72 (19)	0.82 (26)	0.82 (26)	0.86 (26)	0.81 (26)	0.81 (26)	0.92 (26)	0.74 (26)	0.89 (26)													
29 Moment 10	0.50 (19)	0.62 (19)	0.42 (19)	0.76 (26)	0.82 (26)	0.64 (26)	0.75 (26)	0.67 (26)	0.66 (26)	0.67 (26)	0.81 (26)	0.65 (26)												
30. Moment 11	0.50 (19)	0.59 (19)	0.58 (19)	0.77 (26)	0.91 (26)	0.90 (26)	0.91 (26)	0.94 (26)	0.92 (26)	0.67 (26)	0.88 (26)	0.88 (26)	0.74 (26)											
31. Moment 12	0.59 (19)	0.51 (19)	0.49 (19)	0.79 (26)	0.89 (26)	0.90 (26)	0.90 (26)	0.93 (26)	0.88 (26)	0.67 (26)	0.86 (26)	0.86 (26)	0.70 (26)	0.93 (26)										
32. Moment 13	0.78 (19)	0.79 (19)	0.76 (19)	0.92 (26)	0.83 (26)	0.70 (26)	0.82 (26)	0.68 (26)	0.78 (26)	0.94 (26)	0.84 (26)	0.77 (26)	0.69 (26)	0.78 (26)	0.76 (26)									
33. Moment 14	0.61 (19)	0.73 (19)	0.69 (19)	0.90 (26)	0.87 (26)	0.70 (26)	0.81 (26)	0.70 (26)	0.73 (26)	0.83 (26)	0.84 (26)	0.73 (26)	0.72 (26)	0.79 (26)	0.76 (26)	0.87 (26)								
34. Moment 15	0.67 (19)	0.79 (19)	0.77 (19)	0.89 (26)	0.89 (26)	0.81 (26)	0.86 (26)	0.79 (26)	0.83 (26)	0.75 (26)	0.84 (26)	0.81 (26)	0.72 (26)	0.86 (26)	0.82 (26)	0.82 (26)	0.89 (26)							
35. Moment 16	0.67 (19)	0.66 (19)	0.57 (19)	0.84 (26)	0.81 (26)	0.67 (26)	0.77 (26)	0.63 (26)	0.57 (26)	0.76 (26)	0.73 (26)	0.62 (26)	0.73 (26)	0.68 (26)	0.70 (26)	0.80 (26)	0.88 (26)	0.87 (26)						
36. Moment 17	0.67 (19)	0.65 (19)	0.61 (19)	0.88 (26)	0.88 (26)	0.81 (26)	0.86 (26)	0.77 (26)	0.71 (26)	0.76 (26)	0.79 (26)	0.73 (26)	0.67 (26)	0.80 (26)	0.81 (26)	0.84 (26)	0.88 (26)	0.94 (26)	0.92 (26)					
37. Moment 18	0.52 (19)	0.62 (19)	0.55 (19)	0.73 (26)	0.67 (26)	0.63 (26)	0.68 (26)	0.65 (26)	0.65 (26)	0.54 (26)	0.58 (26)	0.58 (26)	0.47 (26)	0.69 (26)	0.70 (26)	0.66 (26)	0.71 (26)	0.82 (26)	0.73 (26)	0.82 (26)				
38. Arm push	0.54 (19)	0.51 (19)	0.47 (19)	0.67 (19)	0.83 (19)	0.83 (19)	0.82 (19)	0.85 (19)	0.68 (19)	0.65 (19)	0.76 (19)	0.67 (19)	0.55 (19)	0.81 (19)	0.86 (19)	0.73 (19)	0.80 (19)	0.81 (19)	0.78 (19)	0.83 (19)	0.61 (19)			
39. Leg flexion	0.70 (19)	0.71 (19)	0.67 (19)	0.77 (19)	0.91 (19)	0.85 (19)	0.87 (19)	0.79 (19)	0.78 (19)	0.75 (19)	0.88 (19)	0.81 (19)	0.70 (19)	0.84 (19)	0.82 (19)	0.85 (19)	0.81 (19)	0.84 (19)	0.80 (19)	0.86 (19)	0.52 (19)	0.85 (24)		
40. Leg extension	0.71 (19)	0.71 (19)	0.71 (19)	0.76 (19)	0.88 (19)	0.86 (19)	0.91 (19)	0.79 (19)	0.83 (19)	0.71 (19)	0.81 (19)	0.80 (19)	0.64 (19)	0.84 (19)	0.85 (19)	0.83 (19)	0.77 (19)	0.86 (19)	0.72 (19)	0.85 (19)	0.69 (19)	0.79 (24)	0.88 (24)	
41. Arm anteflexion	0.61 (19)	0.67 (19)	0.58 (19)	0.80 (19)	0.92 (19)	0.86 (19)	0.91 (19)	0.85 (19)	0.76 (19)	0.75 (19)	0.85 (19)	0.72 (19)	0.70 (19)	0.86 (19)	0.87 (19)	0.86 (19)	0.84 (19)	0.88 (19)	0.82 (19)	0.92 (19)	0.65 (19)	0.85 (24)	0.92 (24)	0.79 (24)

		anthropometry												maximal forces			
		1. Sex	2. Age	3. Body height	4. Body weight	5. Shoulder height	6. Elbow height	7. Elbow reach depth	8. Arm reach depth	9. Upper arm length	10. Tense upper arm girth	11. Relaxed upper arm girth	12. Quetelet index	13. Grip force	14. Pull, shoulder height	15. Push, shoulder height	16. Pull, elbow height
maximal endurance times	*42. Push endurance, 80%*	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-0.42 (18)	-
	43. Push endurance, 60%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	44. Push endurance, 40%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	45. Push endurance, 30%	-	-	-	-	-	-	-	-	-	-	-	-	0.39 (22)	-	-	-
	46. Push endurance, 20%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	47. Push endurance, 15%	-	-	-	-	-	-	-	-	-	-	-	-0.44 (22)	-	-	-	-
	48. Flexion endurance, 80%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	49. Flexion endurance, 60%	-	-	-	-	-	-	-	-	-0.41 (17)	-	-	-	-	-0.42 (17)	-	-
	50. Flexion endurance, 40%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	51. Flexion endurance, 30%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	52. Flexion endurance, 20%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	53. Flexion endurance, 15%	-	-	-	-	-	-	-	-	-	-	-	-	0.57 (18)	0.47 (14)	-	0.54 (14)
	54. Extension endurance, 80%	-0.37 (23)	-	-	-	-	-	-	-	-	-	-	-	-	-0.54 (18)	-0.49 (18)	-0.49 (18)
	55. Extension endurance, 60%	-	-	-	-0.40 (23)	-	-	-	-	-	-	-	-0.38 (23)	-	-	-0.48 (18)	-
	56. Extension endurance, 40%	-	-	-	-0.37 (23)	-	-	-	-	-	-	-	-	-	-	-0.40 (18)	-
	57. Extension endurance, 30%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	58. Extension endurance, 20%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	59. Extension endurance, 15%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	60. Anteflexion endurance, 80%	-0.37 (24)	-	-	-	-	-	-	-	-	-	-	-	-0.40 (24)	-	-	-0.43 (19)
	61. Anteflexion endurance, 60%	-0.37 (24)	-	-	-	-	-	-	-	-	-	-	-	-0.43 (24)	-	-	-
	62. Anteflexion endurance, 40%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	63. Anteflexion endurance, 30%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	64. Anteflexion endurance, 20%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.45 (17)	0.50 (17)
	65. Anteflexion endurance, 15%	0.53 (21)	-	-	-	-	-	-	-	-	-	-	-	-	0.43 (16)	0.58 (16)	0.70 (16)
discomfort	*66. Time to change, 80%*	-0.53 (17)	-	-0.56 (17)	-	-0.56 (17)	-0.55 (17)	-0.67 (17)	-0.67 (17)	-0.56 (17)	-	-	-	-	-	-	-
	67. Time to change, 60%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	68. Time to change, 40%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	69. Time to change, 30%	-	-	-0.43 (17)	-0.51 (17)	-0.46 (17)	-0.48 (17)	-0.47 (17)	-0.60 (17)	-	-	-0.46 (17)	-	-	-	-	-
	70. Time to change, 20%	-	-	-	-0.45 (17)	-	-	-	-0.46 (17)	-	-	-0.49 (17)	-	-	-	-	-
	71. Time to change, 15%	-	-	-	-0.51 (17)	-0.45 (17)	-0.50 (17)	-0.44 (17)	-0.51 (17)	-	-	-	-	-	-	-	-
	72. Number of changes, 80%	-	-	0.53 (17)	-	0.53 (17)	0.53 (17)	0.59 (17)	0.50 (17)	0.60 (17)	-	-	-	-	0.41 (17)	0.47 (17)	-
	73. Number of changes, 60%	-	-	0.48 (17)	-	0.46 (17)	0.46 (17)	0.48 (17)	-	0.49 (17)	-	-	-	-	-	-	-
	74. Number of changes, 40%	-	0.46 (17)	0.45 (17)	-	0.44 (17)	0.47 (17)	0.46 (17)	-	0.50 (17)	-	-	-	-	-	-	-
	75. Number of changes, 30%	-	-	-	-	-	0.50 (17)	-	0.44 (17)	-	-	-	-	-	-	-	-
	76. Number of changes, 20%	-	-	-	0.53 (17)	-	-	-	-	-	-	0.45 (17)	0.53 (17)	-	-	-	-
	77. Number of changes, 15%	-	-	-	0.61 (17)	-	-	-	-	-	-	0.58 (17)	0.57 (17)	-	-	-	-

17. Push, elbow height	18. Torque on jar (free)	19. Torque on jar (fixed)	20. Moment 1	21. Moment 2	22. Moment 3	23. Moment 4	24. Moment 5	25. Moment 6	26. Moment 7	27. Moment 8	28. Moment 9	29. Moment 10	30 Moment 11	31. Moment 12	32. Moment 13	33. Moment 14	34. Moment 15	35. Moment 16	36. Moment 17	37. Moment 18	38. Arm push	39. Leg flexion	40. Leg extension	41. Arm anteflexion
-0.67 (18)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-0.48 (18)	-0.41 (18)	-	-	-0.35 (23)	-	-
-0.49 (18)	-	-	-	-	-	-	-	-	-	-	-0.48 (18)	-	-	-0.45 (18)	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-0.37 (22)	-0.36 (22)	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-0.57 (18)	-0.46 (18)	-	-0.43 (18)	-0.44 (18)	-	-	-	-	-0.40 (18)	-0.54 (18)	-0.44 (18)	-	-	-0.49 (18)	-0.46 (18)	-0.45 (18)	-0.42 (18)	-0.51 (18)	-0.48 (18)	-	-0.45 (23)	-0.45 (23)	-0.44 (23)	-
-0.49 (18)	-	-	-	-0.40 (18)	-	-0.40 (18)	-	-	-	-	-	-0.42 (18)	-0.42 (18)	-0.47 (18)	-	-	-	-	-	-	-0.44 (23)	-0.54 (23)	-0.49 (23)	-0.39 (23)
-	-	-	-	-	-0.42 (18)	-0.41 (18)	-0.42 (18)	-	-	-	-	-	-	-0.49 (18)	-	-	-	-	-	-	-0.45 (23)	-0.45 (23)	-0.43 (23)	-
-0.52 (18)	-0.45 (18)	-	-	-0.51 (18)	-0.40 (18)	-0.44 (18)	-	-	-	-0.47 (18)	-	-0.59 (18)	-	-	-	-	-	-0.56 (18)	-0.41 (18)	-	-	-0.50 (23)	-0.48 (23)	-0.35 (23)
-	-0.43 (17)	-	-	-0.58 (17)	-0.54 (17)	-0.59 (17)	-0.58 (17)	-0.44 (17)	-	-0.65 (17)	-0.51 (17)	-0.51 (17)	-0.55 (17)	-0.52 (17)	-	-	-0.44 (17)	-0.53 (17)	-0.45 (17)	-0.41 (17)	-	-0.41 (22)	-0.47 (22)	-
-	-0.49 (18)	-0.46 (18)	-	-	-	-0.42 (18)	-	-	-	-	-	-	-	-	-	-	-	-0.49 (18)	-	-	-	-	-0.38 (23)	-
-	-	-	-	-	-	-	-	-	-0.40 (19)	-	-	-	-	-	-	-	-	-	-	-	-0.39 (24)	-0.41 (24)	-0.36 (24)	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-0.40 (24)	-0.34 (24)	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0.48 (17)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0.78 (16)	0.69 (16)	0.63 (16)	0.63 (16)	-	-	-	-	-	0.57 (16)	-	-	0.47 (16)	-	-	0.60 (16)	0.50 (16)	-	0.53 (16)	-	-	-	0.45 (21)	0.41 (21)	0.41 (21)
-	-	-0.46 (17)	-0.50 (17)	-	-	-	-	-	-0.48 (17)	-0.44 (17)	-	-	-	-	-0.43 (17)	-0.56 (17)	-0.52 (17)	-0.47 (17)	-0.51 (17)	-0.48 (17)	-0.47 (17)	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-0.43 (17)	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0.44 (17)	-	0.62 (17)	0.48 (17)	-	-	-	-	0.48 (17)	0.55 (17)	0.43 (17)	0.60 (17)	-	-	-	0.48 (17)	0.49 (17)	0.48 (17)	-	0.46 (17)	-	-	0.43 (17)	0.51 (17)	-
-	-	-	-	-	-	-	-	-	-	-	0.42 (17)	-	-	0.42 (17)	-	0.50 (17)	-	-	-	-	0.46 (17)	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.41 (17)	-	-	-	-	0.43 (17)	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

maximal forces	42. Push endurance, 80%	43. Push endurance, 60%	44. Push endurance, 40%	45. Push endurance, 30%	46. Push endurance, 20%	47. Push endurance, 15%	48. Flexion endurance, 80%	49. Flexion endurance, 60%	50. Flexion endurance, 40%	51. Flexion endurance, 30%	52. Flexion endurance, 20%	53. Flexion endurance, 15%	54. Extension endurance, 80%	55. Extension endurance, 60%	56. Extension endurance, 40%	57. Extension endurance, 30%	58. Extension endurance, 20%
42. Push endurance, 80%																	
43. Push endurance, 60%	0.73 (23)																
44. Push endurance, 40%	0.49 (23)	0.67 (23)															
45. Push endurance, 30%	0.47 (22)	0.53 (22)	0.59 (22)														
46. Push endurance, 20%	-	0.54 (21)	0.82 (21)	0.74 (20)													
47. Push endurance, 15%	-	0.48 (22)	0.58 (22)	0.66 (22)	0.72 (20)												
48. Flexion endurance, 80%	-	0.44 (21)	0.65 (21)	-	0.68 (19)	0.46 (20)											
49. Flexion endurance, 60%	-	0.46 (20)	0.54 (20)	0.75 (20)	0.76 (19)	0.58 (20)	0.80 (21)										
50. Flexion endurance, 40%	-	0.45 (21)	0.55 (21)	0.80 (20)	0.89 (19)	0.66 (20)	0.75 (22)	0.81 (22)									
51. Flexion endurance, 30%	-	0.54 (21)	0.55 (21)	0.78 (20)	0.82 (19)	0.68 (20)	0.71 (22)	0.86 (22)	0.92 (22)								
52. Flexion endurance, 20%	-	0.42 (21)	-	0.57 (20)	0.60 (19)	0.57 (20)	0.44 (22)	0.57 (22)	0.62 (22)	0.75 (22)							
53. Flexion endurance, 15%	-	-	-	-	-	-	-	-	-	0.47 (18)	0.62 (18)						
54. Extension endurance, 80%	-	-	-	-	0.53 (20)	-	0.42 (21)	0.56 (21)	0.43 (21)	-	-	-					
55. Extension endurance, 60%	0.51 (22)	0.44 (22)	-	-	-	-	0.45 (21)	0.43 (21)	0.40 (21)	0.41 (21)	-	-	0.72 (23)				
56. Extension endurance, 40%	0.41 (22)	0.39 (22)	-	-	-	-	0.51 (21)	0.45 (21)	0.51 (21)	0.50 (21)	0.44 (21)	-	0.58 (23)	0.81 (23)			
57. Extension endurance, 30%	0.53 (22)	0.38 (22)	-	0.37 (21)	0.45 (20)	-	-	0.52 (21)	0.46 (21)	0.54 (21)	0.63 (21)	-	0.55 (23)	0.68 (23)	0.54 (23)		
58. Extension endurance, 20%	-	0.37 (21)	-	0.37 (20)	0.52 (19)	-	0.55 (20)	0.51 (20)	0.57 (20)	0.63 (20)	0.62 (20)	0.47 (17)	0.46 (22)	0.52 (22)	0.48 (22)	0.71 (22)	
59. Extension endurance, 15%	-	-	-	-	-	-	-	0.41 (21)	0.43 (21)	0.50 (21)	0.64 (21)	0.64 (17)	0.41 (23)	0.40 (23)	0.40 (23)	0.58 (23)	0.84 (22)
60. Anteflexion endurance, 80%	-	-	-	-	-	-	-	-	-	-	-	-0.64 (18)	0.37 (23)	-	-	-	-
61. Anteflexion endurance, 60%	-	-	-	-	-	-	0.42 (22)	-	-	-	-	-	0.37 (23)	-	-	-	-
62. Anteflexion endurance, 40%	-	0.47 (23)	0.67 (23)	0.65 (22)	0.79 (21)	0.50 (22)	0.40 (22)	0.43 (22)	0.59 (22)	0.56 (22)	-	-	0.42 (23)	0.38 (23)	-	0.39 (23)	0.48 (22)
63. Anteflexion endurance, 30%	-	-	0.43 (23)	0.76 (22)	0.80 (21)	0.60 (22)	-	0.39 (22)	0.64 (22)	0.59 (22)	0.38 (22)	-	-	-	-	0.37 (23)	0.39 (22)
64. Anteflexion endurance, 20%	-	-	-	0.58 (20)	0.68 (19)	0.40 (20)	-	-	0.58 (21)	0.63 (21)	0.40 (21)	-	-	-	-	-	0.40 (20)
65. Anteflexion endurance, 15%	-	-	-	0.49 (19)	0.50 (19)	0.50 (19)	-	-	-	0.42 (20)	-	-	-	-	-	-	-
66. Time to change, 80%	-	-	-	-	0.46 (15)	-	0.54 (15)	0.53 (15)	0.54 (15)	0.44 (15)	-	-	0.44 (17)	-	-	-	-
67. Time to change, 60%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
68. Time to change, 40%	-	-	-	-	0.55 (15)	-	-	-	-	-	-	-	-	-	-	-	-
69. Time to change, 30%	-	-	-	0.44 (15)	0.63 (15)	-	0.57 (15)	-	0.59 (15)	0.45 (15)	-	-	-	-	0.58 (17)	-	-
70. Time to change, 20%	-	-	0.45 (16)	0.57 (15)	0.70 (15)	0.46 (15)	0.59 (15)	-	0.60 (15)	0.52 (15)	-	-	-	-	0.57 (17)	-	-
71. Time to change, 15%	-	-	-	-	-	-	0.59 (15)	-	0.62 (15)	0.51 (15)	-	-	-	-	-	-	-
72. Number of changes, 80%	-0.45 (16)	-	-	-	-	-	-	-0.56 (15)	-	-0.46 (15)	-0.47 (15)	-	-	-	-	-	-
73. Number of changes, 60%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-0.52 (17)	-	-
74. Number of changes, 40%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
75. Number of changes, 30%	-	-	-	-	-	-	-	-	-0.47 (15)	-	-	-	-	-	-0.48 (17)	-	-
76. Number of changes, 20%	-	-	-	-	-0.57 (15)	-0.58 (15)	-	-	-0.49 (15)	-	-	-	-	-	-0.54 (17)	-	-
77. Number of changes, 15%	-	-	-	-	-	-0.61 (15)	-	-	-	-	-	-	-	-	-	-	-

Variable	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76
59. Extension endurance, 15%																		
60. Anteflexion endurance, 80%	-																	
61. Anteflexion endurance, 60%	-	0.63 (24)																
62. Anteflexion endurance, 40%	0.36 (23)	-	0.37 (24)															
63. Anteflexion endurance, 30%	-	-	-	0.69 (24)														
64. Anteflexion endurance, 20%	-	-	-	0.64 (22)	0.87 (22)													
65. Anteflexion endurance, 15%	-	-	-	0.52 (21)	0.69 (21)	0.76 (21)												
66. Time to change, 80%	-	0.45 (17)	-	-	0.42 (17)	-	-											
67. Time to change, 60%	-	-	-	-	-	-	-	0.60 (17)										
68. Time to change, 40%	-	-	-	-	0.72 (17)	-	-	0.59 (17)	0.53 (17)									
69. Time to change, 30%	-	-	-	0.45 (17)	0.51 (17)	-	-	0.73 (17)	0.59 (17)	0.63 (17)								
70. Time to change, 20%	-	-	-	0.56 (17)	0.59 (17)	-	-	0.70 (17)	0.61 (17)	0.59 (17)	0.92 (17)							
71. Time to change, 15%	-	-	-	-	-	-	0.63 (14)	-	-	-	0.56 (17)	0.45 (17)						
72. Number of changes, 80%	-	-	-	-	-	-	-	-0.75 (17)	-	-0.43 (17)	-	-	-					
73. Number of changes, 60%	-	-	-	-	-	-	-	-0.63 (17)	-0.83 (17)	-0.52 (17)	-0.59 (17)	-0.54 (17)	-	0.53 (17)				
74. Number of changes, 40%	-	-	-	-	-	-	-	-0.60 (17)	-0.60 (17)	-0.76 (17)	-0.65 (17)	-0.59 (17)	-	0.59 (17)	0.77 (17)			
75. Number of changes, 30%	-	-	-		-0.53 (17)	-	-	-0.61 (17)	-0.45 (17)	-0.83 (17)	-0.82 (17)	-0.66 (17)	-0.57 (17)	0.45 (17)	0.57 (17)	0.77 (17)		
76. Number of changes, 20%	-	-	-	-	-0.65 (17)	-0.49 (15)	-	-	-	-0.73 (17)	-0.72 (17)	-0.69 (17)	-0.55 (17)	-	-	0.59 (17)	0.81 (17)	
	-	-	-	-	-0.55 (17)	-0.46 (15)	-0.61 (14)	-	-	-0.58 (17)	-0.65 (17)	-0.54 (17)	-0.75 (17)	-	-	0.59 (17)	0.78 (17)	0.82 (17)

References

Adams, S.K. and Peterson, P.J., 1988.
Maximum voluntary hand grip torque for circular electrical connectors. *Human Factors*, 30 (6), 733-745.

Arnold, A.-K., 1991.
An ergonomic approach to the design of consumer packaging. In: *Interface '91, proceedings of the 7th symposium on Human Factors and Industrial Design in Consumer Products* (pp. 138-143). Edited by D. Boyer and J. Pollack. Santa Monica, CA: The Human Factors Society.

Atkinson, G., Coldwells, A., Reilly, T. and Waterhouse, J., 1993.
A comparison of circadian rhythms in work performance between physically active and inactive subjects. *Ergonomics*, 36 (1-3), 273-281.

Ayoub, M.M. and Mital, A., 1989.
Manual Materials Handling. London: Taylor and Francis.

Ayoub, M.M., Gidcumb, C.F., Beshir, M.Y., Hafez, H.A., Aghazadeh, F. and Bethea, N.J., 1981.
Development of an Atlas of Strengths and Establishment of an Appropriate Model Structure. Lubbock, Texas: Institute for Ergonomics Research, Texas Tech University.

Ayoub, M.M., Gidcumb, C.F., Reeder, M.J., Beshir, M.Y., Hafez, H.A., Aghazadeh, F. and Bethea, N.J., 1982.
Development of a Female Atlas of Strengths. Lubbock, Texas: Institute for Ergonomics Research, Texas Tech University.

B., P., 1993.
De gouden-tientjes-brief. *Margriet*, no. 4, 22-29 januari 1993, p. 6.

Bandera, J.E., Kern, P and Solf, J.J., 1985.
Ergonomische Kenngrößen für Kontaktgreifarten. Dortmund: Bundesanstalt für Arbeitsschutz.

Berg, V.J., Clay, D.J., Fatallah, F.A. and Higginbotham, V.L., 1988.
The effects of instruction on finger strength measurements: applicability of the Caldwell regimen. In: *Trends in Ergonomics/Human Factors* V, edited by F. Aghazadeh. North Holland: Elsevier Science Publishers.

Berns, T., 1981.
The handling of consumer packaging. *Applied Ergonomics*, 12, 153-161.

Binkhorst, R.A., Hoofd, L. and Vissers, A.C.A., 1977.
Temperature and force-velocity relationship of human muscles. *Journal of Applied Physiology*, 42 (4), 471-475.

Birch, K., McFadyen, I.R., Reilly, T. and Sinnerton, S., 1993.
Menstrual cycle effects on isometric and dynamic lifting.
In: *Contemporary Ergonomics 1993 Proceedings of the Ergonomics Society Conference* (pp. 308-313). Edited by E.J. Lovesey. London: Taylor and Francis.

Bishop, P., Cureton, K. and Collins, M., 1987.
Sex difference in muscular strength in equally-trained men and women.
Ergonomics, 30 (4), 675-687.

Bishu, R.R., Myung, R.H. and Deeb, J.M., 1990.
Evaluation of handle positions using force/endurance relationship of an isometric holding task. In: *Proceedings of the Human Factors Society 34th Annual Meeting*, (pp. 692-696), Santa Monica, CA: Human Factors Society.

Björksten, M. and Jonsson, B., 1977.
Endurance Limit of force in long-term intermittent static contractions.
Scand. J. Work Environ. & Health, 3, 23-27.

Blankesteijn, H., 1993.
Noten en krakers: hard tegen hard. *NRC Handelsblad*, 15 april 1993, p. 6.

Bonney, R., Weisman, G., Haugh, L.D. and Fienkelstein, J., 1990.
Assessment of postural discomfort. In: *Proceedings of the Human Factors Society 34th Annual Meeting* (pp. 684-687). Santa Monica, CA: The Human Factors Society.

Bordett, H.M., Koppa, R.J. and Congelton, J.J., 1988.
Torque required from elderly females to operate faucet handles of various shapes.
Human Factors, 30 (3), 339-346.

Borg, G., 1990.
Psychophysical studies of effort and exertion: some historical, theoretical and empirical aspects. In: *The perception of exertion in physical work* (pp. 3-12).
Editors G. Borg and D. Ottoson. Houndsmills: Macmillan.

Bovend'eerdt, J., Kemper, H. and Verschuur, R., 1980.
De Moper Fitness test. Haarlem: De Vrieseborch.

Brooks, B.M., Ruffell - Smith, H.P. and Ward, J.S., 1974.
An investigation of factors affecting the use of busses by both elderly and ambulant disabled persons. Contract report, British Leyland UK.

Brorson, H., Werner, C.-O. and Thorngren, K.-G., 1989.
Normal pinch strength. *Acta Orthoped. Scand.*, 60 (1), 66-68.

Bullinger, H.J. and Kern, P., 1979.
Beitrag zu Beurteilung von Reibpaarungen zwischen der menschlichen Hand und der Arbeitsmittelhandseite. *Industrie Anzeiger*, 3 (10-1), 20-21.

Burandt, U., 1978.
Ergonomie für Design und Entwicklung. Köln: Verlag Otto Schmidt KG.

Byrd, R. and Jeness, M.E., 1982.
Effect of maximal grip strength and initial grip on contraction time and on areas under force-time curves during isometric contractions. *Ergonomics*, 25 (5), 387-392.

Caldwell, L.S., 1962.
Body stabilisation and the strength of arm extension. *Human Factors*, 4 , 125-130.

Caldwell, L.S., 1963.
Relative muscle loading and endurance. *Journal of Engineering Psychology*, 2, 155-161.

Caldwell, L.S., 1964 a.
The load-endurance relationship for a static manual response.
Human Factors, 6 , 71-79.

Caldwell, L.S., 1964 b.
Body position and the strength and endurance of manual pull.
Human Factors, 6 , 479-484.

Caldwell, L.S., Chaffin, D.B., Dukes-Dobos, F.N., Kroemer, K.H.E., Laubach, L.L., Snook, S.H. and Wasserman, D.E., 1974.
A proposed standard procedure for static muscle strength testing. American Industrial Hygiene *Association Journal*, 35, 201-206.

Caldwell, L.S. and Grossman, E.E., 1973.
Effort scaling of isometric muscle contractions.
Journal of Motor Behaviour, 5 (1), 9-16.

Carlson, B.R., 1969.
Level of maximum isometric strength and relative load isometric endurance.
Ergonomics, 12 (3), 429-435.

Catovic, A., Kosovel, Z., Catovic, E. and Muftic, O., 1989.
A comparative investigation of the influence of certain arm positions on hand pinch grips in the standing and sitting positions of dentists.
Applied Ergonomics, 20 (2), 109-114.

Chaffin, D.B., 1975.
Ergonomics guide for the assessment of human static strength.
American Industrial Hygiene Association Journal, July 1975, 505-511.

Chaffin, D.B. and Andersson, G.B.J., 1984.
Occupational Biomechanics. New York: Wiley.

Chaffin, D.B., Andres, R.O. and Garg, A., 1983.
Volitional Postures during Maximal Push/Pull Exertions in the Sagittal Plane, *Human Factors*, 25, 541-550.

Chen, Y, Cochran, D.J., Bishu, R.R. and Riley, M.W., 1989.
Glove size and material effects on task performance. In: *Proceedings of the Human Factors Society 33rd Annual Meeting* (pp. 708-712). Santa Monica, CA: The Human Factors Society.

Chomcherngpat, C., Mandhani, P., Lum, C. and Martin, C., 1989.
Human lifting strength in different postures.
In: *Proceedings of the Human Factors Society 33th Annual Meeting* (pp. 745-749). Santa Monica, CA: The Human Factors Society.

Churchill, E., Churchill, T. and Kikta, P., 1978.
Intercorrelations of anthropometric measurements: a source book for USA data. Ohio: Wright-Patterson Air Force Base.

Clarke, R.S.J., Hellon, R.F. and Lind, A.R., 1958.
The duration of sustained contractions of the human forearm at different muscle temperatures. *J. Physiol.*, 143, 454-473.

Cochran, D.J. and Riley, M.W., 1986.
The effects of handle shape and size on exerted forces. *Human Factors*, 28 (3), 253-265.

Daams, B.J., 1987.
Onderzoek naar torsiemomenten in de huishouding met betrekking tot ouderen. Internal report. Delft: Faculty of Industrial Design Engineering.

Daams, B.J., 1993.
Static force exertion in postures with different degrees of freedom. *Ergonomics*, 36 (4), 397-406.

Damon, A., Seltzer, C.C., Stoudt, H.W. and Bell, B., 1972.
Age and Physique in healthy white veterans at Boston. *Aging and Human Development*, 3, 202-208.

Damon, A., Stoudt, H.W. and McFarland, R.A., 1969.
The Human Body in Equipment Design. Cambridge: Harvard University Press.

Dean, W., 1988.
Biological aging measurement. Thousand Oaks, CA The Center for Bio-Gerontology.

Deeb, J.M. and Drury, C.G., 1990.
A methodology for muscular isometric endurance and fatigue research. *International Journal of Industrial Ergonomics*, 6, 255-260.

Deeb, J.M. and Drury, C.G., 1992.
Perceived exertion in isometric muscular contractions related to age, muscle, force level and duration. In: *Proceedings of the Human Factors Society 36th Annual Meeting* (pp. 712-716). Santa Monica, CA: The Human Factors Society.

Deeb, J.M., Drury, C.G. and Pendergast, D.R., 1992.
An exponential model of isometric muscular fatigue as a function of age and muscle groups. *Ergonomics*, 35 (7/8), 899-918.

Den Uyl, B., 1979.
Vreemde verschijnselen. Amsterdam: Querido.

Denkert, H., Fähnrig, K.P., Kern, P. and Solf, J.J., 1984.
Ergonomische Kenngrößen für Zufassungsgreifarten. Dortmund, Bundesanstalt für Arbeitsschutz und Unfallforschung.

Dibrezzo, R., Fort, I.L. and Brown, B., 1991.
Relationships among strength, endurance, weight and body fat during three phases of the menstrual cycle. *The Journal of Sports Medicine and Physical Fitness*, 31 (1), 89-94.

Di Prampero, P.E. and Cerretelli, P., 1969.
Maximal muscular power (aerobic and anaerobic) in African natives. *Ergonomics*, 12 (1), 51-59.

Di Prampero, P.E., Piñera Limas, F. and Sassi, G., 1970.
Maximal muscular power, aerobic and anaerobic, in 116 athletes performing at the XIXth Olympic Games in Mexico. *Ergonomics*, 13 (6), 665-674.

Dirken, J.M., 1964.
Subjective experience of work load and ageing. In: *Proceedings of the 2nd International Ergonomics Association Congress* (pp. 91-95). Dortmund.

Dirken, J.M., 1972.
Functional age of industrial workers. Groningen: Wolters-Noordhoff.

Dorrestein, R., 1993.
Heden ik. Amsterdam: Contact.

Dul, J, Douwes, M. and Smitt, P., in press.
Ergonomic guidelines for the prevention of discomfort of static postures can be based on endurance data. *Ergonomics* (in press).

Drury, C.G., 1980.
Handles for manual materials handling. *Applied Ergonomics*, 11 (1), 35-42.

Eastman Kodak Company, 1986.
Ergonomic Design for People at Work. Volume 2. New York: Van Nostrand Reinhold.

Eisler, H., 1962.
Subjective scale of force for a large muscle group. *Journal of Experimental Psychology*, 64 (3), 253-257.

Elbel, E.R., 1949.
Relationship between leg strength, leg endurance and other body measurements. *Journal of Applied Physiology*, 2 (4), 197-207.

Era, P., Lyyra, A.L., Viitasalo, J.T. and Heikkinen, E., 1992.
Determinants of isometric muscle strength in men of different ages. *European Journal of Applied Physiology*, 64, 84-91.

Fähnrig, K.P., Kern, P. and Solf, J.J., 1983.
Ergonomische Kenngrößen für Umfassungsgreifarten. Dortmund: Bundesanstalt für Arbeitsschutz und Unfallforschung.

Fellows, G.L. and Freivalds, A., 1989.
The use of force sensing resistors in ergonomic tool design. In: *Proceedings of the Human Factors Society 33rdAnnual Meeting* (pp. 713-717). Santa Monica, CA: The Human Factors Society.

Fernandez, J.E., Dahalan, J.B., Halpern, C.A. and Viswanath, V., 1991.
The effect of wrist posture on pinch strength. In: *Proceedings of the Human Factors Society 35th Annual Meeting* (pp. 748-752). Santa Monica, CA: The Human Factors Society.

Fothergill, D.M., Grieve, D.W. and Pheasant, S.T., 1991.
Human strength capabilities during one-handed maximum voluntary exertions in the fore and aft plane. *Ergonomics*, 34 (5), 563-573.

Fothergill, D.M., Grieve, D.W. and Pheasant, S.T., 1992.
The influence of some handle designs and handle height on the strength of the horizontal pulling action. *Ergonomics*, 35 (2), 203-212.

Frank, P., Han, F. and Spangenberg, S., 1985.
Krachtuitoefening bij kinderen in een Vliegende Hollander. Internal report no. 66. Delft: Department of Product and Systems Ergonomis, Faculty of Industrial Design Engineering.

Frankel, V.H., Nordin, M. and Snijders, C.J., 1984.
Biomechanica van het skeletsysteem. Lochem: De Tijdstroom.

Fransson, C. and Winkel, J., 1991.
Hand strength: the influence of grip span and grip type.
Ergonomics, 34 (7), 881-892.

Gallagher, S., 1989.
Isometric pushing, pulling and lifting strengths in three postures.
In: *Proceedings of the Human Factors Society 33rd Annual Meeting* (pp. 637-640).
Santa Monica, CA: The Human Factors Society.

Garg, A. and Beller, D., 1990.
One-handled dynamic pulling strength with special reference to speed, handle heights and angles of pulling.
International Journal of Industrial Ergonomics, 6, 231-240.

Gast, S., 1991.
De invloed van flexiestanden in de vingergewrichten, het polsgewricht en het ellebooggewricht op maximale isometrische knijpkracht. Thesis. Amsterdam: Faculty of Movement Sciences.

Genaidy, A., Lento, K. and Jones, K., 1992.
Effects of wrist support on human performance in industry. In: *Contemporary Ergonomics 1992, Proceedings of the Ergonomic Society Conference* (pp. 155-160). Edited by E.J. Lovesey. London: Taylor and Francis.

Genaidy, A. and Karwowski, W., 1993.
The effects of neutral posture deviations on perceived joint discomfort ratings in sitting and standing postures. *Ergonomics*, 36 (7), 785-792.

Graham C.M. and Garbutt, G., 1993.
Angle specific isokinetic talocrural torque ratios.
In: *Contemporary Ergonomics 1993, Proceedings of the Ergonomic Society Conference* (pp. 321-326). Edited by E.J. Lovesey. London: Taylor and Francis.

Grandjean, E., 1967.
Physiologische Arbeitsgestaltung. Thun: Ott Verlag.

Grieve, D.W., 1979a.
The Postural Stability Diagram (PSD): personal constraints on the static exertion of force. *Ergonomics*, 22 (10), 1155-1164.

Grieve, D.W., 1979b.
Environmental constraints on the static exertion of force.: PSD analysis in task-design. *Ergonomics*, 22 (10), 1165-1175.

Grinten, M. van der, 1990.
Preventie beroepsgebonden problematiek van het bewegingsapparaat. Report no. S 91-1. Voorburg: Directoraat-generaal van de Arbeid van het Ministerie van Sociale Zaken en Werkgelegenheid.

Grinten, M. van der, 1991.
Test-retest reliability of a practical method for measuring body part discomfort. In: *Designing for everyone. Proceedings of the 11th Congress of the International Ergonomics Association* (pp. 54-56). Editors: Y. Quéinnec and F. Daniellou. London: Taylor and Francis.

Groot, W.C.M. de, 1990.
Het meten van statische spierkracht in arbeidssituaties. Thesis. Groningen: Movement Sciences, University of Groningen.

Hafez, H.A., Gidcumb, C.F., Reeder, M.J., Beshir, M.Y. and Ayoub, M.M., 1982.
Development of a human atlas of strengths. In: *Proceedings of the Human Factors Society 26h Annual Meeting* (pp. 575-579). Santa Monica, CA: The Human Factors Society.

Hagberg, H., 1981.
Muscular endurance and surface electromyogram in isometric and dynamic exercise. *Journal of Applied Physiology*, 51 (1), 1-7.

Häkkinen, K. and Häkkinen, A., 1991.
Muscle cross-sectional area, force production and relaxation characteristics in women at different ages. *European Journal of Applied Physiology*, 62, 410-414.

Hallbeck, M.S., 1990
Biomechanical analysis of carpal flexion and extension. Unpublished PhD-dissertation. Ann Arbor: UMI.

Hallbeck, M.S., Cochran, D.J., Stonecipher, B.L., Riley, M.W. and Bishu, R.R., 1990.
Hand-handle orientation and maximum force. In: *Proceedings of the Human Factors Society 34th Annual Meeting* (pp. 800-804). Santa Monica, CA: The Human Factors Society.

Hallbeck, M.S. and McMullin, D.L., 1991.
The effect of gloves, wrist position, and age on peak three-jaw chuck pinch force: a pilot study. In: *Proceedings of the Human Factors Society 35th Annual Meeting* (pp. 753-757). Santa Monica, CA: The Human Factors Society.

Hammarskjöld, E., Ekholm, J. and Harms - Ringdahl, K., 1989.
Reproducibility of work movements with carpenters' hand tools.
Ergonomics, 32 (8), 1005-1018.

Haslegrave, C., 1991.
What influences the choice of a working posture? In: *Designing for everyone. Proceedings of the 11th Congress of the international Ergonomics Association* (pp. 24-26). Edited by Y. Queinnec and F. Daniellou. London: Taylor and Francis.

Haslegrave, C.M., 1992.
Predicting postures adopted for force exertion: thesis summary.
Clin. Biomech., 7 (4), 249-250.

Haslegrave, C.M. and Corlett, N., 1988.
Factors determining the posture adopted for forceful manual tasks.
In: *Proceedings of the International Ergonomics Association 10th International Congress.* Edited by A.S. Adams. Sydney: The Ergonomics Society of Australia Inc.

Haslegrave, C.M., Tracy, M. and Corlett, E.N., 1988.
Influence of working posture on strength capability. In: *Contemporary Ergonomics, 1988, Proceedings of the Ergonomics Society Conference* (pp. 476-481). Edited by E.J. Lovesey. London: Taylor and Francis.

Hazelton, F.T., Smidt, G.L., Flatt, A.E. and Stephens, R.I., 1975.
The influence of wrist position on the force produced by the finger flexors. *Journal of Biomechanics*, 8, 301-306.

Hennion, P.Y., Coblentz, A. and Mollard, R., 1990.
Human force exertion: the influence of the direction of the effort.
In: *Proceedings of the Human Factors Society 34th Annual Meeting* (pp. 776-780). Santa Monica, CA: The Human Factors Society.

Hennion, P.Y., Mollard, R. and Coblentz, A., 1989.
Human force exertion: the significance of the measure? In: *Proceedings of the Human Factors Society 33rd Annual Meeting* (pp. 1201-1205). Santa Monica, CA: The Human Factors Society.

Herrin, G.D., 1980.
Standardized strength testing methods for population descriptions
In: *Anthropometry and Biomechanics* (pp. 145-150). Edited by: R. Easterby, K.H.E. Kroemer and D.B. Chaffin. New York: Plenum Press.

Hettinger, T., 1968.
Isometrisches Muskeltraining. Stuttgart: Georg Thieme Verlag.

Hoag, L.L., 1980.
Anthropometric and strength data in tool design.
In: *Anthropometry and Biomechanics* (pp. 253-257). Edited by: R. Easterby, K.H.E. Kroemer and D.B. Chaffin. New York: Plenum Press.

Hoes, M.J.A.J.M., Binkhorst, R.A., Smeekes - Kuyl, A.E.M.C. and Vissers, A.C.A., 1968.
Measurement of forces exerted on pedal and crank during work on a bicycle ergometer at different loads. *Int. Z. angew. Physiol. einschl. Arbeitsphysiol.*, 26, 33-42.

Hof, A.L., 1987
Spiermechanica. Chapter 2 in *Biomechanica.* Edited by R. Huiskes. Alphen aan de Rijn: Samsom Stafleu.

Hook, W.E. and Stanley, J.K., 1986.
Assessment of thumb to index pulp to pulp pinch grip strengths. *The Journal of Hand Surgery,* 11-B (1), 91-92.

Hosler, W.W. and Morrow, J.R., 1982.
Arm and leg strength compared between young women and men after allowing for differences in body size and composition. *Ergonomics,* 25 (4), 309-313.

Hsia, P.T. and Drury, C.G., 1986.
A simple method of evaluating handle design. *Applied Ergonomics,* 17 (3), 209-213.

Hultén, B., Thorstensson, A., Sjödin, B. and Karlsson, J., 1975.
Relationship between isometric endurance and fibre types in human leg muscles. *Acta Physiol. Scand.,* 93, 135-138.

Humphreys, P.W. and Lind, A.R., 1963.
The blood flow through active and inactive muscles of the forearm during sustained hand-grip contractions. *J. Physiol.,* 166, 120-135.

Hurst, P.M., Radlow, R. and Bagley, S.K., 1968.
The effects of D-amihetamine and chlordiazepoxide upon strength and estimated strength. *Ergonomics,* 11 (1), 47-52.

Ikai, M. and Fukunaga, T., 1968.
Calculation of muscle strength per unit cross-sectional area of human muscle by means of ultrasonic measurement.
Int. Z. angew. Physiol. einschl. Arbeitsphysiol., 26, 26-32.

Imrhan, S.N. and Ayoub, M.M., 1990.
The arm configuration at the point of peak dynamic pull strength.
International Journal of Industrial Ergonomics, 6, 9-15.

Imrhan, S.N. and Loo, C.H., 1988.
Modelling wrist-twisting strength of the elderly. *Ergonomics,* 31 (12), 1807-1819.

Imrhan, S.N. and Sundararajan, K., 1992.
An investigation of finger pull strengths. *Ergonomics,* 35 (3), 289-299.

Ingemann - Hanssen, T. and Halkjær - Kristensen, J., 1979.
Force-velocity relationships in the human quadriceps muscles.
Scandinavian Journal of Rehabilitation Medicine, 11, 85-89.

Ingen Schenau, G.J. van, and Groot, G. de, 1983.
On the origin of differences in performance level between elite male and female speed skaters. *Human Movement Science,* 2, 151-159.

Jacobson, B.H. and Edwards, S.W., 1991.
Influence of two levels of caffeine on maximal torque at selected angular velocities. *The Journal of Sports Medicine and Physical Fitness,* 31 (2), 147-153.

Janda, D.H., Geiringer, S.R., Hankin, F.M. and Barry, D.T., 1987.
Objective evaluation of grip strength.
Journal of Occupational Medicine, 29 (7), 569-571.

Jarry, A., 1902
Le surmâle. Roman moderne. Édition 1990. Paris: Ramsay/Jean-Jacqes Pauvert.

Kahn, J.F. and Monod, H., 1984.
A study of fatigue during repetitive static work performed in two different segmental positions. *European Journal of Applied Physiology*, 53, 169-174.

Kallman, D.A., Plato, C.C. and Tobin, J.D., 1990.
The role of muscle loss in the age-related decline of grip strength: cross-sectional and longitudinal perspectives. *Journal of Gerontology: Medical Sciences*, 45 (3), M82-88.

Kanis, H., 1989a.
Het gebruik van koffiemelkkuipjes. Internal report. Delft: Faculty of Industrial Design Engineering.

Kanis, H., 1989b.
Bediening & Handikap. Delft: Faculty of Industrial Design Engineering.

Kanis, H., 1991.
Ergernomie in de trein. *Tijdschrift voor Ergonomie*, 16 (1), 22-24.

Kanis, H., 1993.
Operation of controls on consumer products by physically impaired users.
Human Factors, 35 (2), 305-328.

Karwowski, W. and Mital, A., 1986.
Isometric and isokinetic testing of lifting strength of males in teamwork.
Ergonomics, 29 (7), 869-878.

Kellor, M., Frost, J., Silberberg, N, Iversen, I. and Cummings, R., 1971.
Hand strength and dexterity. *The American Journal of Occupational Therapy*, 25 (2), 77-83.

Kerk, B. van de, and Voorbij, L., 1993.
Hoe sterk zijn kinderen? Onderzoek naar de krachten van kinderen. Internal report. Delft: Faculty of Industrial Design Engineering.

Kleef, B. van, 1987.
Jampotten. De Volkskrant, zaterdag 14 februari 1987.

Klerk. M.M.Y. de, and Huijsman, R., 1993.
Ouderen en het gebruik van hulpmiddelen. Report no. 93.24. Rotterdam: Instituut voor Medische Technology Assessment, Erasmus Universiteit Rotterdam.

Knook, D.L., 1982.
Verouderen, het venijn zit in de cel. *Natuur en Techniek*, 50, 830-849, 1982.

Kroemer, K.H.E., 1970.
Human strength: terminology, measurement, and interpretation of data.
Human Factors, 12 (3), 297-313.

Kroemer, K.H.E., 1977.
Die Messung der Muskelstärke des Menschen. Dortmund: Bundesanstalt für Arbeitsschutz und Unfallforschung.

Kroemer, K.H.E., Kroemer, H.J. and Kroemer - Elbert, K.E., 1986.
Engineering physiology. Amsterdam: Elsevier.

Kroll, W.P., Bultman, L.L., Kilmer W.L. and Boucher, J., 1990.
Anthropometric predictors of isometric arm strength in males and females. *Clinical Kinesiology,* 44 (1), 5-11.

Kroll, W. and Clarkson, P.M., 1978.
Age, isometric knee extension strength, and fractionated resisted response time. *Experimental Aging Research,* 4 (5), 389-409.

Kumar, S., 1990.
Symmetric and asymmetric stoop-lifting strength. In: *Proceedings of the Human Factors Society 34th Annual Meeting* (pp. 762-766). Santa Monica, CA: The Human Factors Society.

Lange, W., 1991.
Kleine ergonomische Datensammlung, 6th edition. Dortmund: Bundesanstalt für Arbeitsschutz.

Larsson, L., 1978.
Morphological and functional characteristics of the ageing skeletal muscle in man. A cross-sectional study. *Acta Physiologica Scandinavica, supplementum 457* (pp 1-36). Stockholm.

Laubach, L.L., 1978.
Human muscular strength. Chapter 7 in *Anthropometric Source Book. Volume I: Anthropometry for Designers.* NASA reference publication 1024.

Lee, K. and Bruckner, A., 1991.
Human lifting strength in different postures. *Journal of Safety Research,* 22 (1), 11-19.

Lee, J.W. and Rim, K., 1991.
Measurement of finger angles and maximum finger forces during cylinder grip activity. *Journal of Biomedical Engineering,* 13 (3), 152-162.

Lusa, S., Louhevaara, V., Smolander, J., Kinnunen, K., Korhonen, O. and Soukainen, J., 1991. Biomechanical evaluation of heavy tool-handling in two age groups of firemen. *Ergonomics,* 34 (12), 1429-1432.

Malina, R.M. and Bouchard, C., 1991.
Growth, maturation, and physical activity. Champaign, Illinois: Human Kinetics Books.

Materials Handling Research Unit, The, 1980.
Grenzen van de voor handenarbeid benodigde lichaamskracht. Luxembourg: IPC Science & Technology Press Ltd.

Marinissen, A.H. and Oldenkamp, I., 1989.
Design and development of a powered vehicle for handicapped people.
Journal of Medical Engineering & Technology, 13 (1/2), 149-155.

Mathiassen, S.E. and Winkel, J., 1992.
Can occupational guidelines for work-rest schedules be based on endurance time data? *Ergonomics*, 35 (3), 253-259.

Mathiowetz, V., Kashman, N., Volland, G., Weber, K., Dowe, M. and Rogers, S., 1985.
Grip and pinch strength: normative data for adults.
Arch. Phys. Med. Rehabil., 66, 68-74.

Mathiowetz, V., Weber, K., Volland, G. and Kashman, N., 1984.
Reliability and validity of grip and pinch strength evaluations.
The Journal of Hand Surgery, 9A (2), 222-226.

Maughan, R.J., Watson, J.S. and Weir, J., 1982.
The relationship between cross-sectional area and strength in the knee extensor muscles in man. In: *Proceedings of the Physiological Society* (49P-50P). April 1982.

Mathiowetz, V., Wiemer, D.M. and Federman, S.M., 1986.
Grip and pinch strength: norms for 6- to 19-year-olds.
The American Journal of Occupational Therapy, 40 (10), 705-711.

McMullin, D.L. and Hallbeck, M.S., 1991.
Maximal power grasp force as a function of wrist position, age and glove type: a pilot study. In: *Proceedings of the Human Factors Society 35th Annual Meeting* (pp. 733-737). Santa Monica, CA: The Human Factors Society.

Mital, A., 1986.
Effect of body posture and common hand tools on peak torque exertion capabilities.
Applied Ergonomics, 17 (2), 87-96.

Mital, A. and Faard, H.F., 1990.
Effects of sitting and standing, reach distance, and arm orientation on isokinetic pull strengths in the horizontal plane.
International Journal of Industrial Ergonomics, 6, 241-248.

Mital, A. and Genaidy, A.M., 1989.
Isokinetic strengths and working posture. In: *Proceedings of the Human Factors Society 33th Annual Meeting* (pp. 632-636). Santa Monica, CA: The Human Factors Society.

Mital, A. and Sanghavi, N., 1986.
Comparison of maximum volitional torque exertion capabilities of males and females using common hand tools. *Human Factors*, 28 (3), 283-294.

Molbech, S., and Johansen, S.H., 1973.
Endurance time in slow and fast contracting muscle groups.
Work-Environment-Health, 10, 62-64.

Molenbroek, J.F.M., Houtkamp, J.J. and Burger, A.K.C., 1987.
Bejaardenantropometrie. Series Industrieel Ontwerpen Bijzondere Onderwerpen no. 6. Fourth edition. Delft: Faculty of Industrial Design Engineering.

Monod, H. and Scherrer, J., 1965.
The work capacity of a synergic muscular group. *Ergonomics,* 8, 329-338.

Morgan, C.T., Cook, J.S., Chapanis, A. and Lund, M.W. (editors), 1963.
Human Engineering Guide to Equipment Design. New York: McGraw-Hill.

O'Connor, P.J. and Morgan, W.P., 1990.
Athletic performance following rapid traversal of multiple time zones. *Sports Medicine,* 10 (1), 20-30.

Page, M., 1981.
An ergonomics evaluation of a reclosable pharmaceutical container with special reference to the elderly. *Ergonomics,* 24 (11), 847-862.

Petrofsky, J.S. and Lind, A.R., 1975a.
Isometric strength, endurance. and the blood pressure and heart rate responses during isometric exercise in healthy men an women, with special reference to age and body fat content. *Pflügers Archives,* 360, 49-61.

Petrofsky, J.S. and Lind, A.R., 1975b.
Aging, isometric strength and endurance, and cardiovascular responses to static effort. *Journal of Applied Physiology,* 38 (1), 91-95.

Peacock, B., Westers, T., Walsh, S. and Nicholson, K., 1981.
Feedback and maximum voluntary contraction. *Ergonomics,* 24 (3), 223-228.

Pheasant, S.T., 1983.
Sex differences in strength - some observations on their variability. *Applied Ergonomics,* 14 (3), 205-211.

Pheasant, S. and O'Neill, D., 1975.
Performance in gripping and turning - A study in hand/handle effectiveness. *Applied Ergonomics,* 6 (4), 205-208.

Pottier, M., Lille, F., Phuon, M. and Monod, H., 1969.
Étude de la contraction statique intermittente. *Le Travail Humain,* 32 (3/4), 271-284.

Putten, R. van, Kanis, H., Marinissen, A.H.M. and Weegels, M., 1990.
Usable does not mean handy. Video. Delft: Faculty of Industrial Design Engineering.

Putto, R., 1988.
Hanteren en kracht. Thesis. Delft: Faculty of Industrial Design Engineering.

Radwin, R.G. and Oh, S., 1991.
Handle and trigger size effects on power tool operation.
In: *Proceedings of the Human Factors Society 35th Annual Meeting* (pp. 843-847). Santa Monica, CA: The Human Factors Society.

Radwin, R.G., Oh, S., Jensen, T.R. and Webster, J.G., 1992.
External finger forces in submaximal five-finger static pinch prehension. In: *Proceedings of the Human Factors Society 35th Annual Meeting* (pp. 843-847). Santa Monica, CA: The Human Factors Society.

Reilly, T., and Hales, A.J., 1988.
Effects of partial sleep deprivation on performance measures in females. In: *Contemporary Ergonomics 1988, Proceedings of the Ergonomics Society Conference* (pp. 509-514). Edited by E.J. Lovesey. London: Taylor and Francis.

Roberts, D.F., Provins, K.A. and Morton, R.J., 1959.
Arm strength and body dimensions. *Human Biology*, 31, 334-343.

Rohmert, W., 1960.
Ermittlung von Erholungspausen für statische Arbeit des Menschen. *Int. Z. angew. Physiol. enschl. Arbeitsphysiol.*, 18, 123-164.

Rohmert, W., 1965.
Physiologische Grundlagen der Erholungszeitbestimmung. *Arbeit und Leistung*, 19 (1), 1-28.

Rohmert, W. and Hettinger, T., 1963.
Körperkräfte im Bewegungsraum. Berlin: Beuth Vertrieb GmbH.

Rohmert, W. and Mainzer, J., 1987.
Theoretische und praktische Bedeutung der Vektogramme von Stellungskräften. *Zeitschrift für Arbeitswissenschaft*, 41 (2), 109-113.

Rohmert, W., Mainzer, J. and Kahabka, G., 1987a.
Analyse biomechanischer und physiologischer Engpässer beim Ausüben von Stellungskräften. *Zeitschrift für Arbeitswissenschaft*, 41 (2), 114-130.

Rohmert, W., Mainzer, J. and Kranz, U., 1987b.
Vektogramme als biomechanisch-physiologische Modelle von Körperstellungskräften. *Zeitschrift für Arbeitswissenschaft*, 41 (3), 169-173.

Rohmert, W., Mainzer, J. and Kranz, U., 1988a.
Individuelle Unterschiede der Vektogramme von isometrischen Stellungskräften. *Zeitschrift für Arbeitswissenschaft*, 42 (2), 102-105.

Rohmert, W., Mainzer, J. and Rückert, A., 1987c.
Einfluß frei gewählter und vorgegebener Körperstellungen auf maximale Stellungskräfte. *Zeitschrift für Arbeitswissenschaft*, 41 (4), 217-223.

Rohmert, W., Samuelson, B., Helbig, R. and Wos, H., 1988b.
Untersuchungen zur maximalen Ausdauer un Erholungszeit bei statischer Muskelarbeit und unterschiedlichen Körperhaltungen. *Zeitschrift für Arbeidswissenschaft*, 42 (2), 113-115.

Roozenburg, N.F.M. and Eekels, J., 1991.
Produktontwerpen, structuur en methoden. Utrecht: Lemma.

Rose, L., Ericson, M., Glimskär, B., Nordgren, B. and Örtengren, R., 1992. Ergo-Index. Development of a model to determine pause needs after fatigue and pain reactions during work. In: *Computer Applications in Ergonomics, Occupational Safety and Health* (pp. 461-468). Editors: M. Mattila and W. Karwowski.

Sanchez, D. and Grieve, D.W., 1992. The measurement and prediction of isometric lifting strength in symmetrical and asymmetrical postures. *Ergonomics*, 35 (1), 49-64.

Sanders, M.S. and McCormick, E.J., 1993. *Human factors in engineering and design*, 7th edition.New York: McGraw-Hill.

Sargeant, A.J., Hoinville, E. and Young, A., 1981. Maximum leg force and power output during short-term dynamic exercise. *Journal of Applied Physiology:* Respirat. Environ. Exercise Physiol., 51 (5), 1175-1182.

Sato, H., Ohashi, J., Iwanaga, K., Yoshitake, R. and Shimada, K., 1984. Endurance time and fatigue in static contractions. *Journal of Human Ergology*, 13, 147-154.

Schaefer, P. and Brödler, H., 1991. Static load limits at dynamical physical work? In: *Designing for everyone. Proceedings of the 11th Congress of the International Ergonomics Association* (pp. 12-14). Edited by Y. Queinnec and F. Daniellou. London: Taylor and Francis.

Schaefer, P. and Schmidtke, H., 1989. Beziehungen zwischen isometrischen und dynamischen Maximalkräften des Menschen. *Zeitschrift für Arbeitswissenschaft*, 43 (2), 86-89.

Schantz, P., Randall - Fox, E., Hutchison, W., Tydén, A. and Astrand, P.-O., 1983. Muscle fibre type distribution, muscle cross-sectional area and maximal voluntary strength in humans. *Acta Physiologica Scandinavica*, 117, 219-226.

Schmidtke, H. (editor),1981. *Lehrbuch der Ergonomie.* Wien: Carl Hanser Verlag.

Schoorlemmer, W., 1989. *Het openen van verpakkingen met schroefsluiting.* Thesis. Delft: Faculty of Industrial Design Engineering.

Schoorlemmer, W. and Kanis, H., 1992. Operation of controls on everyday products. In: *Proceedings of the Human Factors Society 36th Annual Meeting* (pp. 509-513). Santa Monica, CA: The Human Factors Society.

Schoorlemmer, W., 1993. *Bediening van knoppen.* Internal report. Delft: Faculty of Industrial Design Engineering.

Schutz, R.K., 1972. *Cyclic work-rest exercise's effect on continuous hold endurance capacity.* Unpublished PhD-dissertation. Ann Arbor: UMI.

Schutz, R.K., and Chaffin, D.B., 1972.
Cyclic work-rest exercise's effect on local muscle fatigue rates.
AIIE Technical Papers, 107-117.

Serratoz-Perez, J.N. and Haslegrave, C.M., 1992.
Modelling fatigue and recovery in working postures. In: *Contemporary Ergonomics 1992, Proceedings of the Ergonomics Society Conference* (pp. 66-71). Edited by E.J. Lovesey. London: Taylor and Francis.

Singh, M. and Karpovich, P., 1968.
Strength of forearm flexors and extensors in men and women.
Journal of Applied Physiology, 25 (2), 177-180.

Sinnerton, S., Birch, K., Reilly, T. and McFadyen, I.R., 1993.
Weight gain and lifting during pregnancy. In: *Contemporary Ergonomics 1993, Proceedings of the Ergonomics Society Conference* (pp. 303-307). Edited by E.J. Lovesey. London: Taylor and Francis.

Sjøgaard, G., 1986.
Intramuscular changes during long-term contraction.
In: *The Ergonomics of working postures* (pp. 136-143) Edited by: N. Corlett, I. Manenica and J. Wilson. London: Taylor & Francis.

Start, K.B. and Graham, J.S., 1964.
Relationship between the relative and absolute isometric endurance of an isolated muscle group. *The Research Quarterly*, 35 (2), 193-204.

Start, K.B. and Holmes, R., 1963.
Local muscle endurance with open and occluded intramuscular circulation.
Journal of Applied Physiology, 18 (4), 804-807.

Steenbekkers, L.P.A., 1993.
Child development, design implications and accident prevention. Physical Ergonomics Series. Delft: Delft University Press.

Stevens, J.C. and Mack, J.D., 1959.
Scales of apparent force. *Journal of Experimental Psychology*, 58 (5), 405-413.

Swain, A.D., Shelton, G.C. and Rigby, L.V., 1970.
Maximum torque for small knobs operated with and without gloves.
Ergonomics, 13 (2), 201-208.

Swanson, A.B., Matev, I.B. and De Groot, G., 1970.
The strength of the hand. *Bulletin of Prosthetics Research*, 7 (3), 145-153.

Tabachnick, B.G. and Fidell, L.S., 1989.
Using multivariate statistics. Second edition. New York: Harper & Row.

Thompson, D., 1975.
Ergonomics data for evaluation and specification of operating devices on components for use by the elderly. Loughborough: Institute for Consumer Ergonomics.

Thorstensson, A., Grimby, G. and Karlsson, J., 1976.
Force-velocity relations and fibre composition in human knee extensor muscles. *Journal of Applied Physiology*, 40 (1), 12-16.

Tuttle, W.W., Janney, C.D. and Thompson, C.W., 1950.
Relation of maximum grip strength to grip strength endurance. *Journal of Applied Physiology*, 2 (12), 663-670.

Ulin, S.S., Armstrong, T.J., Snook, S.S. and Keyserling, W.M., 1993.
Perceived exertion and discomfort associated with driving screws at various work locations and at different work frequencies. *Ergonomics*, 36 (7), 833-846.

Ulmer, H.-V., Knieriemen, W., Warlo, T. and Zech, B., 1989.
Interindividual variability of isometric endurance with regard to the endurance performance limit for static work. *Biomed. Biochem.* Acta, 48 (5/6), 504-508.

VanCott, H.P. and Kinkade, R.G. (editors), 1972.
Human Engineering Guide to Equipment Design. Washington: USGPO.

Vincent, M.J. and Tipton, M.J., 1988
The effect of hand protection and cold immersion on grip strength. In: *Contemporary Ergonomics 1988, Proceedings of the Ergonomics Society Conference* (pp. 323-327). Edited by E.J. Lovesey. London: Taylor and Francis.

Viitasalo, J.T. and Komi, P.V., 1978
Isometric endurance, EMG power spectrum, and fiber composition in human quadriceps muscle. In: *Biomechanics IV A: International Series on Biomechanics 2A* (pp. 244-250). Edited by E. Asmussen and K. Jorgensen. Baltimore: University Park Press.

Vorst, L.M.T., Kanis, H. and Marinissen, A.H.M., 1992.
User involved design of a remote control. In: *Gerontechnology* (pp. 343-348). Edited by H. Bouma and J.A.M. Graafmans. Amsterdam: IOS Press.

Wang, M.-J. J., 1991.
The effect of six different kinds of gloves on grip strength. In: *Towards Human Work: solutions to problems in occupational health and human work* (pp. 164-169). Edited by M. Kumashiro and E.D. Megaw. London: Taylor & Francis.

Wang, B. and Strasser, H., 1993.
Left- and right-handed screwdriver torque strength and physiological cost of muscles involved in arm pronation and supination. In: *The Ergonomics of Manual Work* (pp. 223-226). Edited by W.S. Marras, W. Karwowski, J.L. Smith and L. Pacholsky. London: Taylor and Francis.

Weiss, M.W. and Flatt, A.E., 1971.
A pilot study of 198 normal children pinch strength and hand size in the growing hand. *American Journal of Occupational Therapy*, 25 (1), 10-12.

Westling, G. and Johansson, R.S., 1984.
Factors influencing the force control during precision grip. *Experimental Brain Research*, 53, 277-284.

Wiker, S.F., 1991.
Fatigue, discomfort and changes in the psychometric function found with repetitive pinch grasps. In: *Designing for everyone. Proceedings of the 11th Congress of the International Ergonomics Association* (pp 368-370). Edited by Y. Queinnec and F. Daniellou. London: Taylor and Francis.

Wiker, S.F., Chaffin, D.B. and Langolf, G.D., 1990.
Shoulder postural fatigue and discomfort.
International Journal of Industrial Ergonomics, 5 (2), 133-146.

Winter, D.A., 1990.
Biomechanics and Motor Control of Human Movement. New York: Wiley.

Winters, J.A. and Chapanis, A., 1986.
Thumb push forces exertable by free-standing subjects.
Ergonomics, 29 (7), 893-902.Woodson, W.E., 1981.

Yamaji, K., Yoshii, T. and Shepard, R.J., 1983.
Cardiovascular responses to sustained isometric arm flexion and knee extension at 10, 20, 30, 40 and 50% MVC. *Journal of Human Ergology*, 12, 173-183.

Zinchenko, V. and Munipov, V., 1989.
Fundamentals of ergonomics. Moscow: Progress Publishers.

Zimmerman, N.J., Eberts, C., Salvendy, G. and McCabe, G., 1991.
Effects of respirators on performance of physical, psychomotor and cognitive tasks.
Ergonomics, 34 (3), 321-334.

Name index

Subject index

Curriculum vitae

Brechtje Johanna Daams was born in Amsterdam on May 9, 1963. She attended the Amsterdam Barlaeus Gymnasium from 1975 to 1981 and took up Industrial Design Engineering at Delft University of Technology in August 1981. She graduated in August 1988 on a project for redesigning Cornetto (ice cream) packaging for Unilever at Sharnbrook (U.K.). In May 1989 she started her PhD project at the Faculty of Industrial Design Engineering of Delft University of Technology, resulting in this thesis.

Her other activities during the past five years include the supervision of design students in their first year and with their graduation projects, and membership of the Faculty Council and the Faculty's voluntary fire brigade. In 1993, she was in Malaysia as a consultant to SIRIM (the Standards and Industrial Research Institute of Malaysia), advising on the ergonomics and design of a public telephone booth.

She has published several articles in scientific journals on topics related to ergonomics and design. She is also a regular contributor of articles on design for recycling to 'Magazine Recycling Benelux', and has been an editor of this magazine since December 1991.