Stellingen

behorende bij het proefschrift van A.J.M. van der Vaart
'Arm movements in operating rotary controls'.

I Binnen de bewegingsanalyse is het juister te spreken over de anatomische mogelijkheden dan over de anatomische beperkingen.

II Een kinematische analyse van de bediening van controls levert inzicht in de manier waarop en de situatie waarin deze controls gebruikt dienen te worden.

III Het routinematig motorisch bedienen van produkten is evenzeer individueel kenmerkend als een vingerafdruk.

IV De menselijke beweging voor het gebruik van een produkt zal nooit volledig voorspelbaar zijn door slechts de produkteigenschappen te kennen.

V Voor volledig begrip van produktgebruik is meer dan natuurwetenschappelijk onderzoek nodig.

VI Met een goede anatomische basiskennis zal een deel van de fysieke ergonomie logisch worden.

VII Oriënterende observatie van bedieningsbewegingen vergen een toets op inter-beoordelaars overeenstemming en daartoe, voorafgaand, explicitering van een referentiekader.

VIII De dikke landingsmat, die in de turnsport veelvuldig wordt gebruikt, dient op grond van biomechanische overwegingen te worden voorzien van een hardere toplaag.

IX De gymnastiek- c.q. turnsport wordt vaak te eenzijdig geassocieerd met vrouwen.

X Migranten in Nederland houden politici voortdurend aan het werk. Helaas is van het omgekeerde geen sprake.

Technische Universiteit Delft, 16 juni 1995.

Arm movements in operating rotary controls

Arm movements in operating rotary controls

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,
door het College van Dekanen aangewezen,
op vrijdag 16 juni 1995 om 16.00 uur door

Augustinus Jozef Maria VAN DER VAART,

geboren te Schiedam,
doctorandus in de bewegingswetenschappen.

Dit proefschrift is goedgekeurd door de promotoren:

Prof. dr. J.M. Dirken
Prof. dr. R.H. Rozendal

Samenstelling promotiecommissie:

Rector Magnificus, voorzitter
Prof. dr. J.M. Dirken, promotor
Prof. dr. R.H. Rozendal, promotor
Prof. dr. ir. C.J. Snijders
Prof. dr. G.J. Smets
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1 Introduction

1.1 Field of the study

This investigation took place at the intersection of three different areas of research: human movement science, ergonomics, and product design. To achieve a better insight into this field of research, we will first define the areas and place them in perspective relative to one another.

Human movement science is the study of the various aspects of human motion. Until recently, research on human movement took place within the confines of the medical and social sciences. Nowadays, this field is accepted as a self-reliant science with independent faculties (e.g. Faculty of Human Movement Sciences of the Free University of Amsterdam) and scientific journals (e.g. Human Movement Science and Journal of Motor Behavior). However the science must be considered as an interdisciplinary field. Human movement can be studied in all sorts of ways. Possible lines of approach are anatomy, physiology, sociology, agogics, psychology, and philosophy. Not all of these areas are important in our study. The field of kinesiology in particular forms an important part of our project. This discipline describes and explains motion of the entire human body and the limbs. In addition, psychology, especially the control of human movement, plays an important role in our research.

Kinesiology can be defined as a scientific approach which focusses on the somatic aspects of human motion (Rozendal et al., 1983 p.11). A characteristic field of research is analysis of the human gait. Important sources include descriptive anatomy, functional anatomy, and biomechanics. In descriptive anatomy, only anatomical structures, such as bones, joints, muscles, etc., are described. Functional anatomy represents an attempt to define more than the spatial relationships between parts of the body and the body as a whole. In functional anatomy the relationship between the structure of the anatomical parts and their function is assessed. Not only the relationships between parts of the body are analysed but also the relationships between parts of the body and the entire organism and its environment. Biomechanics, finally, is used to explain processes of living structures with the help of Newtonian mechanics. Kinematics, the description of motion, forms a part of biomechanics. Other aspects are dynamics, kinetics, and statics, which investigate the action of force, forces that cause or change the motion of bodies, and forces in equilibrium, respectively.

The second area within the field of human movement science which is important to our study is psychology (especially concerning human motor control). In this scientific discipline questions like 'how can people control their movements?' are being answered. People are able to change their position, to move, to grasp objects, and to handle products, but why do people move as they do? Why do people move in a somehow invariant way? How can people learn complex skills? The answers to these questions lie partly in the realm of psychology.

Knowledge obtained from human movement science can, among others, be applied in ergonomics. The science of ergonomics focusses on the relationship between the human being and his material environment, in daily life as well as under professional circumstances. The main goal of ergonomics is to adapt the material environment to the human being. Sanders (1988) defines Human Factors (which is equivalent to ergonomics) as "... the branch of science and technology that includes what is known and theorized about human behavioral and biological characteristics that can be validly applied to the specification, design, evaluation, operation, and maintenance of products and systems to enhance safe, effective, and satisfying use by individuals, groups, and organizations."

Ergonomics is a relatively young science. In fact, however, ergonomics has been a part of the world since the existence of mankind, although not as a science. The human being shapes his environment according to his own dimensions. The human niche became increasingly artificial, i.e. man-made. Products, and therefore also the environment, are becoming more complex. To achieve an optimal attunement between the environment and mankind, knowledge about the human being, his environment and their mutual interactions is needed. This knowledge has to include all aspects. To place the speedometer in the right position in a car requires diverse insights into the human being. For instance, knowledge about the physiology of the eye, since the driver has to see the speedometer. But knowledge about the dimensions of the body is also of great importance. Where exactly will the head of the driver be located? Next, psychology will provide some information. In what manner is the information presented? In addition to these fields of knowledge, many other kinds of information are needed. Knowledge gained from human movement science will be used in ergonomics.

Ergonomics can be applied in already existing situations, e.g. to determine the physical load of the human body in a specific work situation. In product design and workplace design, ergonomics also has to be applied. When a new product is created by a designer who does not know anything about the users, it is obvious that it will be a suboptimal product. Therefore, product designers need not only the technical knowledge but also insight into the human being, especially those facets that will be important for the usage of a product. Ergonomics will provide this information for product designers.

In summary, we can say that knowledge gained from human movement science can, and sometimes must, be used in product design.

1.2 A gap in our knowledge

One of the characteristics of human culture is the use of artifacts. Since the birth of mankind, artifacts have been made. First, people constructed their own tools. At that time, products often were direct extensions of the natural capabilities of the user. Usage at that time was 'handy', i.e. mechanical extensions of hands. In the last few centuries the products have become more complex. Some individuals became specialized in the manufacture of certain products. People became shoemakers, carpenters, etc. Each person gained his own skills and delivered his own products. As a result, the user and the producer became separate entities. Since the producer makes his product, he knows how to handle it. The user, however, does not always know why certain products are made in that special way; consequently, he may not know how to use it. By applying technical insight, normal habits and traditional conventions, the user has to discover how the product should be used. When only simple products are involved, no problems will be encountered. But when the product is totally new or the previous function of the product is based on a new action, problems can be expected to occur. An example was described by Gelderblom and Christiaans (1991). In their experiment, subjects were asked to use a can opener. This opener, however, functioned according to a concept unknown for them. None of the subjects could use the new opener, because they all applied the old concept.

The more complex the product, the more difficult it will be for the user to understand and use the product in the right way. Increasing demands must be made upon product design. The functioning of new products has to be understandable. In addition, users often increase their demands upon products. Things have to be useful, efficient, safe and comfortable.

When designing a new product, multiple norms have to be considered. Moreover, considerable experience has been gained in product design, but fundamental insight is lacking. Why do we apply these norms? And why do we adhere to these customs? Use of a product involves at least three interacting factors: human beings, product, and environment. Each of these factors provides information that should be used in product design. Knowledge about user characteristics and product characteristics alone is not enough. To design products, knowledge about the interaction between user and product is essential. In this field, in particular, there is a gap in our knowledge. For instance, the use of (parts of) the limb as applied to a product is not yet understood. How do we grasp objects, and why do we grasp them the way we do? Such interactions are dependent upon human, environmental, and product characteristics.

One of the relevant characteristics is the structure of the human body. Due to our motor apparatus people can move, although only within the limitations of this apparatus. For instance, the elbow can only be flexed and extended; our anatomy does not allow other movements. The anatomy of the human body is an important factor. But knowledge of the finer details is also essential. The physiology of the human body, including somaesthesia (the perception of one's own body), plays an important role in the capabilities of the human being. In addition to these physical aspects cognitive aspects are also essential. People can control their movements in the correct way. For some interactions people have to learn the right movements before they can develop the required skill. Such aspects as the intention of the user influence, of course, usage of a product. But many other factors also play a role. For instance, is there a limitation on time? Or is a very steady hand required? Other aspects involved in the perception of the product are: what does the user think this product is, and why does he have to use it? On the other hand he will choose a way to use it. Of course, many other aspects are relevant to product usage.

Another category of factors concerns the environment. What is the position of the product relative to the user; what is the distance and orientation? Under what circumstances does product usage take place, what is the illumination, temperature, humidity, etc.?

The third group of relevant factors is product characteristics. Such aspects as material, friction coefficients, texture, and form will influence the interaction with the product. But also factors such as mobility relative to the outer world and the mobility of parts of a product influence the way a product will be used. Things like size influence, for instance, the way an object will be grasped. Texture and mass also influence the grasping of an object. In chapter 2 literature on the usage of simple objects is reviewed, and the influence of product characteristics on usage will be illustrated.

By now it must be clear that many factors influence product usage. The majority of these factors are not yet understood.

Therefore there are many ways to influence the relationships between a product and the user, most of which are as yet unknown. First, we are interested in finding regularities in product usage. In addition, factors relevant to the relationship product - usage have to be identified. These factors are expected to be human, environmental, or product-directed. In addition to regularities, interindividual and intraindividual variances can be found. And finally, in what way do people use products?

Finding an answer to all of these questions would be an impossible mission. Too many variables are involved. If one considers just the motor apparatus of the user alone, then it is apparent that people can use a finger, the hand, arms or legs. In some situations the total body will be used when handling a product, e.g. riding a bicycle. Furthermore, the environment can be very complex. Also the products can range from very simple to very complex; for instance, objects that can move freely compared to objects that can only undergo constrained movement. Finally, it must be stated that product usage in itself can be very complex. Usage can usually be divided into separate phases. For instance, when grasping a simple object, one has to anticipate, reach, and grasp. As a rule, more complex product usage can be divided into even more phases.

Therefore, the objective of our study had to be restricted. In daily life controls are essential; in many cases product usage incorporates the use of controls. Since we do not expect the usage of controls to be a very complex process, we have chosen controls as the central theme of our study. In addition, the indirect coupling between the function and the operation of a control makes them interesting to study. But this category of products also has to be limited, because many different kinds of control exist.

1.3 Overview of controls

The human being can design products for his own benefit. Most of these products have to be controlled. In many cases, special control components, such as knobs, wheels, levers, etc., have to be mounted on products. These elements are called controls. Sanders and McCormick (1993) define the function of controls as the transmission of control information to an apparatus, mechanism, or system. Dirken (1993, p.148) describes some general characteristics of controls. First, controls are often standard components, mounted on the outside of a product. It must be easy to reach the control. Usage is generally very simple, only a simple translation and/or rotation. The effect of a control is an internal action, which can be mechanical, electrical, etc. In (ergonomic) literature several kinds of overviews of controls can be found.

In the German industrial norms DIN 33 401) controls are classified according to the type of movement required to operate them. These movements are: rotate, swing around, push, shove, and pull. In figure 1-1 examples are given of rotary controls. This category can be further subdivided. The first subdivision, the first column in figure 1-1, is formed by the type of interaction used: one finger contact, two finger grip, three finger grip, hand grasp, and full hand grip. The coupling of the hand with the control, due to friction or shape, yields the second subcategory. Thirdly the orientation of the control, horizontal vs. vertical, plays a role. The fourth subdivision is based on the part of the body used to interact with the control: finger, hand, or hand and arm. In figure 1-1 thirty different types of rotary control are illustrated and classified according to the above-mentioned subdivisions. For each of these controls the norms give the suitability, on a three-point scale, for performing certain types of task like: transmission of force, accurate movement, fast movement, etc.

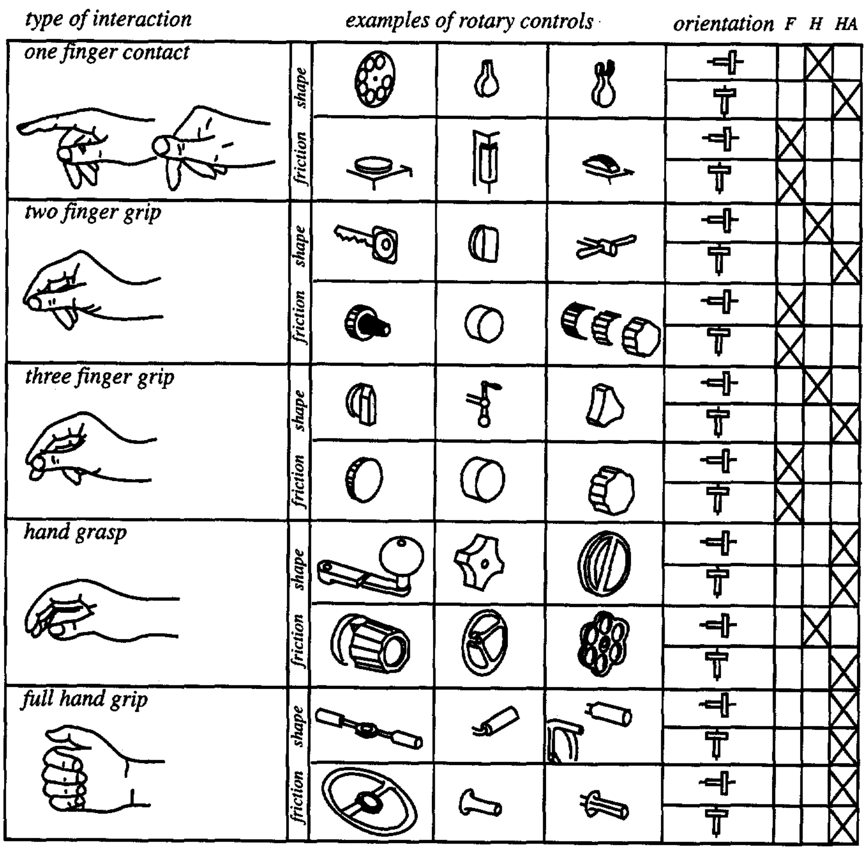


figure 1-1: Classification of controls according to the German industrial norms, examples of rotary controls (supplement of DIN *33 401, p.5). For each grasp six different controls are shown, the upper three are coupled due to shape, and the lower three due to friction. In the last column the part of the body used to interact is listed: F = finger, H = hand, and HA = hand plus arm.*

Another classification of controls is given by Sanders and McCormick (1993, p.334). They define the function of a control as the transmission of control information to some device, mechanism, or system. Consequently, they classified controls according to the type of information transmitted. This results in two broad classes: discrete and continuous information. Another distinction between controls is the amount of force required to manipulate them (large versus small). The amount of force required to manipulate a control depends on the device being controlled, the mechanism of control, and the design of the control itself. These two aspects, type of information and force required, were used by Sanders and McCormick to classify controls (see figure 1-2). This classification system, however, is rather coarse. Moreover, no arguments are given to explain why a control is placed in a certain class.

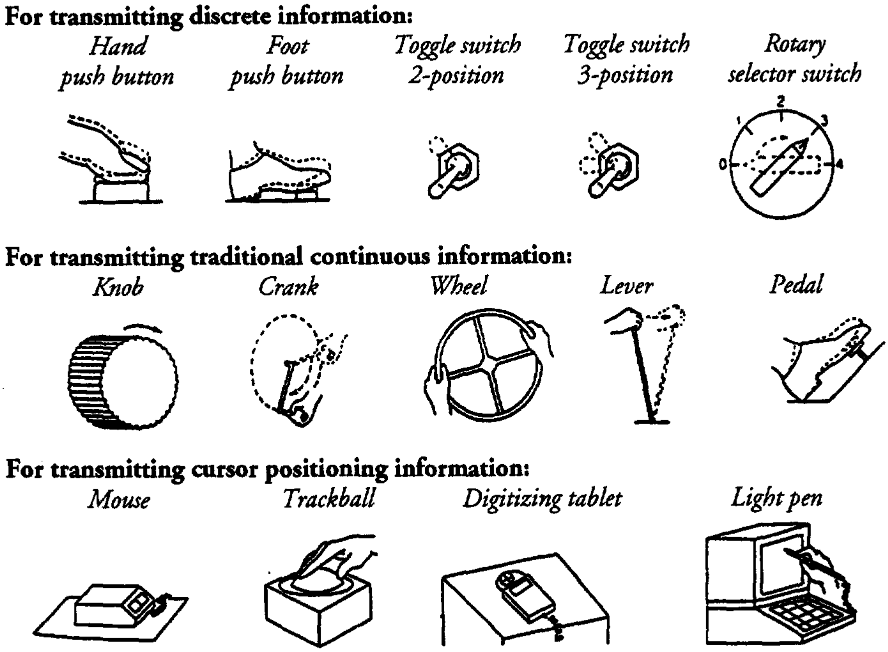
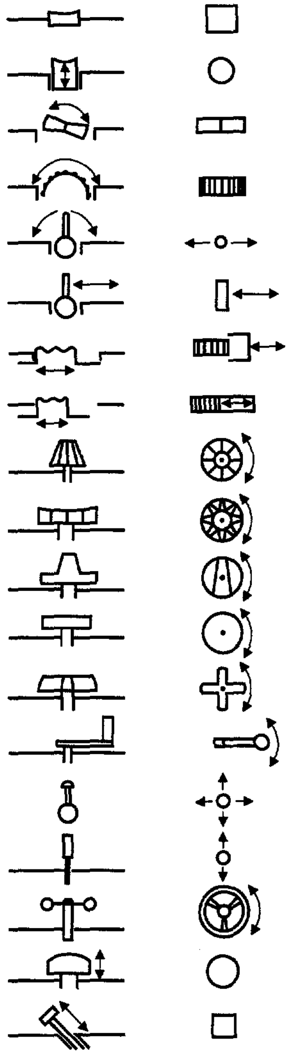


figure 1-2: Examples of some types of control devices classified according to the type of information they best transmit and the force required to activate them (Sanders and McCormick, 1993).

Woodson et al. (1992, p.424) published guidelines on control selection for industrial designers. In these guidelines three selection criteria are given. First one has to choose between hand-operated and foot-operated controls, depending on precision, force, available space, etc. Secondly, the function of the control ('select system power state ON-OFF', 'enter alphanumeric data', etc.) is used to choose one out of ten types of control (toggle switch, push button, bar knob, round knob, thumb wheel (discrete or continuous), crank, rocker switch, lever, and lastly joystick or ball (compare 'type of information' used by Sanders and McCormick, 1993). For each function to be performed, they use a three-point scale to indicate the preference for a type of control. For both the selection of functions and the choice of control, it is not clear why they chose one instead of another. Woodson et al. end



no. name	side view	top view	body part	movement
1. touch button			1	p
2. push button			1/2	p
3. toggle switch			2	sw
4. thumb wheel			2	r
5. lever switch			2/3	sw
7. on/off slide			2/3	sw
6. lever switch			3	sh
8. continuous slide			3	sh
9. fine tune knob			3	r
10. rotary selector switch			4	r
11. bar knob			4	r
12. rotary knob			4/5	r
13. star knob			5	r
14. crank			6/7	r
15. joystick			6/7	p pp r
16. handle			7	p pp
17. hand/arm wheel			7/8	r
18. foor push button			9/10/11	p
19. pedal			9/10/11	p

figure 1-3: Overview of types of control classified according to (parts of) the extremities used to operate the control and the type of movement (Dirken, 1993).

body part:

1 = fingertip	7 = arm	p = push
2 = finger	8 = arm + trunk	pp = pull/push
3 = index + thumb	9 = foot	r = rotate
4 = fingers + thumb	10 = lower leg	sw = swing round
5 = hand	11 = leg	sh = shove
6 = forearm		

movement: see right column above.

with an overview of about thirty types of control, varying from hand-operated push buttons to the hip-operated switch bar and aircraft rudder pedals, giving the criteria for use and human engineering considerations for each. In this last overview no external criteria are given; it is not clear why certain types of control do or do not appear in their list.

Another system for classification of controls is given by Dirken (1993, p.150). He classifies the nineteen most frequently used types of control according to the part of the body used (i.e. fingertip, finger, index and thumb, fingers and thumb, hand, forearm, arm, arm and trunk, foot, lower leg or leg). For each control the type of movement (i.e. push, pull/push, rotate, swing round or shove, compare DIN 33 401) is given. This results in the classification seen in figure 1-3. Other aspects, such as size, movement amplitude, required force, discrete or continuous information, are further specified for each of the controls mentioned.

From this, we can conclude that many types of control do exist. They vary in physical characteristics (form, required force, friction, inertia, type of feedback, etc.) but also in usage (rotation, translation, magnitude and direction of the movements, part of the body used, etc.). Since it is not possible to investigate all of the different kinds of control, we have to restrict ourselves to one type.

In our overview we saw that many types of control exist. Each type of control requires a specific usage. One has to reach the control, grasp it, and in the end manipulate it. For the research project we chose to study the manipulating phase of usage. In this phase the user is directly coupled to the control, and consequently each, i.e. the user and the control, will influence the other. An important aspect when choosing the types of control to be studied is the amount of freedom in usage. For instance, a touch button needs hardly any movement, and consequently is not of any interest to us. To control a continuous slide one needs to move, i.e. a translation has to be performed. Rotary controls require a rotation. Sometimes these controls have to be rotated through more than one turn. Consequently the users have to change their grip while using these controls. Depending on the control, there will be one, two, or three degrees of freedom. The more degrees of freedom, the more complex the study of usage will be. We have chosen to study rotary controls, allowing only rotation around one fixed axis (one degree of freedom). This type of control is frequently found in the home as well as the professional environment. Because a variety of rotary controls exists, we again have to make a choice.

Rotary controls can be used in many different ways. Extreme examples are the fine-tuning knob which only requires finger movements, on the one hand, and the hand/arm wheel requiring upper limb movements, on the other. Each usage involves a specific part of the body, see for instance figures 1-1 and 1-3. Depending on the type of control, the hand will be used either to perform the required movements or to fix the upper limb to the control. In this latter case the possibilities of movement of the fingers will be fully constrained since they may only be used for fixation. We have chosen to study controls which are operated by means of arm movements whereby no change of grip is required. In such cases the hand need only grasp the control. Examples of such controls are: a doorknob, a handle to lock the window, a stopcock, etc.

These controls can be divided into three main categories (see figure 1-4). First, the O-control (figure 1-4a). The main characteristic of this control is the independence of orientation. The frontal view will be the same, whatever the angle of rotation may be. Next there are rotary controls which have a cylindrical bar attached to the rotation shaft. This bar is fixed perpendicular to the axis of rotation. These rotary controls are sensitive to orientation. The frontal view changes when the angle of rotation is changed. The cylindrical bar can be attached to the shaft in many different ways. Two extreme examples are depicted in figures 1-4b and 1-4c. The shaft can be attached in the middle of the cylindrical bar, the T-knob, or at the end, the L-knob. There are, of course, many different kinds of rotary control, for instance the star knob (see figure 1-3, nr. 13). But most can be placed somewhere between the O-, T-, and L-knobs. In our experiments we used only these three rotary controls. In chapters 5 and 6, the experiments conducted with these controls are described.

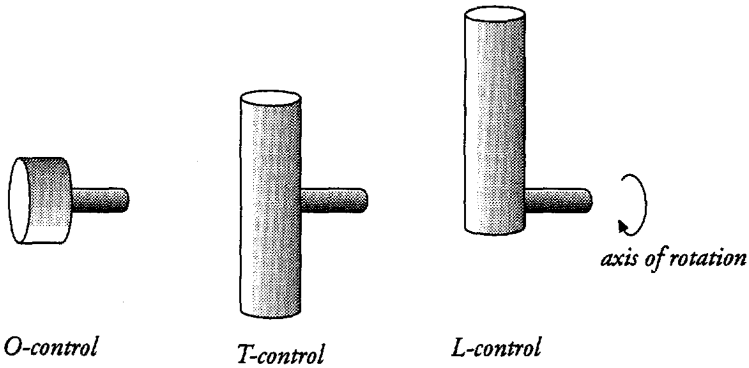


figure 1-4: Schematical side view of three types of rotary controls (O-, T-, and L-control)

The aim of these studies was to perform an exploratory, descriptive investigation of the (in)variant movements, taking interindividual as well as intraindividual differences into account, involved in operating rotary controls and achieving both the control and the task required. To reduce the number of degrees of freedom the study was constricted to an experimental laboratory situation, with emphasis on anatomical and mechanical variables.

1.4 Posture or motion recording

In our research projects the movements involved in the operation of rotary controls were studied. Somehow the movements have to be recorded. One can observe the movements, but one must at least describe the movements observed. There are several kinds of posture and/or motion recording systems available. Some of them are based on observation and subsequent notation of the observed posture or motion. Possibly these notation systems could be used for our research project. Therefore, we will review these systems. These notation systems can be encountered in various professional areas, for instance, in the analysis of labour. In the beginning of this century special notation systems were developed to describe tasks of assemblage. Other fields in which these notation systems are used are ballet and sign language for deaf people.

In the next three subparagraphs we will review these notation systems. First, we will start with notation systems used for analysis of work or ergonomics. The second subparagraph focusses on notation systems used in ballet. In the third subparagraph systems used for sign language will be described. Only notation systems which can be applied to record postures and/or movements of the upper limb are considered. In the end it was concluded that none of these systems are satisfactory for our projects. In the last subparagraph these conclusions are substantiated.

1.4.1 Work analysis

In work analysis registration systems are used mostly to optimize the working environment. People want to increase productivity by working in a more efficient way. One of the possibilities is to lower the physical load. At the start of this century Gilbreth and Gilbreth (1924) developed the concept of motion studies. This method was used to note elementary hand movements made while performing a task of assemblage. An observer notes the motions and writes them down on the operation chart. Figure 1-5 contains an example of an operation chart. Two kinds of movements can be distinguished: transport movements, depicted as a small circle, and actions, depicted as a large circle. To make an operation chart the hands have to be analysed separately. Gilbreth and Gilbreth developed the 'Therblig' (the reverse of the name Gilbreth). Each Therblig describes a part of the total action, such as search, select, grasp, etc. (see figure 1-6). Using Therbligs is easier than producing an operation chart, because the parts of the actions do not have to be described; each symbol indicates its own kind of action. At first only 17 Therbligs were defined. Barnes (1968) developed more Therbligs, to obtain a better differentiation between the various kinds of grasping actions, for instance three fingers and the thumb, stretched hand, two fingers and the thumb, and two hands.

Nowadays ergonomists still register the movements made in working situations. One example is the 'posturegram' (Priel, 1974), in which the joint angles are described by using only visual observation. Similar notation systems were developed by Corlett et al. (1979), Armstrong et al. (1982), Holzman (1982), Kilbom et al. (1985), Keyserling (1986), Gil and Tunes (1989), Van Dieen (1989), and others. A better known notation system is the OWAS (Ovako Working Posture Analysing System). The total body posture can be described by means of four possible trunk postures, three postures for the arms, and seven for the legs (Karhu et al., 1977 and 1981). With this system over eighty different postures can be recorded. Still one cannot say that this system is finely tuned. There is no way to record the many kinds of hand and arm postures. For instance, it is not possible to distinguish the diverse hand and arm postures involved in operating a control. All these systems are relatively coarse, fine alterations in posture cannot be recorded. Consequently intraindividual and interindividual variations at this level cannot be found.

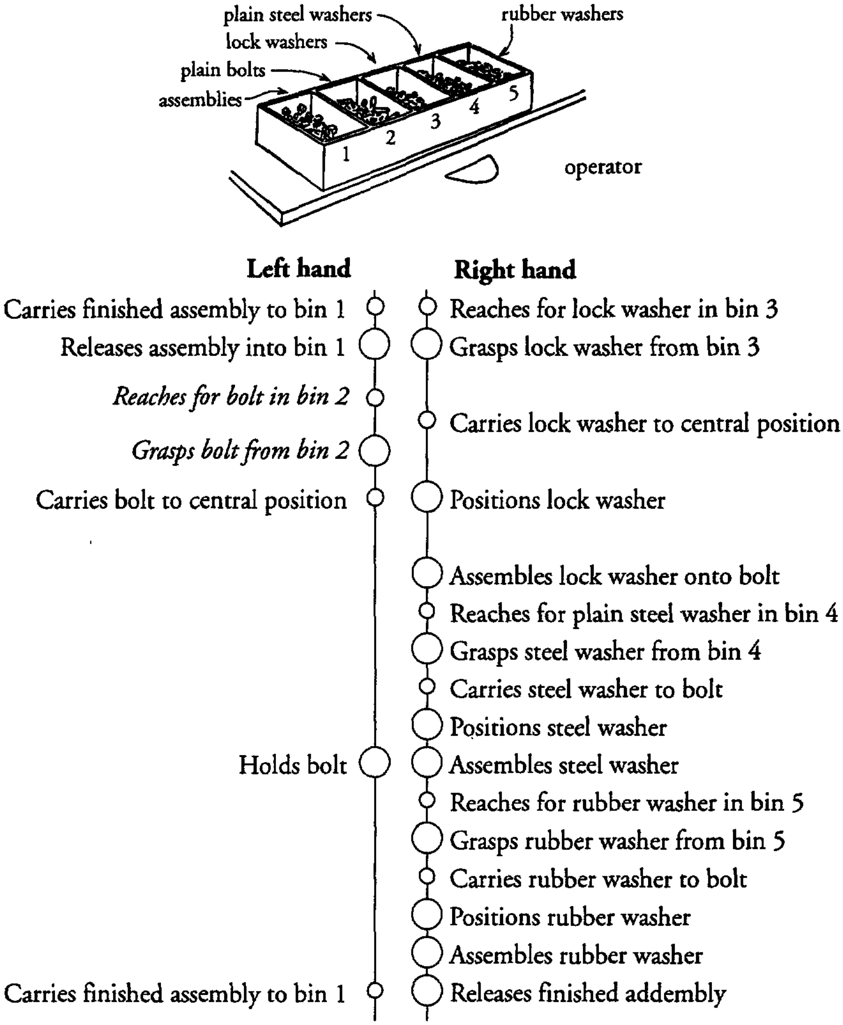


figure 1-5: Operation chart (Barnes, 1968, p.113) describing the process of assembling bolts with washers.

Name of symbol	Therblig symbol	Name of symbol	Therblig symbol
Search	Sh	Inspect	I
Select	St	Assemble	A
Grasp	G	Disassemble	DA
Transport emtpy	TE	Use	U
Transport loaded	TL	Unavoidable delay	UD
Hold	H	Avoidable delay	AD
Release load	RL	Plan	Pn
Position	P	Rest for overcoming fatigue	R
Pre-position	PP		

figure 1-6: The 17 Therblig's (Barnes, 1968, p.136).

These systems are rather coarse, but De Looze et al. (1994) have even shown that the OWAS recording method is not valid. They conclude that dynamic work situations require less simple and therefore more time-consuming methods (e.g. analysing film) than a posture recording method based on direct visual observation.

1.4.2 Dance notation

In ballet, dances are recorded by using posture and motion notation systems. In the sixteenth century Feuillet developed a notation system to record court dances. Many different sorts of notation systems have been developed (for an overview, see Preston-Dunlop, 1969). At this time the commonly used notation systems are the Observable Motion Data Recording system (OMDR), the Benesh Movement Notation system, and the Eshkol-Wachmann notation system. These will be described in short.

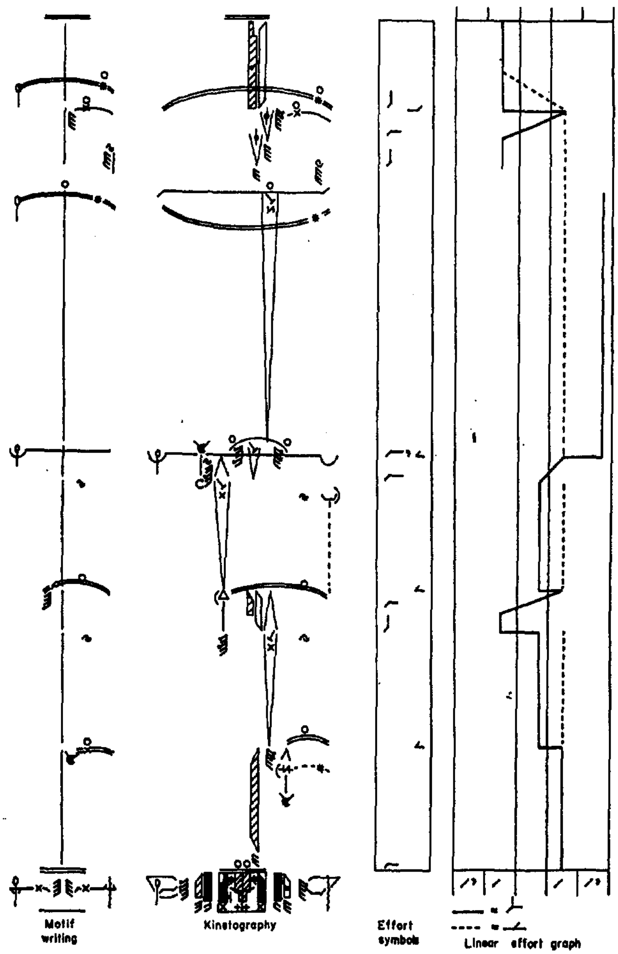


figure 1-7: Threading a needle, registred by OMDR *(Preston-Dunlop, 1969).*

The OMDR technique is based on an older system: the Laban notation system. The OMDR uses three complementary methods to record observed movements (Preston-Dunlop, 1969). 'Kinetography' and 'motif writing' describe movements. The difference between the two is the resolution of the recorded movement. In 'motif writing' only the global goals of the movement are described (e.g. walk to the chair and sit down). In kinetography the same movement is explained in more detail. For each step, the flexing of the knees and movement of the hips are described. With this latter method even finger motions can be recorded. The third part of OMDR is the 'linear effort graph'. This method describes the efforts needed to control and produce the required movements. The observer registers the way in which the 'available space', 'necessary pressure', and 'available time' are used. Next the 'flow element' of the movement is described. This element contains information about the sort of movement: e.g. the 'free flow' of ballistic movements or the 'bound flow' for movements with which one reacts to the environment (e.g. driving a car). The OMDR technique can describe movements in a very detailed way. An example is given in figure 1-7. This figure shows the registration of movements made while threading a needle.

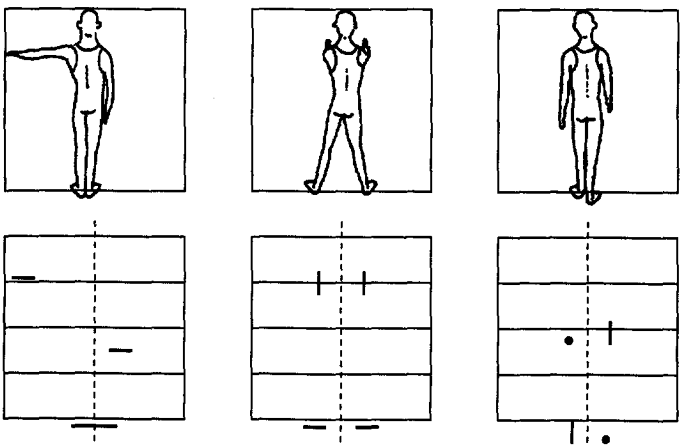


figure 1-8: Examples of posture recording by the BMN *method (McGuinness-Scott, 1983).*

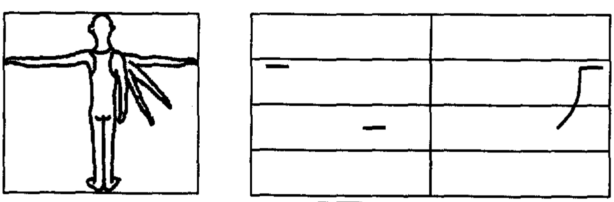


figure 1-9: Initial posture and movement, i.e. abduction of the right arm (McGuiness-Scott, 1983).

Another notation system still in use is the Benesh Movement Notation system (BMN, see McGuinness-Scott, 1982 and 1983). With this notation system movements are written on a sort of musical staff. This staff contains five lines, each indicating a part of the body (feet, knees, middle, shoulder, and head). The positions of the limbs are described relative to these five levels (see figure 1-8a and 1-8b). In this notation system the observer describes the movements as seen from the rear view. The plane of the paper is always the frontal plane of the mover. A position in front of or behind this frontal plane is described by using other signs (– = in the frontal plane, | = in front, and • = behind, see figure 1-8c). Motion can be described as a sequence of postures. As a rule the observer will use lines to suggest movement (see figure 1-9). This system is not only used in ballet. For instance Kember (1976) applied BMN to describe the way people sit on a chair. Another example is the clinical situation, for instance to record the gait pattern (Harrison, 1987).

The third approach to notation of ballet movements is the Eshkol-Wachmann notation system (Eshkol and Wachmann, 1958). This system can be characterized as a semi-quantitative description of movements. Each proximal joint can be viewed as the centre of a sphere. The distal-most point is described relative to the centre. The resolution depends on the dimensions of the sphere. One can divide the sphere into sections of 45°, but other dimensions are also possible. So one can adapt the resolution to the requirements. When the human body is seen as a wire frame, the position of all the parts can be described. In the notation system different kinds of symbols are used to describe for instance a conical or a planar movement. Figure 1-10 shows the movement of the figure in the upper left-hand corner. The resulting notation is at the bottom. This system too is used in other situations. Examples are animal movements (Szechtman, 1985; Eilam and Golani, 1988) and sign language (Cohen et al., 1977).

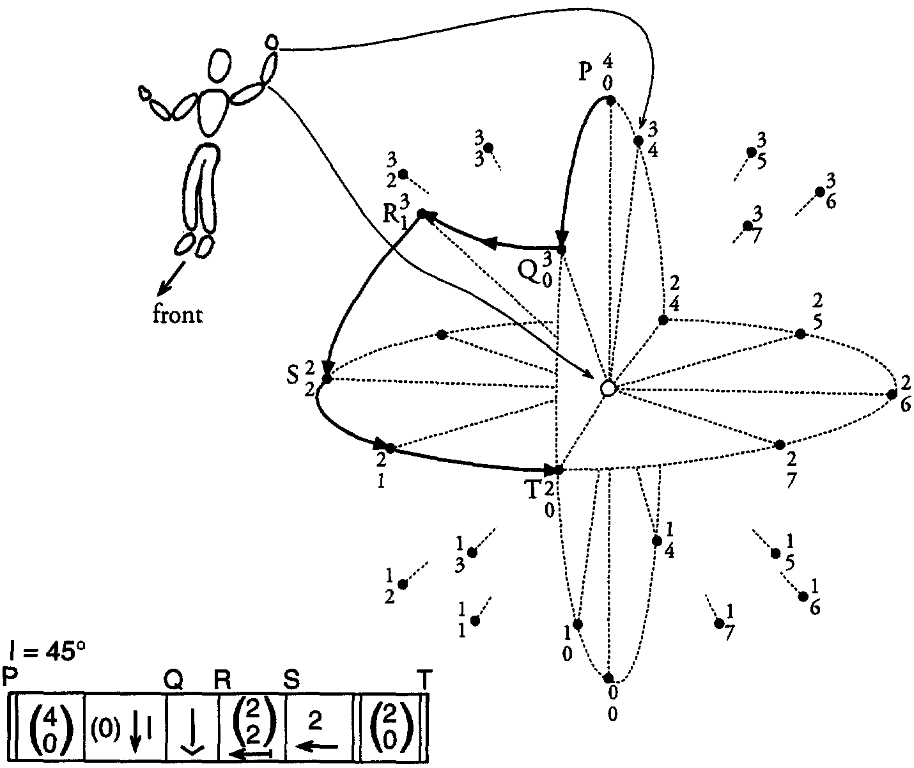


figure 1-10: The Eshkol-Wachmann movement notation, the figure on the left indicates the movement, resulting in the Eshkol-Wachmann notation at the bottom (Singleton, 1982, p.158).

1.4.3 Notation systems used for sign language

Hand and arm movements play an important role in sign language. Logically, notation systems have been developed to note these movements. Examples are 'Sutton Movement Shorthand' (Sutton, 1978a and 1978b), a notation system used for Dutch sign language (KOMVA, 1988), and the previously mentioned Eshkol-Wachmann notation system (Cohen et al., 1977).

Sutton Movement Shorthand (Sutton, 1978a and 1978b) consists of abstract pictures of the human body. The resolution of the system can vary from very detailed, e.g. detailed finger motion, to very coarse. The system was first designed to register dance movements. Nowadays the system is used mainly for sign language. But all kinds of movement can be recorded (e.g. sport, mime, and gait patterns). The point of observation can be from any position relative to the moving person (in contrast to BMN). In general, however, the frontal view is preferred. In this system a staff as in BMN is used. Here too the five lines represent five levels of the body. Movements are usually described by means of lines, as in BMN. To register the sign language only three lines have to be used, only when necessary will all five lines be used. In sign language not only the posture of the body is important, but also the position and orientation of the hands relative to the body. Several symbols have been designed to provide this information. In figure 1-11 an example of Sutton Movement Shorthand is given.

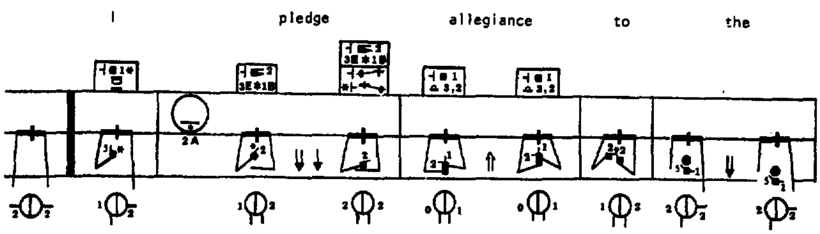


figure 1-11: An example of translation into Sutton Movement Shorthand (Sutton, 1978a, p.67).

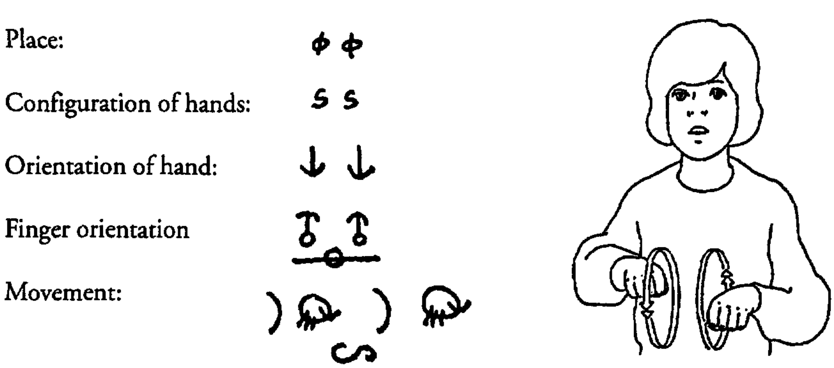


figure 1-12: An example of the Dutch Sign Language (KOMVA, 1988, p.79) for the word 'bicycle'.

For Dutch sign language there is a specific notation system (KOMVA, 1988). During the KOMVA project (improvement of the communicative skills of deaf adults and children) this system was developed to study sign language. In this notation system five aspects of sign language are recorded and described: -1- the position of the gesture, -2- the form of the hand, -3- palm and finger orientation -4- movements made in the gesture, and -5- non-manual components of a gesture. At least the first four components are necessary to register a gesture. In figure 1-12 the movements made to 'say' bicycle are shown.

1.4.4 Conclusion

The main similarity between the above-mentioned posture and motion notation systems is the necessity to observe the movement first. Sometimes video is used to register first, and then after analysing the video tape several times the notation is made. All systems differ in resolution. Some are very coarse, e.g. the operation charts of Gilbreth and Gilbreth, and some are very detailed, e.g. the Eshkol-Wachmann notation system. The main characteristic of all systems is that the observer must be highly skilled. Also most of the systems are very time-consuming. To make a full Laban score of a forty-minute ballet, it would take almost a full year to observe and record the movements (Macourt, 1985).

An important aspect of these systems is the way the movement is abstracted, i.e. the resolution. If the resolution is fine enough, every rehearsal of the first movement will be different from the former one. If, on the other hand, the resolution is rather coarse, every repetition of a movement will result in exactly the same movement. To register movements, one must know which parts or elements of the performance are important, and which parts are only slight disturbances imposed on the movement. In ballet this is possible, because the choreographer designed the ballet. In product usage this will be more difficult. One does not know which parts of the movement are essential and which parts are only variations of the theme. It is therefore hard to define the degree of resolution. This resolution is of great importance to the outcome of the study.

Since a notation system is not valid (De Looze et al., 1994) and it is not possible to determine the level of resolution of the recording, we have chosen not to use any of these registration methods. The human movement sciences accept the use of objective motion recording systems. In 1872 Muybridge was one of the first investigators who used an objective motion recording system. In 1955 a book was published containing reprints of moving people. In his method he used photo cameras to record the movements. Later the systems became more advanced, it became possible to quantify the movements people made. At this time mainly opto-electronic motion recording systems are used. These systems quantify the coordinates of markers attached to the body of the moving person. A comprehensive overview of these recording systems was presented by Cappozzo et al., 1992. In the last few years the spatial and temporal resolution of these systems has improved remarkably. Nowadays we can quantify movements very accurately. In paragraph 4.5 the opto-electronic motion recording system used in our study (OPTOTRAK) is described.

1.5 Plan of the study

Chapter 2 contains a review of the literature. This literature concerns human movement science in particular. The chapter deals first with the problem of degrees of freedom, which is one of the main questions in human movement science. This problem refers to the situation in which a performer has more degrees of freedom than strictly required by the motor task. The consequence is that motor performance is indeterminate, i.e. there is more than one way to perform the task. In the next section literature on various tasks is discussed; most authors consider the problem of degrees of freedom. The decision was made to review only literature on hand and arm movements. Moreover, the reviewed studies had to deal with interactions with objects or products. The experiments described are grouped according to task. We start with the pointing task, followed by the grasping task and end with the manipulating task. Each category is in fact an extension of the previous one. The last category resembles the tasks of our experiments the most; in our experiments the subjects had to operate three kinds of rotary control.

Chapter 3 starts with a concise description of the anatomy of the upper extremities. Then the two joint angles used in our experiments are defined. The method used to determine the angles is then described. In our experiments we used a motion recording system (OPTOTRAK). In the last paragraph of this chapter the validity and reproducibility of the method are evaluated.

In the next chapter (4), some general descriptions of the experimental conditions are given. The controls used in our experiments are also described. Furthermore some information about the motion recording system is presented. At the end the calculation methods and the software are discussed.

In the next two chapters (i.e. 5 and 6) the experimental results are reported. The data are presented, analysed, and discussed. In these experiments subjects had to rotate three kinds of controls which yield only one degree of freedom. Subjects were able to use two degrees of freedom, which exceeds the number of required degrees of freedom. Consequently an infinite number of performances is possible in principle. In our experiments we will examine whether subjects perform these rotations in an invariable way, or not. The performances will be compared to some of the concepts described in the second chapter. Furthermore we will try to explain the findings by using physical aspects and spatial characteristics of the control, goal of the task and the ranges of movement of the joints of the upper limb. Chapter 7 contains the general discussion and conclusions of the study. In this last chapter we will also present the practical implications of the results.

2 Review of literature

2.1 Introduction

For many years human movement has been an area of interest in scientific research. In the late nineteenth century investigators were already studying control of human movement. One type of human movement is the motor skills. Schmidt (1982, p. 20) defines skills as "Movements that are dependent on practice and experience for their execution, as opposed to being genetically defined." One of the earliest systematic approaches to motor skills was described by Woodworth (1899). Since then our knowledge has increased remarkably, but all questions still have not been answered, and new questions continue to arise. Is it possible to predict the way a movement will be performed? When we reach for an object, why do we take that specific path and not one of the other possibilities? When we open a door, why do we grasp the door handle with an overhand grip and not an underhand grip? What aspects of a product determine the way it will be handled? In the last few decades, these questions have become the aim of many scientific studies.

In paragraph 2.2 a review of the literature on this kind of human motion will be given. The publications concern the (in)variability of human arm motion, and the relationship between the environment, in a broad sense, and the way the movement is performed. The 'degrees of freedom' problem will also be discussed. In the next three subparagraphs, the experiments to be described are grouped according to task. The first (paragraph 2.2.1) is the pointing movement. The next section (2.2.2) focusses on grasping experiments, in which subjects were instructed to grasp various kinds of objects. These experiments contain a transport phase, like the pointing experiments, as well as a grasping phase. In the last section (2.2.3) manipulating experiments are described. Manipulating an object means transporting the hand towards an object, grasping it, and then manipulating it. These experiments resemble our experiments. In our study the subjects had to manipulate an object, i.e. a rotary control, by performing a rotation task. In the last paragraph (2.3) various outcomes relevant to our study are reviewed.

2.2 Movement control and learning

In the last century the idea of movement control was represented by the concept of the so-called homunculus. This little-man-inside-the-head organised the patterns of movement. The essence of this control was the open loop link, i.e. the movements are only controlled centrally, not by any form of feedback from the periphery. The homunculus selects from memory a plan for movement and implements the plan by manipulation of the cortical motor strip. The information could be sent in terms of motor units, muscles or joints. When the amount of information processed nowadays is considered, an enormous number of variables has to be known. When controlling, for instance, the position of the hand at the joint level, seven variables have to be set and organised (shoulder 3, elbow 1, forearm 1 and wrist 2). But when working at the muscle level, the number of variables increases to 26. An even more realistic idea is controlling at the motor unit level. Then, at a conservative estimate, there are 2600 elements to be regulated at one time (Turvey et al., 1982).

Jongen et al. (1989) offer a theory to explain the activation patterns of muscles during voluntary and reflex induced contractions. The theoretical predictions of the recruitment threshold of motor units for six arm muscles during contraction were in agreement with the experimentally observed behaviour of a large population of motor units within each muscle. Although this model has its limitations, for instance only isometric contractions can be predicted, it could be implemented in a total biomechanical model of the human body. Such a total model is not available yet, only models of a (part of a) limb exist. For instance An et al. (1981) and Raikova (1992) both made models of the elbow, including the muscles. From this, it is clear that a total model, including all joints and muscles and their activation patterns, is very complex and is therefore not feasible yet.

For the theory of a homunculus, therefore, it appears that there are far too many individual elements of the body that have to be regulated separately. This problem is called the 'degrees of freedom' problem. Saltzman (1979) defines degrees of freedom as "the least number of independent coordinates required to specify the position of the system elements without violating any geometrical constraints". The larger the number of degrees of freedom in a system, the more difficult it is to make the system behave as desired. Bernstein (1967) was the first to address this problem of the degrees of freedom. In 1967 the English translation of Bernstein's major publications was published. This book comprised a collection of his more important publications, written between 1934 and 1962. In 1984 Whiting incorporated and discussed this work of Bernstein. More recently the work has been published in German (Bernstein, 1988).

A closely related class of problems is the 'functional non-univocality' of the connections between the motor centre and the periphery (Bernstein, 1967). The homunculus is supposed to operate by means of an open loop control. It is not aware of the context of the actions, so it cannot be aware of any results of the actions. Under changing external conditions, any action of the homunculus will have a different outcome, i.e. functional non-univocality. Furthermore, every action will result in a different starting position for any following action. These changes introduce a fundamental type of variability into the system.

Bernstein (1967) defined three major sources of variability. First the anatomical factors, for instance variations in the function of one and the same muscle group at a multiaxial joint in relation to the position of limb segments. At these joints, the muscles playing the role of agonist and the muscles playing the role of antagonist are not fixed but change, depending on the trajectory of the movement and the context within which it occurs.

The second source of variability is mechanical. When, for instance, the elbow is 90° flexed, then activation of the brachial muscle will further flex the elbow. When, however, activation of the muscle is started after slowly extending the elbow, the same activation of the brachial muscle can result in either retardation of the extension, termination of the extension or even flexion of the elbow. This all will depend on the way the elbow was first extended. Therefore the same activation of the same muscle under different conditions will have different effects.

The final group of sources of variability, given by Bernstein, is called the physiological group. The cortex controls the muscles by sending pulses through the nerves. The pathway between the cortex and the muscles is, however, not one isolated path. On the way down, many interneurons in the spinal cord are needed to conduct the signal to the muscle. These interneurons do not only connect the central neuron with the peripheral neuron. Interneurons are connected to each other. Consequently the signal, proceeding from the brain, can be influenced by other signals: "… the motoneuron is sensitive to, but not subservient to, the signal from the brain" (Turvey et al., 1982, p. 251).

Another aspect of the degrees of freedom problem is the issue of indeterminacy (Jordan and Rosenbaum, 1989). The term indeterminacy was introduced by Bernstein to represent the total problem of the degrees of freedom. Jordan and Rosenbaum, however, use this term to indicate the motor equivalence problem only. Indeterminacies arise when the number of degrees of freedom of the system carrying out some task exceeds the number of degrees of freedom needed to specify the task to be carried out. In such cases there can be multiple solutions to the control problem, as described previously. When, for instance, subjects are asked to point to a spot in 3D space within reach of the arm and they are allowed to use their arm, there will be innumerable solutions to this task. The reason for this is that the arm contains seven degrees of freedom (shoulder 3, elbow 1, forearm 1, and wrist 2), whereas only three are needed. We know that the motor control system can solve indeterminate problems; otherwise humans would not have the capacity for motor equivalence, i.e. the ability to achieve the same physical objective in more than one way (Jordan and Rosenbaum, 1989).

Bernstein discussed the difficulty of coordination due to the extreme abundance of degrees of freedom. From his point of view it may be logical that learning a complex skill is not that easy. The way people learn skills, however, can help us to understand the way movement control is organized.

According to Bernstein, skills are improved in the learning phase by utilizing all possible roundabout methods to reduce the number of degrees of freedom to a minimum. In this perspective control will be less complex. Later on the number of degrees of freedom could be increased by releasing those degrees of freedom which were prohibited before. In this stage coordination of the movement is improved. Bernstein gives the example of a novice at a sport. First he will move rigidly, will spastically fix and hold the limbs involved or even his whole body to reduce the number of kinematic degrees of freedom which he is required to control. Having mastered the first degree of freedom, the organism increasingly lifts the ban imposed on further degrees of freedom, resulting in a greater economy of movement and diminishing fatigue. Later on he will remove all restrictions, employing entirely the reactive phenomena which arise. An example of this strategy is described by Kamon and Gormley (1968). They studied the EMG patterns of the superficial muscles of the trunk, arm and thigh made during the performance of the single knee circle mount on the horizontal bar (see figure 2-1). The EMG of a fluent performance by the gymnast showed strong bursts of activity of shorter durations. Findings such as these suggest that greater skill means more efficiency. It must, however, be noted that the movements, i.e. the order of the postures in time, in figures 2-1a and 2-1b are not the same. However the two movements represent the same task, i.e. the performance of a single knee circle mount.

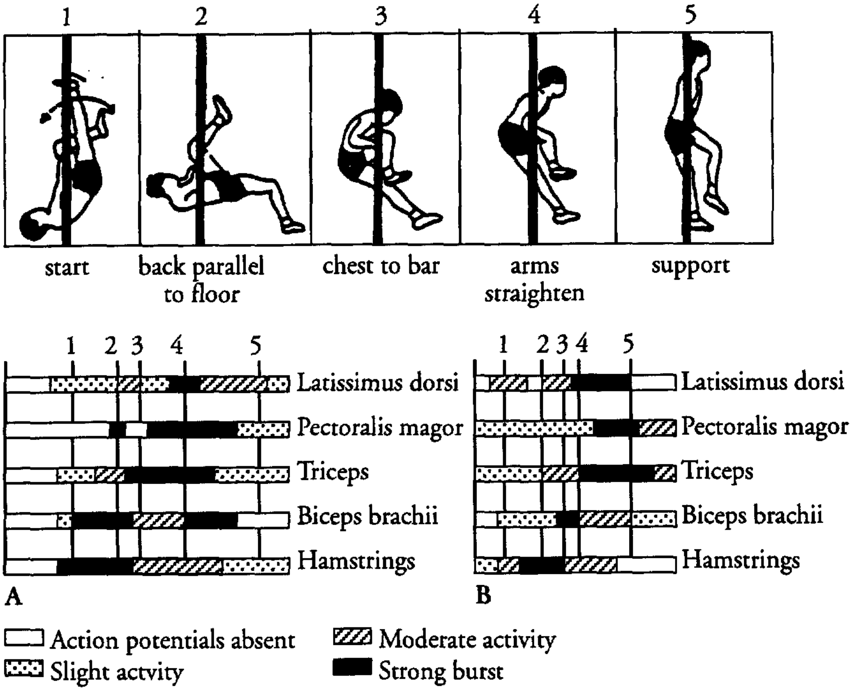


figure 2-1: Changes in the amount and timing of muscle activity in novice gymnasts (A) and practised gymnasts (B) while performing the exercise shown in the top panel. Numbers in the bottom panels correspond to the five phases of the exercise. (From Kamon and Gormley, 1968)

Skills are not innate but have to be learned. Depending on the complexity, the learning phase will be hard or very easy. During the initial learning period the individual improves his skilfullness: for instance, the end point variability of pointing tasks will decrease, and therefore the effectiveness of movements will improve (Ludwig, 1982; Darling and Cooke, 1987). This will continue until the maximum performance or plateau is reached. This 'ceiling effect', as defined by Schmidt (1982, p.471), is "a limitation, imposed by the scoring system or by physiological-psychological sources, that places a maximum on the score that a performer can achieve in a task." After achievement of the maximum, the individual will perform in an almost constant way. It is, however, possible that subjects will change their strategy, again achieving a ceiling. However, the total performance, when compared with the former plateau, has now increased. Therefore even when an individual has acquired a skill, he can still change the movement strategy, e.g. when other strategies are more convenient or efficient.

The question of how an individual, when moving, is able to cope with all degrees of freedom still has not been answered. Bernstein (1967, see also Tuller et al., 1982) hoped to solve the problem by thinking in terms of hierarchical coordinative structures. According to Hinton

(1984) Bernstein did not give a clear explanation of this approach in his publications, but it appears to be a way to handle complexity that should be familiar to all computer programmers. The idea of hierarchical coordinative structures is to break the gap between the motor output and the neural impulses into smaller parts, instead of one single span. At the highest level there are schemes that translate the motor problem into terms that are more suitable for the lower level. This continues until the actual muscles are reached. The advantage of this hierarchical approach is that higher levels need not be concerned with low-level details. The idea of hierarchical coordinative structures is very attractive but, as Hinton (1984) writes, it is underspecified and there are several ways to make it more precise. One interpretation is qualitative hierarchy in which each level deals with a different type of entity. When performing a movement task, one has to have an action plan (Turvey, 1977) to control the movement, i.e. a multileveled structure representing action at different levels of abstraction. This action plan is said to incorporate both abstract information from long-term memory and specific information about the current demands, the physical state of the environment, and the physical state of the peripheral motor apparatus. Saltzman (1979) distinguished seven levels in the complex structure of an action plan:

- 1- *Conceptual.* At this level, the act is defined in terms of symbolically coded and interrelated component actions, e.g. 'reach', 'lift', and 'transport' (cf. the therbligs of Gilbreth and Gilbreth, 1924).

- 2- *Environmental-space motion.* The motor task is defined in an external spatial reference system, e.g. transport an object from point A to point B.

- 3- *Effector.* The acting part of the body, the body segments that link it to the trunk, and the set of muscle groups associated with the control of this effector system are specified.

- 4- *Body-space motion.* The action is represented: for instance, as a specification of the right hand's spatial trajectory relative to the trunk as a function of time.

- 5- *Joint motion.* To enable the hand to perform a particular body-space motion at a particular speed, the changes in joint angles must be specified as functions of time.

- 6- *Joint torque.* Given the change in joint angle as a function of time, the resultant torque which must be produced actively at each joint can be computed.

- 7- *Muscle.* First, the forces needed to produce the desired torque at a given joint must be determined. Then, muscle innervation must be computed.

At each of these levels synergies, i.e. coupling between two or more degrees of freedom, may result in an effective reduction of the number of degrees of freedom. The consequence will be a less complex system, which will be easier to control. Tuller et al. (1982) applied the concept of coordinative structures to describe muscle linkage. In this case muscles are not independently controlled but are related to each other. The kinematics of movements is what we are interested in, i.e. levels 3 and 4. Therefore, the literature review will mainly contain experiments dealing with the degrees of freedom problem at this level.

Often the word 'constraint' is used, meaning a restriction of the freedom of movement. Cruse (1986) defines control constraints and geometrical constraints. Control constraints represent a redundant motor apparatus (i.e. the arm, for instance, consists of more degrees of freedom than strictly required by the task) and therefore decrease the degrees of freedom. Geometrical constraints are those that determine the boundaries of the work space. They are determined by the geometrical properties of the motor apparatus, i.e. the length of the links and the extreme angles which can be assumed by the different joints. Rosenbaum et al. (1992a) offer another distinction between constraints. They divide the constraints into 'soft' and 'hard' ones. The soft constraints are preferences rather than rules. These constraints are coupled to attention, perception, and computated motor control. They resemble control constraints, as defined by Cruse (1986). Hard constraints, in contrast, require specific movements (e.g. constraints imposed by gravity, tensile strength of bones, and the maximum speed of muscle contraction). The geometrical constraints defined by Cruse (1986) form only part of the hard constraints.

It should be noted here that the problem of the degrees of freedom does not imply that there are too many degrees of freedom. Due to the number of degrees of freedom one can reach a target in various ways, for instance in case of an obstruction by making an enveloping movement. Motor equivalence, i.e. the ability to achieve the same physical objective in more than one way, is an important aspect of human movement. In psychology Brunswik (1950) generalized this notion as the most goal-directed behaviour, stressing the concept of 'vicariousness'; the latter means that there are in most cases several ways of carrying out a task, reaching a target, etc. Therefore one should use the term abundancy, meaning that there are many (but not too many) degrees of freedom. The abundancy of degrees of freedom, however, raises the question of why we move like we do. Do we move in an invariable way, and, if so, is this invariance typical of one person, one situation, one instruction, etc.? Which aspects of the environment, e.g. (part of) products, influence human movement? This question is especially relevant when analysing improvements which could be added to controls or task instructions.

Since Bernstein insight into human movement has increased remarkedly. Many studies have, for instance, found possible sollutions to the problem of the degrees of freedom (see next section). Turvey (1990) describes all these studies as being the first round in dealing with Bernstein's problem. He states (p.942) that "... this round was conducted of understanding how one would go about regulating an artifact of very many independent variables without ascribing to any one subsystem excessive responsibility." Like Rosenbaum (1991, p.388), he gives prospects for the future. In round two, they both see the importance of the physical approach to biology, to regard living systems as ordinary physical systems. In this round non-linear dynamics appears to be a suitable way to describe (and explain) movements. Until now we found that they have only used this method to study rhythmic movements (e.g. juggling, see Beek 1989). Our next literature review is concerned with object handling. Most of these handlings are non-repetitive. We conclude that the non-linear dynamic approach does not contribute (yet?) to our subject and will, therefore, not be incorporated into our review.

In the next sections experiments involving the control of arm movements will be described. Human movement in daily life is very complex, i.e. many joints are used at the same time. Studying these movements appears to be rather difficult. In human movement science, therefore, at first only simple movements are studied. The more complex a movement, the more difficult the analysis will be. In the next three sections pointing, grasping and manipulating experiments will be described. These experiments vary from very simple tasks of aiming to manipulating tasks, in which aiming is only a part of the task. The latter resemble our experimental tasks. The main aspects of interest are the (in)variability of human movement, relationships between degrees of freedom (synergies), and relationships between controls and human arm movement. The latter topic is not of major concern in human movement science. The products used were mainly very simple objects, such as a wooden dowel, a cup, or a handle. Moreover, these objects were only used to gain a better insight into human motor control. Our interest focusses predominantly on the relationship between control characteristics and the way people use the control.

2.2.1 Pointing experiments

As we move our limbs more rapidly, we become more inaccurate in terms of the goal we are trying to achieve. Woodworth (1899) was probably the first to attempt to study this relationship between rate of movement and its accuracy scientifically. In 1954 Fitts conducted experiments in which subjects had to move a stylus from one target to another. In his experiments he changed the distance between the two targets and the width of both targets. He found that movement time was linearly related to the index of difficulty. This index was based on the width of the targets and the distance between targets. The task, however, was cyclic. In 1964 Fitts and Peterson described the same relationship for discrete aiming tasks. The movement time (as quickly and accurately as possible) was also related linearly to the index of difficulty.

Recently, more advanced registration systems were used to assess subjects who performed a Fitts'-like task: single aiming movements. Opto-electronic motion registration systems can trace the path the wrist makes when performing a single aiming movement. The wrist trajectory and tangential velocity profiles appeared to be invariable for movements of different speeds and different targets (Morasso, 1981; Soechting and Lacquaniti, 1981; Abend et al., 1982; Lacquaniti and Soechting, 1982; Soechting, 1984; Atkeson and Hollerbach, 1985). The trajectory of the wrist, from starting point to target position, seems to be approximately straight (Morasso, 1981). More detailed examination revealed that some of the paths were slightly curved. These curvatures were thought to be caused by inertial forces, acting on the arm (Hollerbach and Flash, 1982). Recently, De Graaf (1994) examined the initial direction of slow goal-directed arm movements. She found that subjects can start a slow movement accurately, i.e. the variability is low. However, the initial direction of the movement deviated consistently from the straight line through the starting and target positions. The maximum deviation (5° to 10°) was found for targets ±30° from zero. The deviations were all away from the medial plane.

In addition, the outcomes of pointing experiments could be used to test the existence of a general motor programme (Schmidt, 1982 p.303). The idea behind the generalized motor programme is that a motor programme for a particular kind of action is stored in memory and that a unique pattern of activity will result when the programme is executed. In order to execute the programme, however, certain parameters (e.g. which muscles, in what order, acting as relative or absolute forces and in which temporal relationships) must be defined which in turn determines exactly how the motor programme for that particular movement will be executed. Schmidt et al. (1979) and Meyer et al. (1982) applied the theory of the generalized motor programme in order to understand the linear speed-accuracy tradeoff recognized in single aiming movements. They found that in a single-aiming task, the effective target width, i.e. the deviation from the target centre, is related linearly to the average velocity (target distance divided by movement time). They concluded that all acceleration-time functions of aimed hand movements are generated from one pattern. Zelaznik et al. (1986) showed, however, that generalized motor programmes for aimed movements cannot be based on a simple time-acceleration pattern. It seems to be more complicated. The results of MacKenzie et al. (1987) suggest that a generalized programme exists for a given target width with inherent parameters or scales. They concluded that the velocity profiles are not symmetrical (in contrast to Meyer et al., 1982). The deceleration phase took relatively longer than the acceleration phase. In a discrete Fitts' task three identical indices of difficulty produced three identical spans of time but different movement trajectories. These results suggest that a generalized motor programme exists for a given target width with parameters or scales which depend on the amplitude of movement.

The speed and accuracy of goal-directed movements seem to be inversely related to each other. The accuracy can, however, increase, without losing speed. Georgopoulos et al. (1981), for instance, showed that the acquisition of aiming skill by rhesus monkeys was accompanied by an exponential reduction in spatial variability of the movement trajectories. While training, neuromuscular changes occurred, resulting in decreasing endpoint variability (Ludwig, 1982). Not only the endpoint variability but also the variability of the whole trajectory decreased with practice (Darling and Cooke, 1987).

Studies have been carried out to determine not only the trajectory of the wrist but also the relationship between the shoulder and the elbow angle. When pointing in a sagittal plane, the angular elevations at the shoulder and elbow exhibit covariance (Lacquaniti et al., 1982; Soechting and Lacquaniti, 1981; Soechting and Lacquaniti, 1983). This relationship occurred during deceleration of the movement, independently of movement speed, target location and load. This relationship was not influenced by the presence or absence of a concomitant wrist rotation (Lacquaniti and Soechting, 1982). The same occurs when making movements in three-dimensional space, i.e. point-to-point movements (Lacquaniti et al., 1986) as well as circular drawings (Soechting et al., 1986).

Kots and Syrovegin (1966) studied motor tasks whereby the subjects were instructed to carry out movements involving simultaneous rotation of the elbow and the wrist in all possible combinations of flexion and extension. They claimed to have found periods of movement when the two joints were displaced by a constant ratio of their angular velocities. Bishop and Harrison (1977), however, were not able to reproduce these findings.

In conclusion, it can be said that when subjects perform a pointing task, it occurs to some extent in an invariable way. The invariance refers especially to the trajectory of the wrist, and the coupling between the shoulder and elbow angles. Next, one can ask why do we perform these invariable movements. In literature diverse explanations can be found. The predominant idea is that people move in an efficient manner (cf. Nelson, 1983): for instance, minimalization of the mean squared jerk where jerk is the rate of change of acceleration or the third derivative of position (Hogan and Flash, 1987) or minimalization of torque change (Uno et al., 1989). On the basis of these ideas, among others, Rosenbaum et al. (1993a and 1993b) constructed a model for reaching a control. Their stick model can move in the sagittal plane by bending the hip, shoulder and elbow. Reaches are achieved by the model of target postures selected by evaluating stored postures (see Rosenbaum et al., 1992b, in which they argue for motor planning based on stored postures rather than computing each situation separately). Target postures are obtained by calculating weighted averages of the stored postures, whereby the weights assigned to each stored posture depend on their effectiveness for the task. The movements, from starting posture to target posture, are achieved by reducing the distance in joint space between the two.

Cruse and colleagues explained the way in which subjects point by means of cost functions (Cruse, 1986; Cruse and Brüwer, 1987; Cruse et al., 1990; Cruse et al., 1993). These cost functions are located in the joints involved. The task was to point to a target in a horizontal plane. While performing, the subject could use the shoulder, elbow and wrist joints. For each subject a triplicate cost function was calculated for the combination of three joints in order to describe the experimental results in the sense of the smallest mean square deviation. In addition to this method, they also determined the cost function by psychophysical methods. The outcomes of the two methods exhibited close agreement. The way in which subjects move could be explained by minimizing the total cost of the three joints involved. Brüwer and Cruse (1990) transformed the idea of Cruse and colleagues to a neural network. Such a neural network is capable of converting, for instance, the 3D end position of a hand into the joint angles required to achieve this position.

From these pointing experiments it can be concluded that people move to some extent in an invariable way. However, when the conditions changed, i.e. target size or accuracy, the movements varied. An important feature of the regulation of movement is efficiency. Examples of movement efficiency are minimization of jerk or change of torque. In addition to these kinematic parameters psychophysical parameters are also used to regulate movement. One can predict the way a pointing movement will be performed by applying cost functions to the joints involved. In addition to these constraints, there is also an important synergy. In pointing movements, the shoulder and elbow movements are coupled. The wrist, in contrast, is found to be independent of the other arm joints. Nevertheless these invariables may to some extent apply to the average human being, and it may be that somewhat different habits, tactics or strategies will be chosen or just followed by different persons under different circumstances.

2.2.2 Grasping experiments

The experiments described in subparagraph 2.2.1 concern the shape of the wrist trajectory. In most grasping experiments, however, not only the wrist trajectory is determined. Grasping an object means transporting the hand towards the object and preshaping the hand to grasp it, when possible. These two actions (i.e. transport and grasp) are carried out by anatomically separate muscle groups of the shoulder/arm and hand. It has been suggested that this separation of function extends beyond the anatomy to processes underlying the control of these movements, and therefore these functions are expected to be independently controlled (Brinkman and Kuypers, 1973). This would result in a indirect linkage of the reach and grasp components.

Jeannerod (1981) split objects into two 'elemental' visual properties: intrinsic properties and extrinsic properties. Intrinsic properties include size, shape, texture, or colour. Such properties belong intrinsically to the objects and are constituents of their identity. Extrinsic (as opposed to intrinsic) properties include orientation, distance with respect to the body, or location in the frontal plane. Jeannerod proposed that the spatial characteristics of transport of the hand by the arm and the anticipatory formation of grasp with the digits are under the control of two separate, specialized subsystems or visuomotor channels. The transport component is determined by the extrinsic properties (this does not agree with the above-mentioned findings on target width, see Fitts, 1954), while the intrinsic properties establish the grasp component. The degree of hand opening varies for objects of different sizes (see also Marteniuk et al., 1990). In 1993 Newell et al. showed that adults, as well as infants (5 to 8 months old), vary their grip configuration systematically with object size. They showed that when object size is scaled to hand size, common dimensionless ratios, such as cup diameter divided by hand length, define the grasping patterns and the transitions between grasping patterns in a similar manner for both adults and infants. Jeannerod (1981) showed that changes in the intrinsic properties of an object, such as shape, affected only the grasp and not the transport. The grasp and transport, however, cannot be seen as independent objectives; there is at least a temporal requirement that the hand be open before the position of the object is attained. The maximum opening was observed at the same time as the hand slowed down to approach to the object (Jeannerod, 1981 and 1984).

Weir (1994) noted that not only visual properties but also the haptic properties of an object influence the movements made by subjects. Since this kind of property cannot always be determined visually (sharpness, for instance, can often be assessed visually), the subjects had to touch and feel to determine these properties. For instance, the weight of an object is usually known when the subject holds it; visual information is not enough, although it may yield an estimate. Klatzky et al. (1987b) have shown that substance-related properties, such as hardness and texture, are more easily encoded by means of haptics, while structure-related properties, such as shape and size, are more easily encoded by means of vision. In conclusion, it can be stated that not only elemental visual properties but also non-visual properties can be relevant for object grasping.

Recently, Stelmach et al. (1994) conducted an experiment in which subjects had to grasp, with their thumb and index finger pads, an elongated object resting on a horizontal surface and placed at six different orientations with respect to the subject (see right upper corner of figure 2-2). Depending on the orientation, the subjects had to align their fingers with the object. This realignment was accomplished through rotation (called pronation; in paragraph 4.2 the movements of the joints of the upper arm will be identified) of the forearm as well as rotation of the shoulder joint (which involves both internal rotation and abduction). When full rotation is required, the thumb and index finger exchange their positions relative to the midline, i.e. the thumb is now to the right and the index finger to the left. The results (see figure 2-2) showed that for object angles of 70°, 80°, and 90°, almost all grasps were executed without realignment of the fingers. As the angle increased to 100°, a mixed manner of grasping was noted. For the larger angles of 110° and 120°, the inconsistency disappeared because the subjects systematically added pronation to the transport phase.

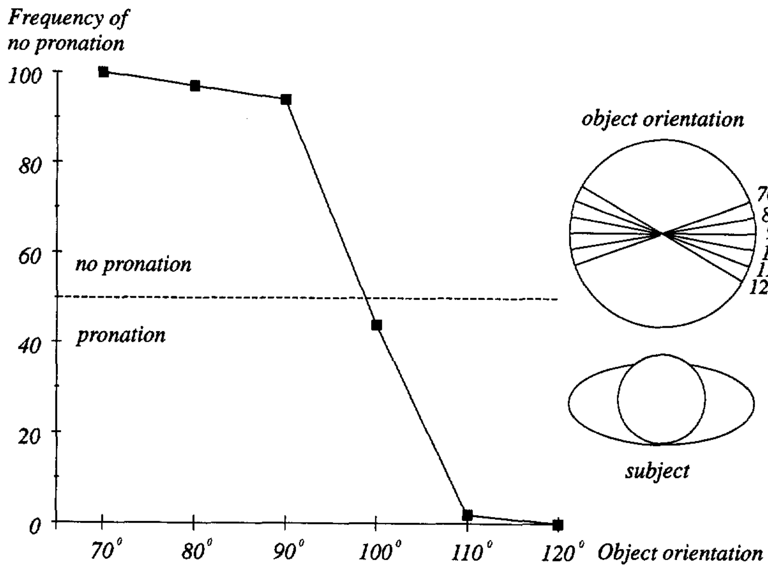


figure 2-2: The frequency, in percent, of movements with the nonpronated and pronated hand as a function of object orientation. The object's orientation with respect to the subject's body axis is shown at the upper right (from Stelmach et al., 1994).

Like Jeannerod, Arbib (1981 and 1985) also suggested that the transport and grasp components are controlled via different visuomotor channels. Although assuming separate operation of the visuomotor channels for transport and grasp. Arbib proposes a coordinated control programme, consisting of a number of 'schemas' and 'subschemas' which regulate coordination of the two components. A schema can be defined here as a rule, based on practice or experience with certain aspects of past responses; e.g. the relationship between past commands and response outcomes (Schmidt, 1982 p.525). An interesting test that supports the concept of schemas was conducted by Raibert (1977). Subjects produced writing samples with the hand, arm, mouth or foot. The samples showed a remarkable similarity despite the fact that different muscles were used. This can also be seen as an extreme case of motor equivalence, i.e. a given task can be performed in a variety of ways.

In 1985 Arbib et al. implemented the idea of a coordinated control programme for grasping a mug. In their description the fingers of the hand have three major functions: to provide a downward force from above the handle (VF1), an upward force from within the handle (VF2), and, if necessary, a third force to stabilize the handle from below (VF3). They hypothesized that each of these functions can be represented as the task of a 'virtual finger'. The fingers within a virtual finger move in conjunction with and have the same characteristics as real fingers. In a real situation, the translation of the real fingers to the virtual fingers will depend on the characteristics of the mug. In figure 2-3a the subject grasps a cup with only a small handle. Consequently, only the index finger is mapped to the second virtual finger. If the handle is larger, the second virtual finger will also include the third finger (figure 2-3b) and even the fourth finger (figure 2-3c). Therefore, depending on the size of the handle of the mug, VF2 will contain one, two, three or even four fingers. In the last case VF3 will be empty, i.e. no real finger is used to stabilize the handle from below. For grasping a mug a top-down schema can be generated. Preceding the actual movement, a perceptual schema must judge the size of the handle and pass this information to a schema which will assign the five actual fingers to the three virtual fingers. From that time on, control proceeds in terms of the three virtual fingers. Simultaneously, a reach schema and a grasp schema will be activated. Given the actual position of the hand and the required position of the hand, the target position to which the wrist is to be directed can be determined. Once the initial phase has been completed, control is then transferred to VF2 which passes through the handle and VF1 which presses down on the handle.

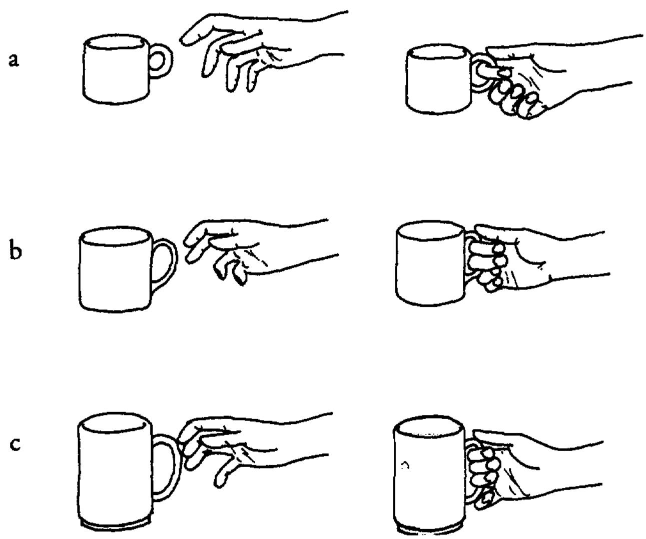


figure 2-3: Various combinations of real fingers can be mapped into virtual fingers for differently sized objects (From Arbib et al., 1985).

In this model of Arbib and colleagues, data transfer is vertically organized and does not include links between grasp and transport. Therefore Arbib's model, like that of Jeannerod, retains some aspects of the concept of two visuomotor channels. More recent studies have shown that the two components cannot be completely independent of each other (Paulignan et al., 1990 and 1991; Bootsma and Van Wieringen, 1992; Weir, 1994). Recently, Hoff and Arbib (1993) presented an updated model. The two major changes in the model are: (a) the transport phase is no longer divided into two separate phases, and (b) the one-way flow of activation from the transport to the grasp schema is replaced by a two-way interaction. Consequently, the two phases, transport and grasp, seem to become more dependent upon each other; actually, anticipation of subsequent phases begins to play a role. In this respect it could be speculated that psychologically the entire motor task is experienced mainly as its final goal and final effect. Phases could be logical artefacts.

In a grasping experiment Wing et al. (1986) compared the grasp size for normal, fast and blind prehension tasks. They argued that, before movement, formation of the grasp is planned to take into account not only the perceived characteristics of the object but also internalized information (based on past experience) about the likely accuracy of the transport component. The manipulation component is determined not only by the perceived physical dimensions of the object but also by the dynamic aspect and the accuracy constraints of the whole action of prehension.

In prehension tasks, object weight and texture may influence the reach to grasp the object. These properties cannot be completely determined visually. Weir et al. (1991a and 1991b) showed that object properties that require new haptic information do not influence the movement trajectories prior to contact. It appears that this kind of property, however, does influence the finger-object interaction phase, i.e. the time between contact with the object, when haptic assessment begins, and the start of lifting the object.

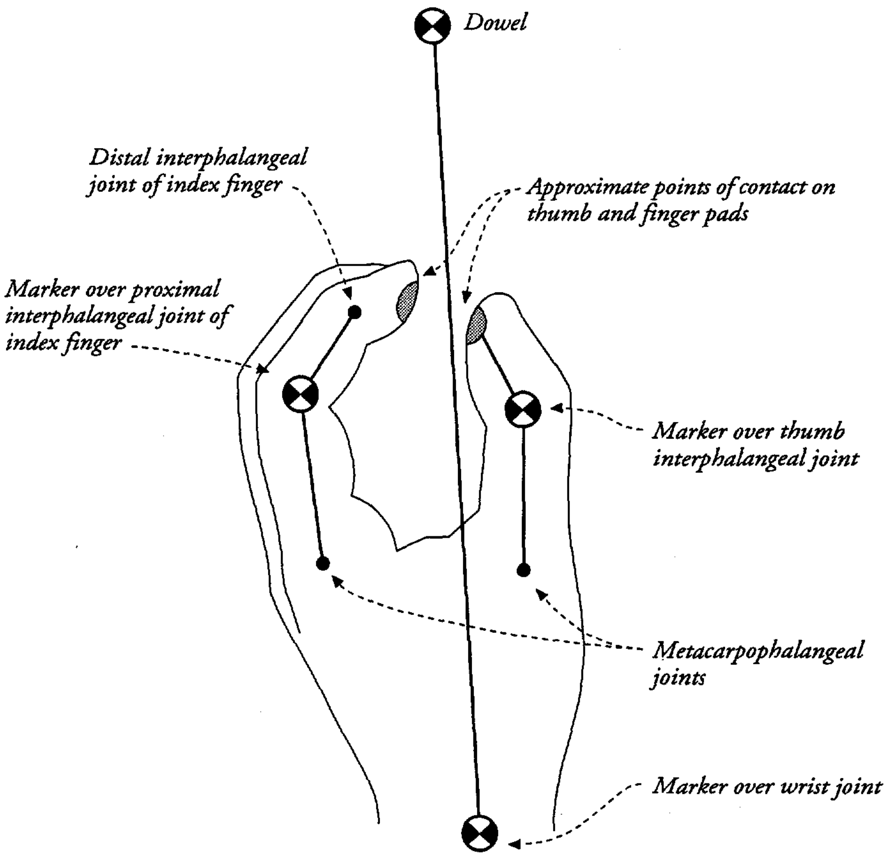


figure 2-4: Drawing of the hand to indicate position of markers used to digitize the transport and grasp components of reaching (Wing and Fraser, 1983).

Analysis of grasping movements can be performed at different levels. So far only experiments in which the grasp has been analysed on the basis of the aperture of the hand have been described. In other experiments the movements of the fingers and thumb were examined.

Wing and Fraser (1983) studied the way the fingers (thumb and index finger) move while grasping a wooden dowel. In their experiment they recorded the position of the wrist, thumb and index finger, as illustrated in figure 2-4. From these positions they determined the distance of the thumb and index finger from an axis joining the wrist and the object. Their results showed that hand closure is primarily conducted by movement of the index finger. The position of the thumb is relatively invariable. They believe that the thumb is used for visual control of the transport component of prehension. For large apertures thumb movement, relative to the wrist, is indispensable.

Cole and Abbs (1986 and 1987) studied the kinematics of the thumb and the index finger. In their experiment they recorded the movement of the metacarpophalangeal and proximal interphalangeal joints of the index finger and the interphalangeal joint of the thumb (see figure 2-4). Their results showed a great variability in the kinematic features of grasping. In 1988 Darling et al. assessed the joint angles of four joints (two joints of both the index finger and thumb). Their results indicated that, in contrast to pointing, the variability of the endpoints of finger and thumb joint does not increase with increasing rates of movement. Practice caused a significant reduction in the variability of the endpoint of joint end positions only for the slowest movements (duration 400 ms).

Therefore the conclusion, relevant to our research, seems to be that the important features of grasping experiments are the intrinsic and extrinsic properties, as defined by Jeannerod (1981 and 1984). For prehension tasks, he distinguished the transport and grasp components, each affected by specific properties of the objects to be grasped. Later, it became clear that strict independence of these two components cannot be upheld. There seems to be a cross-over influence of the intrinsic properties on the transport component and the extrinsic properties on the grasp component. We, therefore, contend that the intrinsic and extrinsic properties are both important factors in the relationship product - user. Moreover, the concept of intrinsic properties must be extended. Not only visual properties influence the grasping component but also, for instance, haptic aspects.

2.2.3 Manipulating experiments

In subparagraph 2.2.1 pointing experiments were described. Marteniuk et al. (1987) showed that the formation of the wrist trajectory, as discussed in the previous subparagraph, appeared to be more complicated than can be expected on the basis of the simple pointing experiments. The trajectory also depends on the action the subject has to perform after reaching the 'target'. They recorded three-dimensional movement trajectories under the following conditions: pointing at a target with the index finger versus grasping a disk the same size as the target; grasping a fragile object versus a soft resilient object; and grasping a disk and throwing it into a large box or placing it into a tight slot. They showed that when the accuracy is kept constant (as measured by the size of the object to be pointed at or grasped) but the goal of the task differs (point vs. grasp, grasp a light bulb or disk, or grasp a disk to throw or to insert it), different movement trajectories are produced.

Klatzky et al. (1987a) asked subjects what handshapes they would use when interacting with 90 abstract square and spherical artificial objects, varying in height and size. Subjects could choose between four handshapes (see figure 2-5). The outcome of their experiment revealed that a relationship exists between the dimensions of the object and the handshape chosen by the subjects.

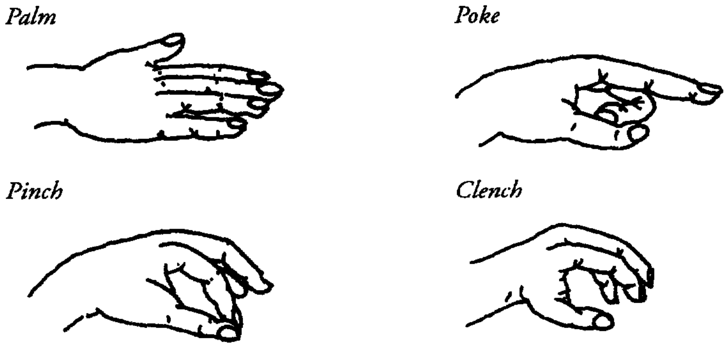


figure 2-5: Stereotypic examples of the four response classes: palm, pinch, poke, and clench (From Klatzky et al. 1987a).

The experiment of Klatzky et al. contained no actual movements (only intended movements). Rosenbaum and colleagues, however, conducted experiments in which subjects reached, grasped and manipulated an object. In all of their experiments the subjects had to perform a rotating task. In one of the experiments, the subjects had to transport a cylindrical bar to a disk placed to the left or right of the bar. This bar was positioned horizontally, and subjects were instructed to place either the right end or the left end of the bar onto the disk. They could easily grasp the bar in either an overhand grip or an underhand grip. Depending on the task, all subjects chose for only one of the two alternatives (see figure 2-6). Rosenbaum et al. (1990) tested the results against several hypotheses. They conducted a rating study to find the perceived awkwardness of holding the bar in every static position that was possible in the experiment. These ratings were used to test predictions about alternative methods that subjects used to determine grip preferences. They had to reject the idea that subjects performed rotating tasks by working backwards, i.e. first considering the consequences of a move before actually starting it. Also the theory that the subjects tried to avoid awkward postures whenever possible turned out to be false. A third hypothesis was that subjects tried to minimize the time spent in awkward postures. Their data, however, did not support this hypothesis. The only hypothesis that did survive was: exploiting awkwardness. The thought was that the subjects anticipated the rotation task by assuming an uncomfortable arm position at the start of the movement in order to end in a comfortable position. When, for instance, they performed the rotation task by means of clockwise rotation, the subjects anticipated by rotating their hand counterclockwise first. The authors postulated that the subjects stored elastic energy while moving in the counterclockwise direction and used this energy to allow passive rotation of the arm into the desired final position. Rosenbaum et al., however, mentioned that it is doubtful that the only constraint used for the selection of action is an extreme joint angle. They call this an end-state comfort effect (see also Rosenbaum and Jorgensen, 1992). More constraints, such as minimalization of jerk (Hogan, 1984) and minimalization of distance, time, peak velocity, energy, and peak acceleration (Nelson, 1983), are expected to play a role in determining the actual movement.

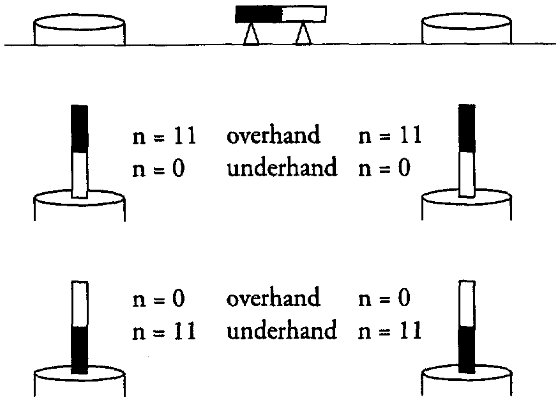


figure 2-6: Grabbing the bar with an overhand or underhand grip (From Rosenbaum et al., 1990).

In another experiment Rosenbaum et al. (1992a, see also Rosenbaum et al., 1988) asked subjects to rotate a handle through 180° (the direction of rotation was free, either clockwise or counterclockwise). The orientation of the handle was in the direction of one of eight numbers, equally distributed through 360°, i.e. every 45°. A pointer was attached to one side of the handle; this pointer covered one of the eight targets. The handle could be grasped in two ways: thumb towards the pointer or away from it. Their results revealed that the end position had a greater effect on the chosen grasp than the initial position. Subjects avoided 'awkward' hand positions at the end but not at the beginning. In 1988 they hypothesized that subjects moved on the grounds of their mechanical properties, i.e. they stored elastic energy to convert it into kinetic energy. Later they questioned this theory (Rosenbaum et al., 1992a). At that time the explanation for end-state comfort was 'precision'. A comfortable position would allow the subject to complete the task precisely. As yet, however, they have not found any evidence for the precision hypothesis.

Another aspect described by Rosenbaum et al. was the 'thumb-towards bias'. Superimposed upon the preference for end-state comfort is a preference for holding the handle with the thumb, or the base of the thumb, on the same side of the handle as the pointer. The explanation for this bias is a perceptual concept; due to the thumb-towards bias the tab can be seen both during and at the end of the movement. Wing and Fraser (1983) believe that, in grasping tasks, the thumb plays a role as visual control of the transport component of prehension. Similarly it is possible that during rotating tasks, the thumb plays a role by guiding the hand.

Rosenbaum and colleagues mainly studied the way in which a bar is grasped. They did not record the actual movements made while performing the task. It can be expected that the subjects would use distal arm movements as well as the more proximal arm movements to finish the required rotation. Bullinger and Solf (1979) state that, although their theory is not supported by empirical data, they believe that a required hand rotation is accomplished by applying first the possibilities of distal rotation (i.e. supinating or pronating the forearm) and then, when the distal possibilities have been used, the possibilities of a more proximal rotation, i.e. moving the whole arm (see figure 2-7).

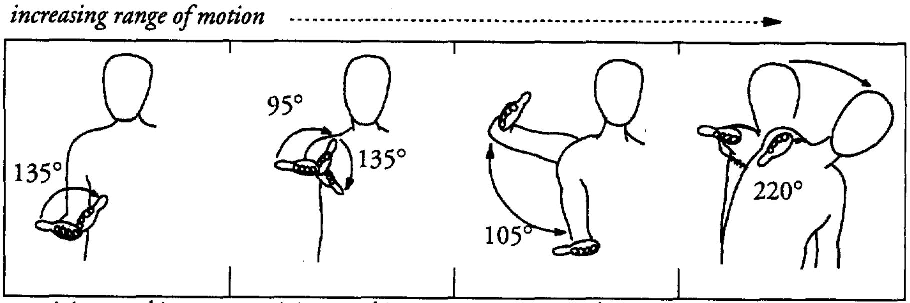


figure 2-7: The use of segments with increasing ranges of movement (after Bullinger and Solf, 1979).

In the above-mentioned experiments the investigator gave the subjects a specific task, which influenced the movements the subjects made. In daily life, however, people do not follow specific instructions from investigators. When, for instance, a user sees an object and directly relates the object to previous experiences with it or with similar objects, the user will interact in a way that is familiar. This theory has been substantiated by Gelderblom (in press). He describes an experiment in which subjects had to operate a coffee machine. Subjects could fill a cup with coffee by turning a knob. This knob worked in both directions: clockwise as well as counterclockwise. Then both the knob and the appearance of the machine were changed (see figure 2-8). The knob became either a water tap or an amplifier dial. The colour of the machine was either black so that it resembled an amplifier or white, as is customary for sanitary objects. Consequently, four different combinations were possible. Before the experiments the subjects were not informed about either the function or the operation of the knob. The subjects were not aware of being part of an experiment. Normally a water tap functions when turned counterclockwise; the other knob, however, has the same function (i.e. opening), but this knob is normally rotated clockwise. The outcome of this experiment shows that subjects base their actions on former ideas: the water tap was turned counterclockwise significantly more often and the dial was turned clockwise significantly more often. The colour of the machine had no influence on manipulation of the control. Therefore, only the intrinsic properties of the control, and not the whole machine, were important for this task.

Thus, the literature suggests that, in our study, we should take into account the task to be performed. Depending on the task, subjects will change their movements. This will also be the case for movements before the actual task. When, for instance, the task is to grasp an object and throw it away or grasp it and place it somewhere else, the transport component preceding prehension will be influenced. Furthermore the way an object is grasped, for instance by an overhand or underhand grip, will depend on the task to be performed after grasping.

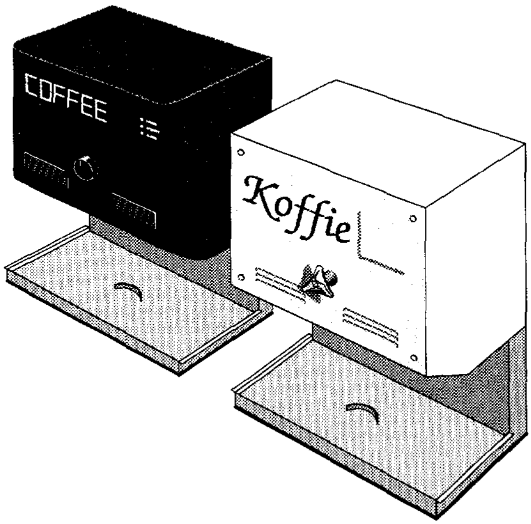


figure 2-8: Two of the four possible settings of the controls on the appropriate machines, i.e. water tap on the white box and the dial on the black box (From Gelderblom, in press).

2.3 Conclusion

In the above paragraphs human (arm) movements are discussed. Human movements appear to be very complex due to the number of degrees of freedom. Depending on the level of analysis one has to control anywhere from several up to thousands of degrees of freedom. Movement coordination is therefore very complicated. The essence of coping with the abundant number of degrees of freedom is given by the word constraints. Constraints are preferences or rules for the regulation of a movement. These constraints can be either hard or soft (Rosenbaum et al., 1992a). An example of a hard constraint is the reach area of the arm. Due to the anatomical construction of the joints and bones, the hand can only be placed within a certain reach envelope. Another example of a hard constraint is the passive relationship between the length and the tension of a muscle. An example of a soft constraint is the cost function, as used by Cruse and colleagues. Some of these constraints are called synergies. A synergy is the coupling of two or more degrees of freedom. The effect of having synergy will be a reduction in the effective number of degrees of freedom.

There are three important aspects of the control movements involved in product usage. The first is the physical aspect of a product. These properties are more than just the visually determined features and must be expanded to include, for instance, haptic features. In addition to these properties, place and orientation also influence the way a product will be grasped or handled. Moreover, the task in itself plays an important role. Experiments have shown that the task will influence the way an object is grasped. The way an object is grasped, e.g. with an overhand or underhand grip, also seems to be determined by the task to be performed.

In addition to the influence of the human - product relationship on product usage, the movements people make are constrained by diverse rules. Efficiency rules such as minimizing jerk but also psychophysiological cost functions reduce variations in the performance of movements. Finally user preconceptions, prior experiences, prejudices and anticipatory guesses cannot be excluded as influences on the motor sequence of reaching, grasping, and manipulating objects.

3 Rotations of the arm[1]

3.1 Introduction

When the given task is rotation of a knob (≤ 120°), a subject will generally use his hand to apply a moment to the shaft of the knob. Therefore, the hand has to be in contact with the knob. Due to the anatomical construction of the arm, i.e. the bones, joints and muscles, the subject can do this. The range of movement of the joints is, however, limited. Because of the anatomy of the joints, i.e. shape of the bones, ligaments, articular capsule, and muscles, the possibilities of rotation are restricted. In paragraph 3.2 a concise description will be given of the anatomy and kinesiology of the upper limb. For a more detailed description of the anatomy, see standard anatomy handbooks, e.g. Gray's anatomy (Williams et al., 1989). In the experiments (chapter 5, and 6) the degree of motion is given by the supination angle and the combined arm rotation. In paragraphs 3.3 and 3.4 the definition of and mathematical formulas for joint angles will be given. In the next paragraph (3.5) the technique used to assess joint rotation angles is described. The reproducibility and validity of the measuring method are discussed in paragraph 3.6. In the last paragraph (3.7) conclusions based on the material discussed in this chapter are presented.

3.2 The anatomy of the upper limb

The human thorax forms the base of the upper limb. The thorax consists of the thoracic vertebrae, which form part of the vertebral column, and the ribs (see figure 3-1). In front the ribs come together at the sternum. The shoulder girdle is attached to this bone, whereby the clavicles articulate on the cranial side of the sternum (sternoclavicular joint). At the acromion, the scapula is attached to the other end of the clavicle, forming the acromio-clavicular joint. The body of the scapula rests on the latero-dorsal surface of the thorax. The scapula articulates with the upper arm. The glenoid cavity of the scapula and the head of humerus form the shoulder joint. The arm consists of the humerus, to which the radius and ulna are attached at the elbow joint. On the distal side of the radius the wrist joint forms the connection with the hand. The hand contains the following parts: carpus, metacarpus and digiti (built up of phalanges). The carpus includes eight bones, two rows of four each. On the distal side of the carpus five metacarpal bones articulate (carpometacarpal joint), each for one finger. The first metacarpal bone articulates with the thumb. This finger contains two phalanges, a proximal and a distal one. The four other fingers each contain three phalanges (proximal, medial, and distal). The joint between two adjacent phalanges is called the interphalangeal joint. Four fingers have two of these joints, a proximal and a distal one.

[1] The major part of this chapter, i.e. the methodology used to determine the supination angle, has been published in: Van der Vaart, A.J.M. (1994) Measurement of forearm rotation: the technique, and its reproducibility and validity. *Behavior Research Methods, Instruments, & Computers*, 26(4), 409-415.

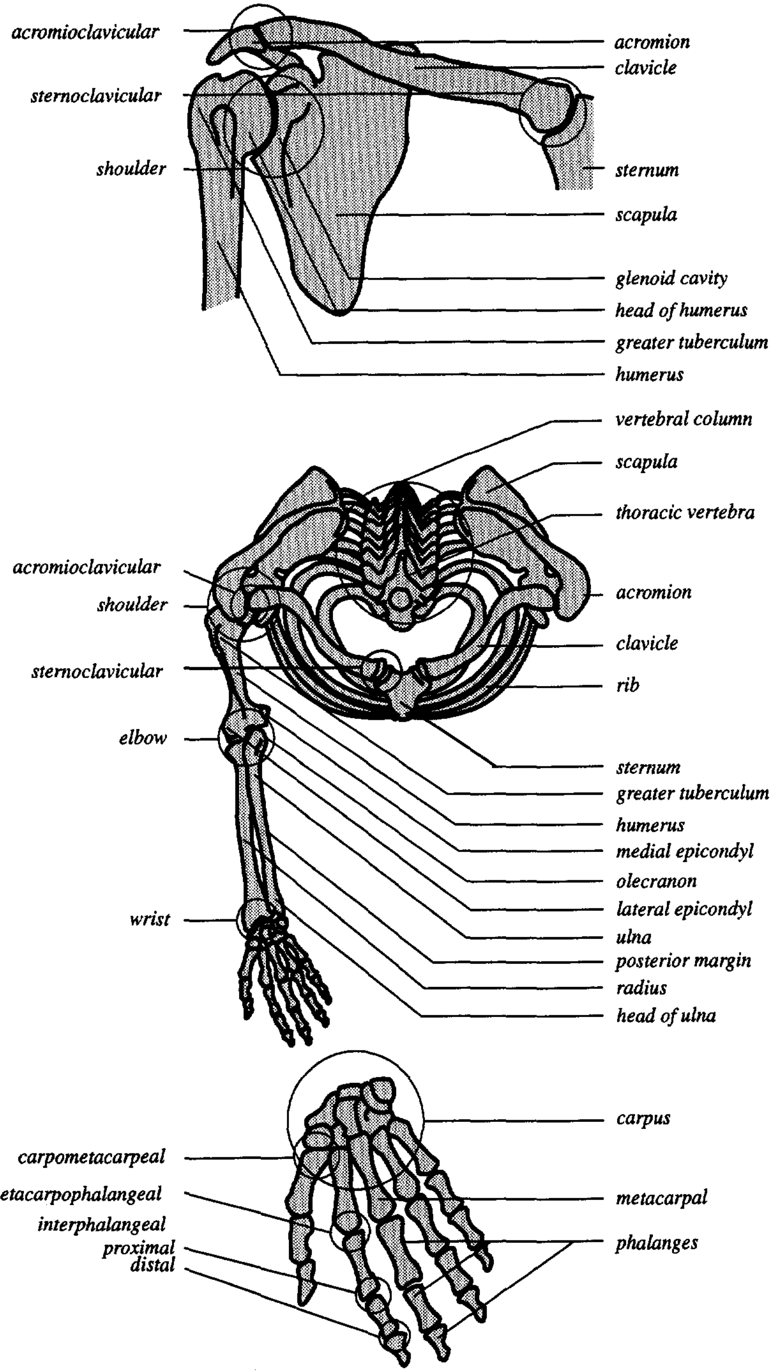


figure 3-1: View of the skeleton of the trunk, shoulder girdle and arm. The top figure represents the frontal view of the shoulder girdle (the ribs and vertebral column are removed). The middle figure shows the trunk, shoulder girdle and arm, seen from the top. The right arm is bent forwards (45°) with the forearm horizontal, seen from the top. The bottom figure represents a palmar view of the hand.

These bones and joints can partly be palpated (i.e. examined by feeling with the hand) from outside the body, although the skeleton is covered by skin. Moreover, most of the upper limbs are also covered with muscles and tendons. Only the distal part of the humerus can be palpated directly under the skin. On the medial and lateral sides the epicondyles can be felt (lateral and medial epicondyle, respectively). The proximal part of this bone, for instance the greater tuberculum, can only be detected through the overlying deltoid muscle. Only a small proximal part and the distal part of the radius can be palpated directly. The rest is covered with forearm muscles. The ulna, however, can be palpated along its entire length on the posterior side. This edge is called the posterior margin. Other parts of the ulna can also be directly palpated, such as the olecranon on the proximal side and the head of ulna on the distal side.

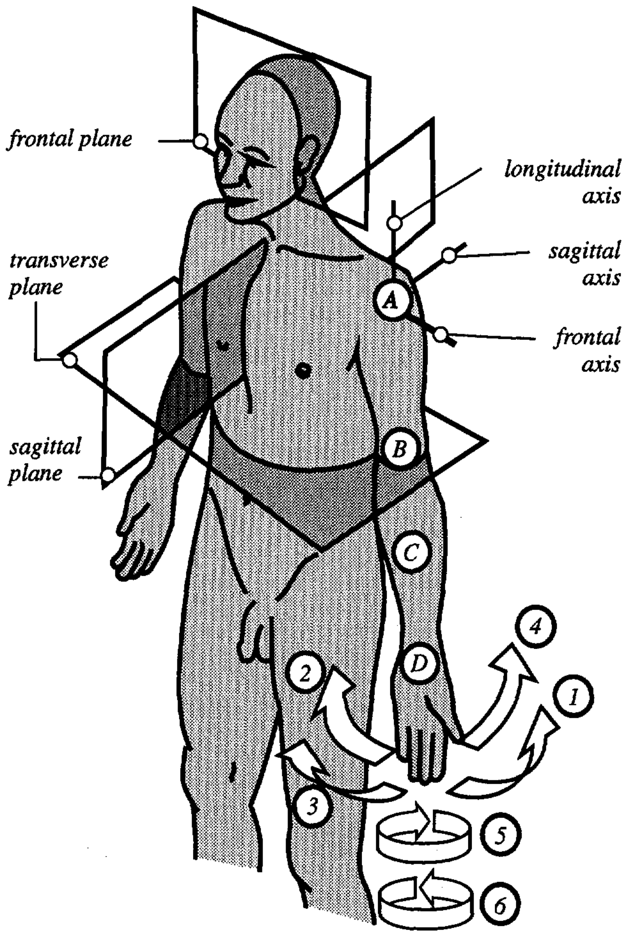


figure 3-2: The anatomical position, including the reference planes and direction of rotation (see text for explanation of indices).

Due to the anatomy of joints, bones can rotate relative to one another. In kinesiological studies such rotations are only defined in three orthogonal planes (see figure 3-2), i.e. the frontal plane, the sagittal plane and the transverse plane. Rotations in these planes occur around the sagittal axis, the frontal axis and the longitudinal axis, respectively. Moreover, only rotations which start from the anatomical position are valid. In the anatomical position the subject is erect, and the upper limbs hang down along the sides of the trunk with the thumbs pointing outwards.

From this point of view, upper arm movements can be divided into: abduction (fig 3-2: A1) and adduction (A2) - around the sagittal axis -; anteflexion (A3) and retroflexion (A4) - around the frontal axis - ; and internal rotation (A5) and external rotation (A6) - around the longitudinal axis -. This joint therefore has three degrees of freedom. In the elbow joint three bones articulate: the distal part of the humerus and the proximal parts of the radius and the ulna. Articulation of humerus and the ulna leads to one degree of freedom, namely rotation around the frontal axis: flexion (B3) - extension (B4). Articulation of the humerus and the radius, and the radius and the ulna in conjunction with the distal radio-ulnar joint allows the forearm to rotate around a (quasi) longitudinal axis (see paragraph 3.3), resulting in supination (C6) - pronation (C5). The carpal bones can perform complex movements relative to one another (see e.g. Savelberg, 1992, for a detailed description); moreover, these bones can move relative to the distal part of the ulna. These movements give the wrist joint two degrees of freedom; the hand can be rotated around a sagittal axis: radial abduction (D1) - ulnar abduction (D2), and around a frontal axis: palmar flexion (D3) - dorsal (volar) flexion (D4). Positioning of the hand relative to the shoulder involves no less than seven degrees of freedom (3 + 1 + 1 + 2).

The metacarpal bones articulate with the distal row of the carpal bones. The carpometacarpal articulation of the thumb is called a saddle joint. This joint allows movements in two directions: abduction vs. adduction and flexion vs. extension. Due to this construction the thumb is able to oppose, i.e. place the pollicial pad opposite the pads of the other fingers. The carpometacarpal joints of the next three fingers are almost immobile, giving the palm its strength, while that of the little finger helps to adapt the palm to spherical surfaces. The other metacarpals are also placed such that they form a longitudinal hollow. The interphalangeal joints of the fingers allow flexion and extension. These joints are hinge like, so that the fingers move in the plane of their metacarpals, i.e. they converge in flexion.

The human hand represents a unique evolution for achievement of prehensile functions. Of particular importance is the improvement in the wrist and the acquisition of independent finger movements. The motility of the little finger together with the metacarpal hollow is important for prehension of larger objects like a tennis ball. The opposable thumb is critical for the realization of a precise and fully oriented grip, allowing prehension and manipulation of small objects (Napier, 1956).

To identify the positioning possibilities of the hand relative to the shoulder, the ranges of movement of the diverse joints have to be known. The most important study on the range of movements was performed by Dempster (1955), see table 3-1. In recent publications, e.g. Woodson et al., 1992 (p. 552), these data are still presented. It must however be noted that the ranges are not very precise. For instance, in one of the standard Human Factors books by Sanders and McCormick (1993), the data of Houy (1983) are presented. These data give different values for joint ranges. As in all cases, the method used to determine the ranges is of major importance (e.g. passive or active movements) Since joint ranges vary with the subject, it might be better to give only an indication of the range of movement with an accuracy of only 5° (see for instance Schnelle, 1964). The American Academy of Orthopaedic Surgeons (AAOS, see British Orthopaedic Association, 1966) and the International Standard Othopaedic Measurements (ISOM, see Russe and Gerhardt, 1975) give only general estimates, rather than specific standards. For orthopaedic surgeons it is suggested that, when examining a patient's range of motion, the opposite (i.e. healthy) extremity is perhaps the best 'normal' standard (British Orthopaedic Association, 1966; Boone and Azen, 1979) because of the wide variation in the degrees of motion among individuals of varying physical build and age groups.

table 3-1: Ranges of movement: mean (and std) in degrees (adults, male and female).

joint	movement	Dempster	Houy	Schnelle	AAOS*	ISOM**
shoulder	anteflexion	188 (12)	178 (10)	150 - 180	180	170
	retroflexion	61 (14)	58 (11)	50	60	50
	abduction	134 (17)	124 (10)	170	180	170
	adduction	48 (9)	51 (5)	-	75	75
	internal rotation	97 (22)	95 (12)	80 - 90	80	60
	external rotation	34 (13)	32 (9)	60	60	70
elbow	flexion	142 (10)	138 (7)	130 - 140	150	150
	extension	0 (0)	0 (0)	0	0	0
forearm	supination	113 (22)	107 (17)	70 - 85	80	90
	pronation	77 (24)	65 (13)	60 - 80	80	80
wrist	ulnar abduction	47 (7)	31 (5)	30 - 40	30	30
	radial abduction	27 (9)	22 (5)	20 - 30	20	20
	palmar flexion	90 (12)	68 (10)	60 - 90	80	60
	dorsal flexion	99 (13)	62 (9)	60 - 90	70	50

* *Data of the American Academy of Orthopaedic Surgeons, reprinted by The British Orthopaedic Association, 1966.*

** *Data of the International Standard Orthopaedic Measurements, see Russe and Gerhardt, 1975.*

In our experiments subjects who sat in a chair had to rotate a rotary control which was placed in the same sagittal plane as the shoulder of the hand used (see figure 4-4; in chapter 4 the experimental conditions will be described in detail). Turning a rotary control mounted on an immovable object does not involve all seven degrees of freedom. When the subject holds a knob, some of the degrees of freedom are coupled and others cannot be used. When the hand is coupled to the knob, the upper limb forms a closed kinematic chain. The general consequence of closing a kinematic chain is a reduction in the degrees of freedom (see Huson, 1974). Firstly, the wrist will act as a 'cardan joint', i.e. rotating movements of the arm will be conveyed to the knob. Depending on the position of the arm, the wrist joint will automatically undergo radial or ulnar abduction and/or palmar or dorsal flexion. The wrist movements are therefore completely dependent on the arm movements. In addition to this reduction, the position of the hand relative to the shoulder is also constrained in our experiments: the three-dimensional coordinates of the wrist relative to the shoulder are fixed. Consequently, the number of degrees of freedom of the arm will be reduced to two.

Since some degrees of freedom are coupled, the kinesiological definitions cannot all be applied in the analysis used in this project. A subject can rotate the knob clockwise by supinating his forearm (see paragraph 3.2). In the case of a fixed shoulder position relative to the knob, flexion of the elbow will be constant. In addition to supination (SUP), the subjects can also use the whole arm to rotate the knob; then the upper arm movements will be composed of anteflexion or retroflexion, abduction or adduction, and internal rotation or external rotation. These three degrees of freedom are directly coupled with one another, leaving only one degree of freedom. It is therefore useless to describe arm movements by means of these three components. In our study, the second degree of freedom is called 'combined arm rotations' (CAR, see paragraph 3.3). Consequently, when rotating a knob as in our experiments, the subject has only two degrees of freedom: CAR and SUP. In figure 3-3 these two degrees of freedom are depicted in a mechanical model. The figure in the middle represents a model of the arm in which both joints are in the 0° position. The two figures at the top illustrate the minimum and maximum CAR positions (SUP remains 0°). The two figures at the bottom illustrate the extremes of SUP.

Analysis of these two degrees of freedom reveals that CAR forms the basis of SUP. When a subject grasps the knob, the forearm will be in line with the shaft of the box to which the rotary controls are attached (see figure 4-4). When the subject performs a negative CAR rotation, the upper arm will be 'abducted', and consequently the forearm will be out of line with the shaft. The possibilities of rotating the knob by supination remain the same: the basis of SUP is displaced but due to the cardan construction of the wrist, SUP can still be applied to the shaft of the knob. For this purpose, however, we assume that the cardan construction of the wrist will always allow the rotation of the arm to be conveyed to the rotary control. So the range of movement of SUP can be added to the range of movement of CAR. Consequently CAR and SUP are commutative, i.e. the end position is not dependent on the order of the two rotations. In figure 3-4 the commutative relationship of CAR and SUP is shown: whether the hand is first rotated 45° by SUP (figure 3-4a to b) followed by a CAR rotation of -45° (b to d), or the CAR rotation (a to c) comes first and then the SUP rotation (c to d), the end position of the hand will be the same.

In our experimental situation the total range of combined arm rotations (CAR) is about 180°, i.e. outwards through 60°, resulting in a clockwise rotation of the knob, and inwards through 120°, resulting in a counterclockwise rotation. This range is determined by passive structures, such as the ligaments and fibrous capsule of the shoulder joint. We positioned the subjects such that anteflexion of the upper arm was 45° in order to keep the trunk from restricting the positive limit of the range of movement of CAR. This would, for instance, be the case when the upper arm hangs down near the trunk. The range of movement of CAR will be different for every position of the wrist relative to the shoulder, e.g. when the wrist is in the same frontal plane as both shoulders and at shoulder height, the range of motion will

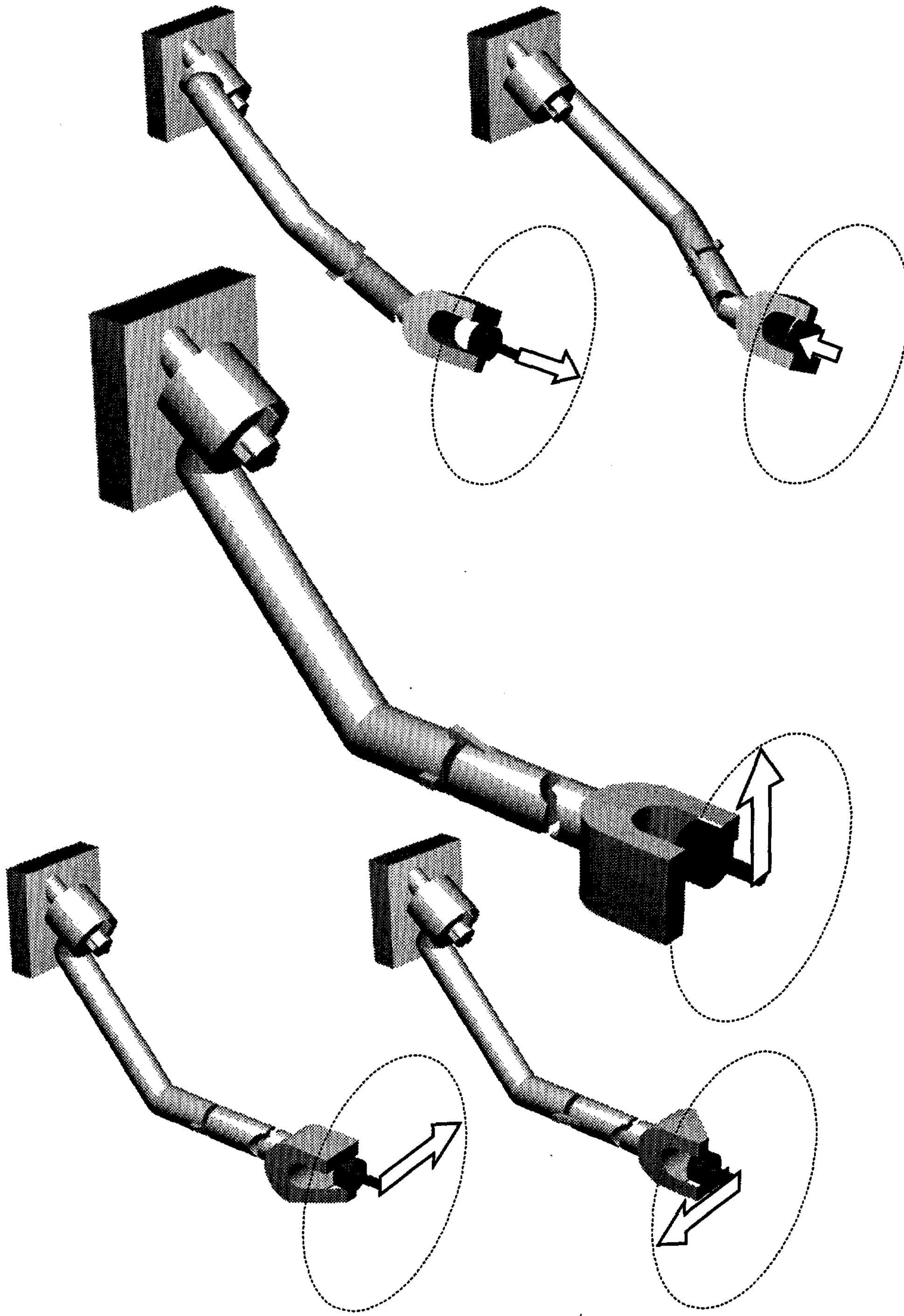


figure 3-3: The central figure represents a mechanical model of the arm with two degrees of freedom: CAR *and* SUP*. Both are in the neutral position, i.e. 0°. The two figures at the top show the minimum and maximum* CAR *angles. The figures at the bottom represent the two extreme positions of* SUP.

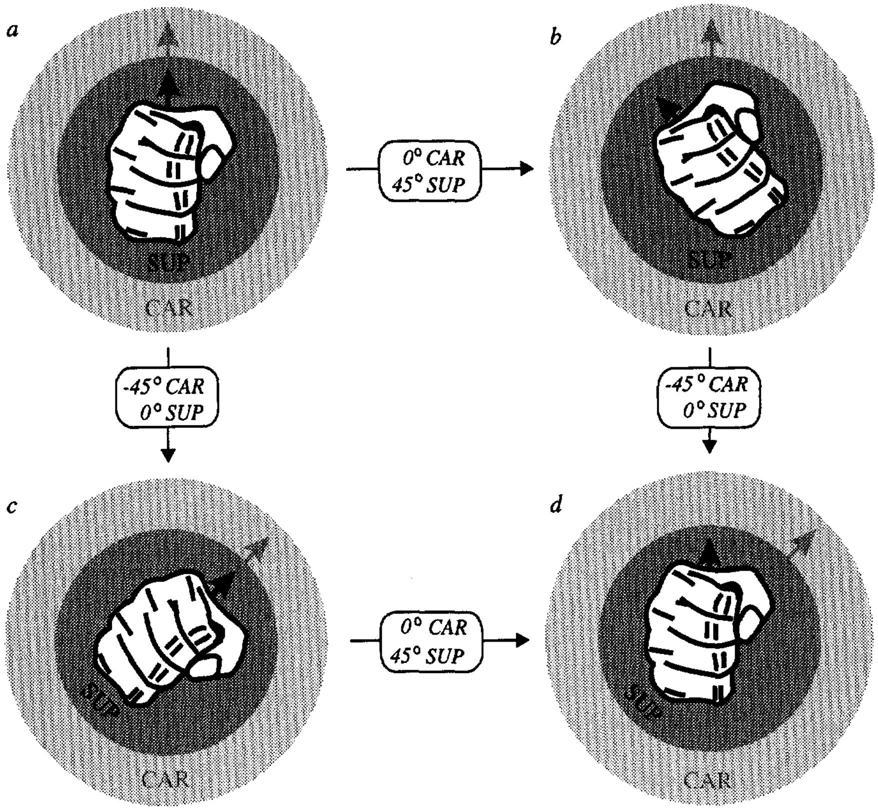


figure 3-4: The commutation of CAR *and* SUP. *In each figure the orientation of the hand is shown, the inner circle indicates the basis of* SUP, *which will be altered when* CAR *is changed. In case of* SUP *rotation, the fist will rotate relative to the inner circle. A* CAR *rotation results in a rotation of the inner circle. The effect of* CAR *is shown in the outer circle. In figure a the* SUP *and* CAR *angles are 0°; in figure b the* SUP *angle is 45°, while the* CAR *angle remains 0°; in figure c the* CAR *angle is -45° (consequently the basis of* SUP *is changed), while the* SUP *angle is still 0°; in figure d the* SUP *angle is 45°, and the* CAR *angle is -45° (consequently the orientation of the hand is the same as in figure a).*

only be about 40°. The explanation for this alteration in the range of movement is the change in the position of the upper arm relative to the scapula. Due to the construction of the shoulder joint, including all relevant ligaments, the range of movement will decrease markedly.

Examination of the muscles involved (see table 3-2) reveals that the two movements, SUP and CAR, may be - on the kinesiological level - nearly independent of one another (only the biceps contributes to both). It must, however, be stated that the effects of the muscles described in the table are not valid in daily life situations. The underlying assumptions of schemas like table 3-2 are that the subject starts in the anatomical position and that no other external forces will be involved. In our experiments neither assumption holds.

table 3-2: Scheme of the muscles acting on combined arm rotation (CAR) *by upper arm movements: anteflexion, retroflexion, abduction, adduction, external rotation and internal rotation, and forearm movements* (SUP)*: pronation and supination.* • = *effect of the muscle working alone,* o = *effect of the muscle working in combination with other muscles.*
Source: Rozendal et al., 1983, p. 325-326.

		CAR						SUP	
		ant	ret	abd	add	ext	int	pro	sup
shoulder and trunk	m. supraspinatus			•					
	m. infraspinatus					•			
	m. teres minor					•			
	m. subscapularis				o		•		
	m. teres major		•		•		•		
	m. deltoideus pars clavicularis	•		o	o		o		
	m. deltoideus pars acromialis			•					
	m. deltoideus pars spinata		•	o	o	o			
	m. pectoralis major	•			•		•		
	m. latissimus dorsi		•		•		•		
upper arm	m. biceps brachii caput breve	o		o	o				•
	m. biceps brachii caput longum	o							•
	m. coracobrachialis	o			o				
	m. triceps brachii caput longum	o			o				
forearm	m. pronator teres							•	
	m. pronator quadratus							•	
	m. brachioradialis							o	o
	m. extensor carpi radialis longus								o
	m. supinator								•
	m. abductor pollicis longus								o
	m. extensor pollicis brevis								o
	m. extensor pollicis longus								o

For our knob-rotating tasks, the subjects did not start from the anatomical position. This will change the effect of the muscles involved. The joint(s) involved, however, will always be the same. Since CAR and SUP are motions in two separate joints (the shoulder and the radioulnar joints of the forearm, respectively), the muscles involved will be different for each movement. Only the biceps muscle will contribute to both.

Next, external forces can be introduced. Since the arm, while rotating the knob, must be described as a closed kinematic chain, other external forces are introduced. Rotation, however, is not the result of activation of only the SUP muscles or activation of only the CAR muscles. Let us consider the model of an arm in figure 3-5. In this simple model the hand is attached directly to the forearm (both are dark grey). The forearm can rotate relative to the upper arm (light grey). Also the upper arm can rotate, around the axis, relative to the trunk (white). The trunk is considered to be fixed globally. In this model there are also four muscles. Two muscles induce the +SUP and -SUP movements (muscles 1 and 2), the other two induce +CAR and -CAR (muscles 3 and 4). When muscle 3 is activated, this muscle will contract, inducing a positive moment of the upper arm. If there is rotational friction along the shaft of the control, the forearm will not rotate, and muscle 1 will become elongated. Activation of muscle 3 will only result in rotation of the control if muscle 1 prevents elongation. This can be achieved by activating muscle 1 to induce, for instance, an isometric contraction. The same applies for all other muscles. Therefore, in case of rotation consisting only of SUP, i.e. the CAR angle remains constant, the muscles which induce CAR must also be activated. From this we can conclude that the functions of muscles cannot be distinguished as specifically as is presented in table 3-2. When a knob is rotated by CAR movement, and the biceps muscle is assumed to be non-existent, the muscles of the shoulder will be active. The forearm muscles will also be statically active because of the grasping hand and maintenance of the SUP angle. Also when the knob is rotated by SUP only, the forearm muscles as well as the shoulder muscles have to be active. In this latter case the activity of the shoulder muscles will be static.

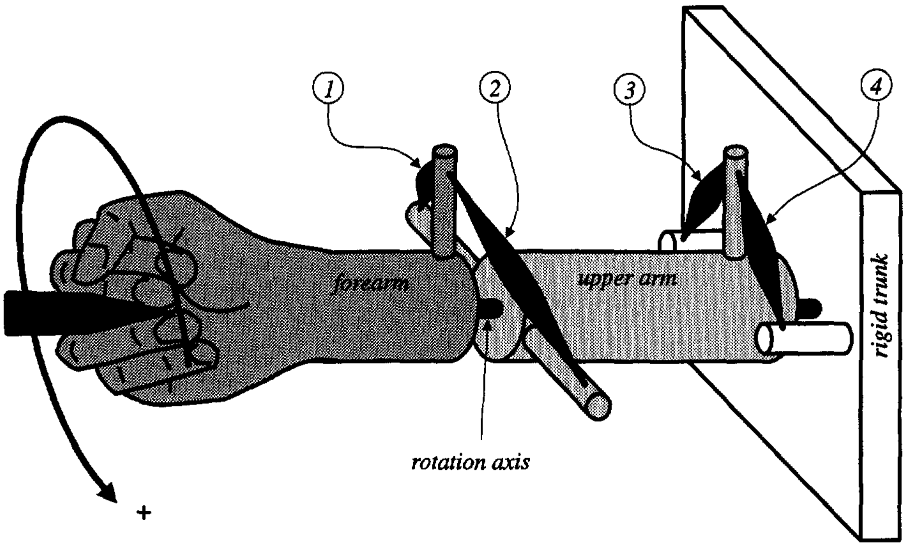


figure 3-5: A simple model of the arm with the muscles which induce SUP *and* CAR *movement. See text for further explanation.*

In addition to these two degrees of freedom, the subject is, of course, able to increase the possibilities for rotation of the knob by using movements other than supination or combined arm rotation. First he can use extensive shoulder movements to gain further rotation. The subject can even bend the trunk sidewards. Moreover, movement of the fingers can be used. To eliminate these possibilities, the subjects are asked to perform rotation with arm movements only (i.e. no trunk movements; remain seated in the upright position) and to hold the knob firmly.

3.3 Supination

3.3.1 Definition

In literature on anatomy, human motion is always defined as starting from the anatomical position (see figure 3-2). In this position, as said, the upper limbs hang down along the sides of the trunk with the thumbs pointing outwards. For most movements this results in inadequacy when the standardized anatomical terms for human movement are used (Pronk, 1991 p.31). For instance, when the upper arm is anteflexed 90°, followed by rotation around a vertical axis through the shoulder joint, none of the anatomical terms can be used to describe this motion (see also paragraph 3.4).

Therefore, the term supination has to be made operational. The anatomical definition of supination, however, can be used in studies of human motion without alterations. This is because supination is defined locally, relative to the ulna and not a global coordinate system.

Joseph (1982, p. 370) defines pronation starting from the anatomical position as "the movement in which the head of the radius rotates and its lower end crosses over the medial side of the ulna so that the hand faces backwards. Supination is the restoration of the pronated forearm to the anatomical position in which the radius lies alongside the ulna and the hand faces forwards." Supination is defined as a local rotation of the radius along the ulna.

In this study the term supination will be used to mean: rotation of the radius in the distal and proximal radioulnar joints, resulting in local rotation around an axis which is fixed relative to the ulna (see figure 3-6). Negative supination equals pronation.

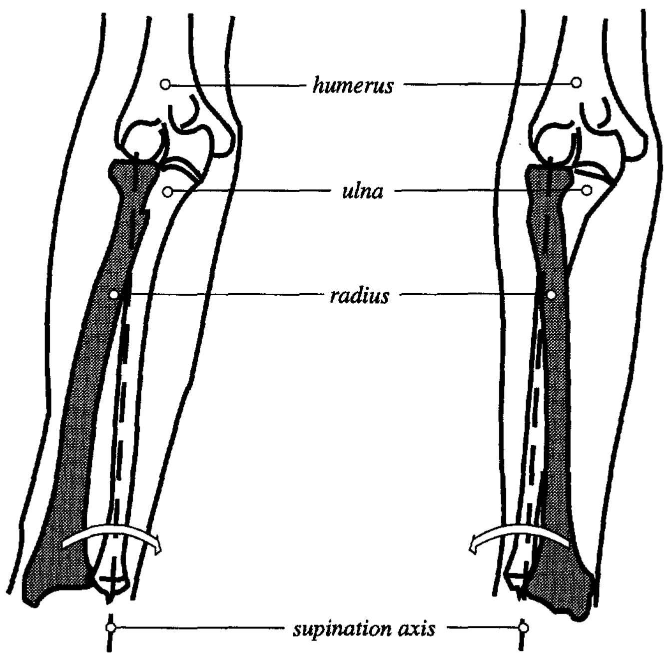


figure 3-6: Frontal view of the right forearm, starting with pronation, from the anatomical position. The reversed movement (from right to left) is called supination. The two positions shown are the two extremes.

3.3.2 Mathematical description

If the arm is represented by three vectors (see figure 3-7):
- 1- the upper arm ($\vec{ua}$), from the shoulder joint to the elbow,
- 2- the forearm ($\vec{fa}$), from the elbow to the ulnar side of the wrist, and
- 3- the wrist ($\vec{wr}$), from the ulnar side to the radial side of the wrist,

then the supination angle can be determined.

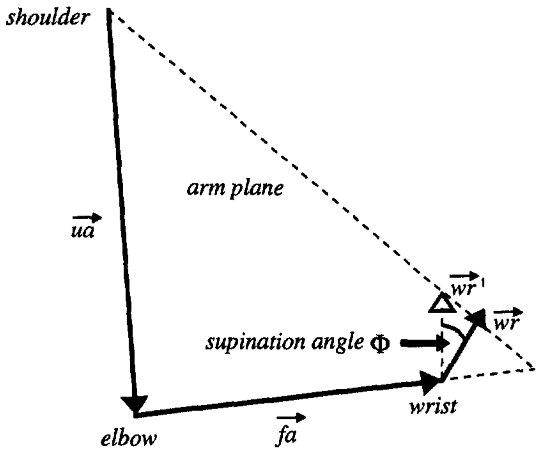


figure 3-7: Vectorial representation of the arm and SUP *angle.*

If $\vec{fa}$ coincides with the axis of supination, the supination angle (ϕ) will be the angle between the wrist vector ($\vec{wr}$) and its projection ($\vec{wr}'$) on the plane of the arm as defined by $\vec{ua}$ and $\vec{fa}$. Given the 3D vectors for the shoulder ($\vec{s}$), the elbow ($\vec{e}$) and the two wrist points ($\vec{w}_2, \vec{w}_1$), the other vectors can be determined:

$$\vec{ua} = \vec{e} - \vec{s}$$

$$\vec{fa} = \vec{w}_1 - \vec{e} \qquad (1)$$

$$\vec{wr} = \vec{w}_2 - \vec{w}_1 \qquad (2)$$

and the angle of supination can be calculated from:

$$\phi = 90 - \arccos\left(\frac{(\vec{ua} \times \vec{fa}) \cdot \vec{wr}}{|\vec{ua} \times \vec{fa}|\ |\vec{wr}|}\right) \qquad (3)$$

The angle of supination (ϕ) will be zero when the distal end of the radius (w_2) is located in the plane formed by the upper arm and the distal end of the ulna (w_1), i.e. when the thumb is 'up' and in the plane defined by the two arm segments. This method implies that the angle of supination cannot be determined when the elbow is fully extended.

3.4 Combined arm rotations

3.4.1 Definition

The second way to rotate the knob in our study is by using upper arm movements. These movements can be described by the kinesiologically accepted terms: internal rotation - external rotation, anteflexion - retroflexion and abduction - adduction. These rotations, however, are not interchangeable as far as sequence is concerned (i.e. not commutative): it is essential to know the order of the rotations, which makes it hard to interpret them. Moreover, these rotations are coupled to each other and may therefore not be interpreted as isolated events. Therefore it was decided that this manner of rotating a knob would be described by one term, namely combined arm rotations.

We define combined arm rotation as the angle between the plane of the arm, formed by shoulder, elbow, and wrist, and the vertical plane through the shoulder and wrist (see figure 3-8). A rotation resulting in adduction of the upper arm, i.e. a clockwise rotation of the knob with the right arm is defined as positive.

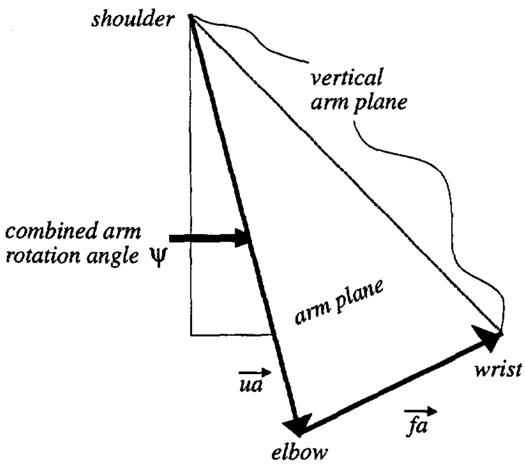


figure 3-8: Vectorial representation of the arm and CAR *angle.*

3.4.2 Mathematical description

The plane of the arm can be determined by using the two arm vectors, the upper arm and the forearm ($\vec{ua}$ and $\vec{fa}$), and the vectors for the shoulder ($\vec{s}$). Given the vertical vector through the shoulder ($\vec{s}_z$) and the vector from the shoulder to the wrist and adding the upper arm vector ($\vec{ua}$) to the forearm vector ($\vec{fa}$), the vertical plane through the shoulder and the wrist can be determined. The angle between these two planes, defined as the combined arm rotation (ψ), will be:

$$\psi = \arccos\left(\frac{(\vec{ua} \times \vec{fa}) \cdot \quad \vec{s}_z \times (\vec{ua} + \vec{fa})}{|\vec{ua} \times \vec{fa}| \quad |\vec{s}_z \times (\vec{ua} + \vec{fa})|}\right) \qquad (4)$$

The combined arm rotation (ψ) will be zero when the elbow (e) lies in the vertical plane through the shoulder (s) and the distal end of the ulna (w_I). This also implies that the angle of combined arm rotation cannot be determined when the elbow is fully extended.

3.5 Technique

3.5.1 Motion recording system

Forearm rotations are a point of interest in several areas of scientific study, such as neuroscience (Lacquaniti and Soechting, 1982), orthopaedics (Morrey et al., 1981), biomechanics (Langrana, 1981) and ergonomics (Marras and Schoenmarklin, 1993). Up to now, many methods have been developed for recording forearm rotations; these methods include the use of visual observation (Davis, 1977), ordinary goniometers (Boone and Azen, 1979), gravity goniometers (Laupattarakasem et al., 1990), electrogoniometers (Chao, 1980), biplanar videotaping (Langrana, 1981), and 3D measurement (Safaee-Rad et al., 1987). Also for other arm movements, too, diverse motion registration systems can be used (e.g., goniometers, biplanar videotaping, and active marker systems). In a recent publication (Mochimaru and Yamazaki, 1994) a motion registration method based on image processing was described. With this method no markers are used, the subject can move without restraints. The accuracy of finger motions was within 2°. The only problem was the processing time: for a hand model, consisting of 21 segments, each frame took 3-5 min. In this chapter a new, accurate (error less than 2°), and valid method for assessing arm rotation angles is described.

Because of advances in technology, methods for determining this angle have gradually become more precise, quicker, and easier. Nowadays, special motion registration systems are available for determining human motion accurately. In our experiments we used the OPTOTRAK 2010 opto-electronic motion registration system (see paragraph 4.5 for a

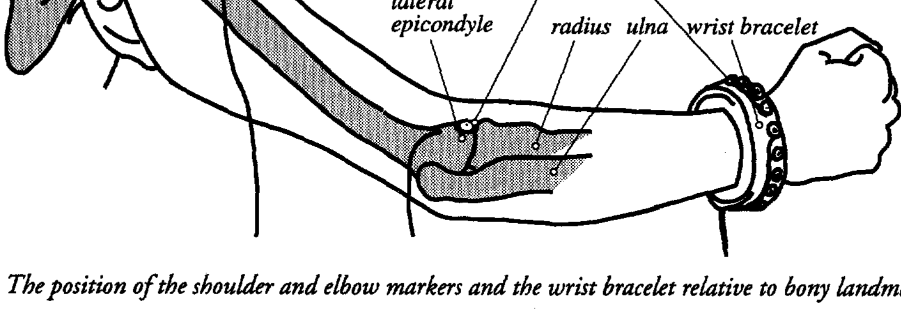


figure 3-9: The position of the shoulder and elbow markers and the wrist bracelet relative to bony landmarks.

description of this system). This system measures the position of infrared emitting diodes (IREDs), placed as markers on the body. A major problem, however, of most of the opto-electronic motion registration systems is the fact that some markers lie outside the field of view of the cameras. Thus the 3D positions of these markers are lost, and joint rotation cannot be determined continuously. When one is assessing forearm rotations, it is impossible to find a position in space that would allow an observer to see a point on the wrist in every supination angle at any time. Since it is necessary to have at least two wrist points in constant view of the cameras, these systems can only be used in limited situations.

An easy way to solve the problem of the disappearing marker would be to use more cameras, so that each marker would be in constant view of some camera. Since this solution would require a major investment, we found another way. Our solution consists of a rigid wrist bracelet in which wrist points are defined locally. When the position of this bracelet in the global coordinate system is known, the wrist point positions, which are known in the local coordinate system of the bracelet, can be determined, and thus the supination angle can be calculated.

3.5.2 Marker positions

Because of the definitions of supination and combined arm rotation used here, the most correct positions of the markers would be at the centre of rotation within each joint. Ideally the shoulder marker should be placed at the centre of rotation of the head of the humerus; the elbow marker should be at the junction of the elbow flexion axis, the longitudinal rotation axis of the humerus, and the supination axis; the first wrist marker should lie on the axis of supination at the head of the ulna; and the second wrist marker, somewhere on the distal side of the radius. Since it is not feasible to fasten the markers directly onto bony landmarks or at the rotation centres, the shoulder marker is fixed above the major tubercle of the upper arm, and the second marker is placed on the elbow above the lateral epicondyle of the upper arm (see figure 3-9). When the subject moves the arm into an extreme position (by using pronounced combined arm rotation), this marker can disappear from the cameras. An easy solution is placement of a 'butterfly' on the elbow. The butterfly contains seven IREDs, see figure 3-10, the centre marker being placed on the lateral epicondyle of the upper arm. The position of each marker relative to the others is known. In case the central marker cannot be seen, its position can easily be determined from the positions of three of the lateral markers.

Because the wrist markers will frequently disappear from the cameras, the two wrist points are defined in terms of the local coordinate system of a wrist bracelet, which is located on the distal part of the forearm (see paragraph 3.5.3); its position in the global coordinate system can always be determined. An easy way to define the two wrist points is to place the first wrist point at the centre of the bracelet. However, because of the distance from the first wrist point to the actual supination axis, this will increase the inaccuracy of the method (up to 7°, see reproducibility, paragraph 3.6.1). Therefore, we chose to place the first wrist point as precisely on the supination axis as possible. The second wrist point is on the distal side of the radius.

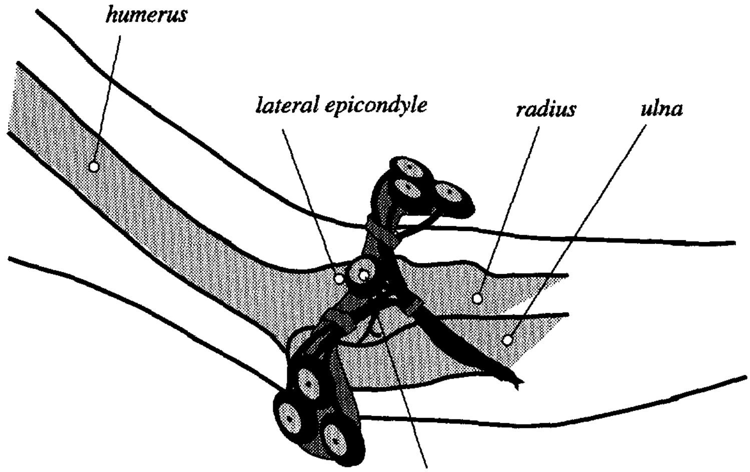


figure 3-10: The 'butterfly' which is attached onto the lateral side of the elbow. The centre of the butterfly gives the position wanted.

3.5.3 Wrist bracelet

The bracelet (see figure 3-11) consists of an aluminium ring; the outer diameter is 100 mm, the inner diameter is 90 mm, the width is 25 mm, and the weight 150 gr. To fix the bracelet onto the distal part of the radius, an inflatable rubber tube functions as a cuff inside the bracelet. The internal pressure in the tube (about 0.7 bar), needed to fix the bracelet to the arm, is far less than the diastolic blood pressure, indicating that no occlusion of blood flow will occur. On the outside of the bracelet 18 equal facets have been made at successive angles of 20° to each other. The valve of the tube passes through one facet, while IREDs are glued to the other 17 facets. In this way, at least three markers will always be in view of both cameras. The vector, in the local coordinate system of the bracelet, to each IRED ($\vec{b}_{i_0}$, $i = 1, \ldots, 17$, $n = 0$, indicating the local coordinate system) is known.

The bracelet has to be fixed to the radius, but not the ulna. To keep motion of the head of ulna from disrupting the position of the bracelet relative to the radius, a stiff aluminium plate is wrapped around the head of the ulna, between the tube and the skin (see figure 3-12). The tube is then fixed to the radius and the aluminium plate. Consequently, the head of the ulna will not influence fixation of the bracelet to the radius.

3.5.4 Supination axis

The position of two wrist points in the local coordinate system of the bracelet can be determined by the following procedure. First the axis of supination is determined. This axis is intersected by a plane defined by the bracelet. This point of intersection, which represents the previously mentioned first wrist point, is given by w_I. The second wrist point, given by

w_2 , lies 50 mm from the first wrist point within the local coordinate system of the bracelet. Consequently, this point is defined by the same local coordinate system, located on the distal side of the radius, as the first wrist point.

figure 3-11: The wrist bracelet on the distal part of the forearm.

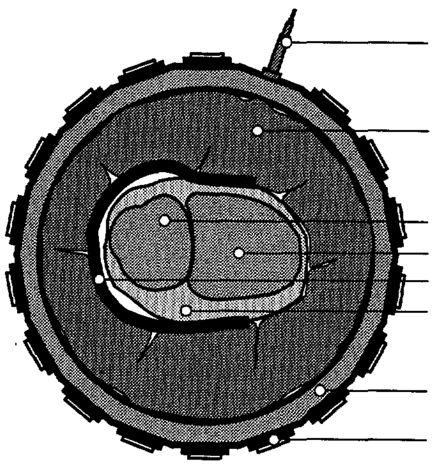


figure 3-12: Placement of the wrist bracelet on the forearm (transversal cross-section). Due to the aluminium plate, the bracelet is only secured to the radius, and not the ulna.

As mentioned before, the supination axis is defined as the axis around which the radius rotates in relation to the ulna. To determine the position of this axis of supination, a special trial is performed. In this trial, the axis of supination is determined in the global coordinate system, because it is not possible to do this in the local coordinate system of the ulna. If, however, the position of the ulna remains constant, the global coordinate system of the ulna can be substituted for the local coordinate system. Therefore, the subject has to sit in a chair and put his arm on an armrest, on which a block with a longitudinal groove is placed. The upper arm hangs straight down, the elbow is flexed 90°. The subject has to place the ulna into the groove in the block. Since the dorsal margin is directly below the skin, the subject can use tactile information to check for movement of the ulna relative to the block. Under these conditions pure supination can be performed; the ulna does not move relative to the block, i.e. the global coordinate system.

In the initial position, the subject has to hold his hand in the sagittal plane, with the thumb pointing upwards. The task is to perform pronation followed by supination. Neither rotation is allowed to be maximal, because maximal forearm rotation often induces movement of the ulna relative to the block. The total range of rotation is therefore about 90°. This motion is sampled by the system to determine the rotation axis – the supination axis – of the bracelet.

In this trial, the transportation of the bracelet consists only of rotation around the supination axis. One method for describing the change in position of the bracelet is to use a helical axis. If an object is considered rigid and its movement between two subsequent positions is taken to be a screw motion, such a motion can be described by the position of the screw or helical axis, the angle of rotation about this axis and the translation along this axis (Spoor and Veldpaus, 1980). In case of a movement that consists only of rotation, the helical axis will be the same as the rotation axis; in other words, the translation component along the helical axis is zero. In the situation described above, the change of position of the wrist bracelet is due only to rotation of the radius relative to the ulna; for supination, no translation component is expected, and the helical axis will be the same as the supination axis. The method is most exact when the two positions needed to determine the helical axis form an angle of about 90° with respect to each other. Therefore, the two outer positions of pronation and supination are used to determine the helical axis.

Spoor and Veldpaus (1980) describe a method for calculating the helical axis based on the spatial coordinates of the markers. Their method consists of two parts. The first is determination of the rotation matrix and the translational vector, the second is determination of the helical axis.

In our study the first step was carried out by the program RIGID (Northern Digital Inc.). This program calculates for each frame (n) the transformation of the rigid body of the bracelet from the local coordinate system (n = 0) to the global coordinate system. Consequently the position of each marker (i = 1, ..., 17) can be determined:

$$\vec{b}_{i_n} = R_n \vec{b}_{i_0} + T_n \qquad (5)$$

The output of this program consists of a rotation matrix (R_n) and a translation vector (T_n) for each frame (n). The rotation matrix and translation vector, which are needed as input for the second step, must, however, describe the transformation between two subsequent positions (n and n+1). These can be easily calculated as:

$$R_{n \to n+1} = R_{n+1} R_n^{-1}$$

$$T_{n \to n+1} = T_{n+1} - R_{n \to n+1} T_n$$

The rotation matrix and translational vector are used as the input for the second part of the method of Spoor and Veldpaus (1980). The outcome of the second step is the helical axis, i.e. the axis of supination.

3.5.5 Wrist points

As described earlier, the vector to the first wrist point ($\vec{w}_{1_0}$), in the local coordinate system of the bracelet (n = 0), will be defined by the point of intersection of the supination axis and the plane of the bracelet. The frame used to determine the position of the plane of the bracelet is taken from the start of the trial (n = 1). The plane of the bracelet, in the global coordinate system, can be determined by using bracelet vectors $\vec{b}_{1_1}$, $\vec{b}_{7_1}$ and $\vec{b}_{13_1}$ (three equidistant markers of the bracelet; see figure 3-13).

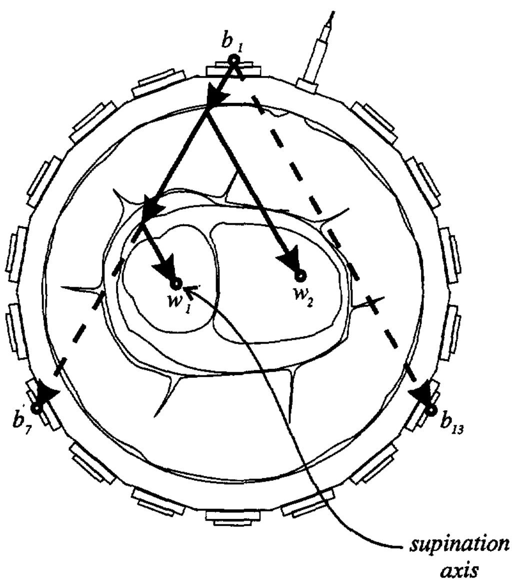


figure 3-13: Representation of the two wrist points in the local coordinate system of the bracelet.

With the output of the program RIGID, the actual positions of the three needed bracelet IREDs are determined (equation 5). The vector to the intersection point, $\vec{w}_{1_1}$, can be described bt the vectors ($\vec{b}_{7_1} - \vec{b}_{1_1}$) and ($\vec{b}_{13_1} - \vec{b}_{1_1}$), The contribution of each of these two vectors is given by the scalars λ_1 and μ_1. The second wrist point also lies in the plane of the bracelet, above the first wrist point. This wrist point can be described locally with the scalars λ_2 and μ_2.

If the parameters λ_i and μ_i (i = 1, 2) are known and the actual positions of the three bracelet IREDs within a specific frame are known, the two wrist points can be determined within that frame (n):

$$\vec{w}_{i_n} = \vec{b}_{1_n} + \lambda_i (\vec{b}_{7_n} - \vec{b}_{1_n}) + \mu_i (\vec{b}_{13_n} - \vec{b}_{1_n}) \qquad (i = 1,2)$$

which solves equation (1) and (2); consequently, the supination angle (ϕ) in equation (3) and the combined arm rotation angle (ψ) in equation (4) can be determined.

3.5.6 Calibration

The neutral position of supination is defined as the initial position of the forearm during the special trial (see paragraph 3.5.4): the hand and arm in a sagittal plane and the thumb pointing upwards. In this position the supination angle is defined as $\phi = 0$. During this trial the initial posture of the arm is also used to determine the neutral position of the combined arm rotations, i.e. $\psi = 0$.

At the start of this trial two wrist points are defined. When calculating the angles, the positions of the shoulder and the elbow also have to be taken into consideration (see equations 3 and 4). The two markers, indicating the position of the shoulder and the elbow, are fixed to the body. Consequently, due to the skin and muscles, these marker positions will deviate from the actual desired positions. In all cases this will result in a systematic difference between the calculated and defined angles. Correction for this deviation is calculated from the initial position used for the special trial (and controlled by the investigator). In this trial the supination angle and the combined arm rotation are defined as being equal to zero. The joint angles calculated initially, insofar as they differ from zero, can be considered the deviations. Therefore, for each assessment of supination and combined arm rotation, the initial calculated value is subtracted from the measured value.

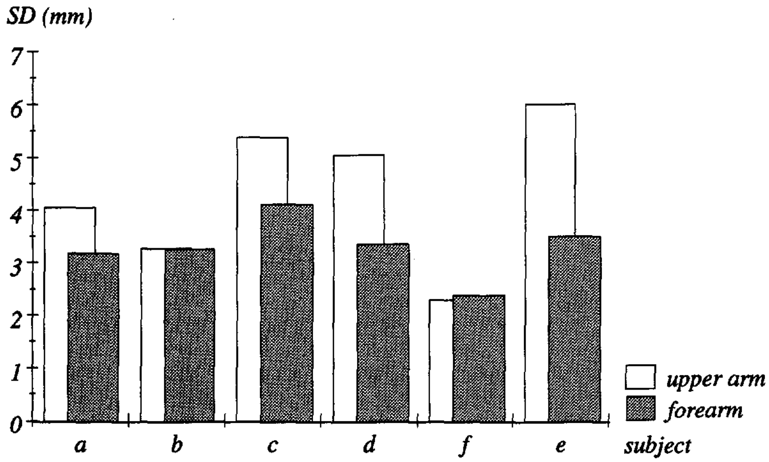


figure 3-14: The standard deviation (in mm) of the length of the upper arm and forearm of six subjects while performing rotation tasks.

3.6 Evaluation of the method used

3.6.1 Reproducibility

As mentioned before, the markers on the shoulder and elbow are fixed to the body. While moving the arm, the skin will be displaced relative to the bony landmarks due to either active or passive soft tissue deformation (Cappozzo, 1991). To determine the amount of marker displacement, the change in distance between the shoulder and elbow markers and between the elbow marker and the first wrist point was measured in six subjects (the distance between the two wrist points is, of course, always 50 mm). For each subject over 3000 trials were performed, consisting of arm movements like those used in the experiments. Figure 3-14 shows the standard deviation of the change in length for these subjects. The standard deviation ranges from about 2 mm to about 6 mm. Determination of the length of the forearm showed that the standard deviations are less than for the upper arm. The reason for this is that the wrist bracelet is well fixed and is not expected to move relative to the radius. The change in the length of the forearm is therefore due only to the change in the position of the elbow marker. Since the elbow marker and shoulder marker will move, the standard deviation of the length of the upper arm will be greater. The changes in length, however, are relatively small when compared to the length of the upper arm and forearm, about 28 and 24 cm, respectively, and will, therefore, have little influence on the CAR and SUP angle.

The reproducibility of the supination and combined arm rotation angles will depend mainly on the reproducibility of the first wrist point. To determine the reproducibility of the first wrist point, one subject was asked to perform the special rotation task five times. During these trials, the position of the bracelet relative to the forearm was not altered. Therefore, the position of the first wrist point, in the local coordinate system, was expected to be constant. Table 3-3 shows the x and y coordinates of the first wrist point in the local coordinate system of the bracelet. The root mean square of the distances of these points relative to the mean rotation point, was 1.5 mm.

table 3-3: The position of the rotation point of the bracelet in the local coordinate system (xy). This point was determined on a subject's forearm. RMS *is the root mean square of the differences between the individual and mean rotation points.*

trial nr	x [mm]	y [mm]
1	55.7	-11.8
2	56.9	-11.4
3	56.9	-13.1
4	57.6	-9.2
5	58.3	-11.6
RMS	1.5	

This position error for the wrist point determination will influence the outcomes of the supination calculations. The position error for the second wrist point is by definition the same as that for the first wrist point. Since the plane of the arm is very important for determination of both supination and combined arm rotation (see equations 3 and 4), the effect of these errors on the outcomes of the calculation of the angle will depend on the flexion angle of the elbow: owing to the position error for the wrist points, the position of the wrist vector as well as the orientation of the plane of the arm will be influenced. In the case of a flexion of 90°, there will be no influence, but when the elbow is nearly extended or fully flexed, the influence will be greater. When the position of the wrist points changes less than 1.5 mm, and the elbow angle changes within a range of 10° to 90°, this error will be less than 2° (see figure 3-15). Therefore it can be concluded that the supination angle and the combined arm rotation angle can be reproduced within a range of 2°.

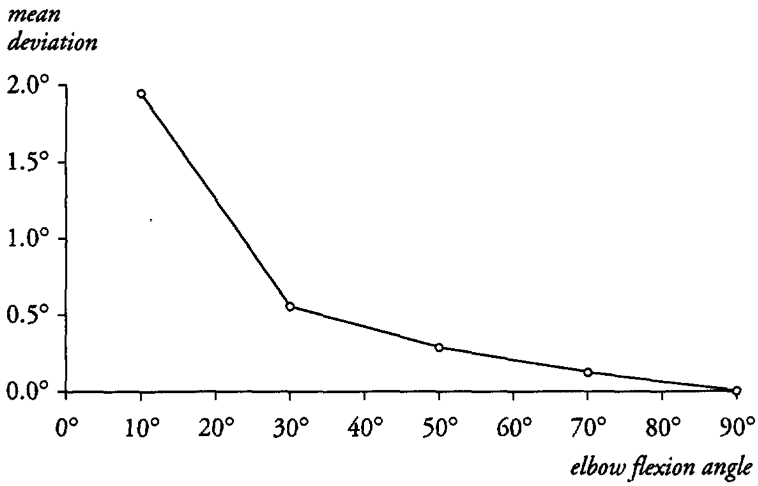


figure 3-15: The error of SUP *and* CAR, *depending on the angle of flexion of the elbow.*

In a small pilot experiment the effect of the correctness of the position of the first wrist point was assessed. It was found that when the first wrist point was simply defined as being in the centre of the bracelet (which makes the method of determining the position of the axis of supination superfluous), the difference between this method and the method described above (i.e., the first wrist point on the supination axis) could be as much as 7°. The size of this difference depends on the size of the wrist: the bigger the wrist, the larger the difference. Moreover, the size of this difference depends on the actual angle of supination, which makes it difficult to apply corrections.

3.6.2 Validity

The method is based on two assumptions that may turn out to be invalid:
- 1- the translation component of the helical axis is zero,
- 2- supination takes place around one fixed axis.

1- zero translation component
When using the helical axis to estimate the axis of rotation of the joint, the translation component along the helical axis was assumed to be zero. This assumption was demonstrated to hold if the bracelet was fixed to a stiff rod. In five independent trials, the mean translation component was only -0.10 mm, with a standard deviation of 0.14 mm. Subsequently, five subjects were asked to perform the trial in which the helical axis was determined. The mean translation component was -0.3 mm with a standard deviation of 1.5 mm. The comparison of this outcome with the accuracy of the OPTOTRAK system (0.5 mm) led to the conclusion that the translation component was negligible.

2- one fixed axis
In the technique described here, only one local fixed axis of supination is assumed. If this is not correct, the calculation of the wrist points, and therefore also the supination angle, will be erroneous. Since the forearm rotates in two distinct joints, the proximal and distal radioulnar joints, it is expected that the axis of rotation will be fixed in relation to the ulna. However, the size of the contact area in the two joints depends on the angle of supination (Hagert, 1992), which indicates that neither radioulnar joint is an ideal hinge joint. Theoretically, this will result in a change in the position of the axis of supination during supination.

When the bracelet was attached to the stiff axis with ball bearings at both ends, the fluctuation of the rotation point within one trial was determined. Between each two subsequent frames, the location of the rotation point of the wrist bracelet was calculated. Since the axis remained fixed in relation to the global coordinate system, this point was expected to be constant in the global coordinate system. The root mean square of the differences between the calculated 3D position and the mean assessed 3D position was 0.4 mm. Comparison of this value with the accuracy of the OPTOTRAK system (less than 0.5 mm) indicated that, in case of an axis with ball bearings, the assumption holds true.

To see whether the assumption of one fixed axis holds in the experimental situation, the following experiment was carried out. With the ulna fixed in the groove of the block, six subjects performed a forearm rotation (about 0.5 Hz). The positions of the IREDs were read at a sample frequency of 25 Hz. In the range between outer pronation and outer supination, the supination axis was determined in subsequent frames. In addition, a helical axis was determined using only the two outer positions (resulting in the supination axis used in the calculations). Each axis, when intersected by the plane of the bracelet, would result in a locally defined wrist point. In the case of a constant supination axis relative to the ulna, this position would not deviate from the point calculated by using only the two outer positions. The root mean square of the distance between the continuously determined and the local wrist points was 0.7, 1.3, 1.3, 1.4, 1.7 and 1.9 mm, respectively.

These values are all greater than 0.5 mm (i.e. the accuracy of the system). Therefore it must be concluded that the helical axis changed position during forearm rotation, and consequently that the second assumption should be invalidated. However, since the root mean square values, compared with the reproducibility of the rotation point, were within an acceptable range, it may be concluded that the assumption of one fixed axis is reasonable and therefore can be used. It can also be argued, in view of the accuracy needed for our analyses of arm rotations, that the validity of the method is quite sufficient.

3.7 Conclusion

The method reported here enables us to determine the angle of supination through the use of an opto-electronic motion registration system. To determine the combined arm rotation angle, the 3D-positions of the shoulder, elbow and first wrist point need to be assessed. To determine the angle of supination a fourth marker position, called the second wrist point, is needed. During knob rotation, the two wrist points will frequently disappear out of the field of view of the cameras. To assess the position of these wrist points in the global coordinate system, a bracelet is used, and the two wrist points are defined in relation to this bracelet. The positions of these wrist points are reproducible to within 1.5 mm in the local coordinate system of the bracelet. When the positions of the shoulder marker and the elbow marker and the global coordinates of the bracelet are known, the angle of supination and the combined arm rotation angle can be calculated. Compared to the purchase of more cameras, the investment required is low. The results of this method have proven to be reproducible within two degrees of arc and are sufficiently valid.

4 Experimental situation

4.1 The choice of controls

In chapter 2 the (in)variability of human movements during object handling was discussed. One of the conclusions of that chapter was the fact that object characteristics will influence the way the object will be handled. The physical properties of the object and its location and orientation, relative to the user, play an important role in the movements of subjects (Jeannerod, 1981 and 1984; Weir, 1994). Marteniuk et al. (1987) showed that prehension was also influenced by the goal of the reach. When the requirements of accuracy remained constant, but the goal of the reach differed, different movement trajectories were demonstrated. Also Rosenbaum and colleagues (e.g., Rosenbaum et al. 1988, 1990 and 1992a) showed that the way a bar was grasped depends on the initial orientation as well as the rotational task that has to be performed. Therefore, in our experiments, the following features were used to describe the experiment:

- Physical aspects, i.e. the elemental perceptual features such as shape of the object to be rotated,
- Spatial characteristics, i.e. the location, distance and orientation of the control relative to the user,
- Goal of the task, i.e. what has to be done with the control (rotated clockwise or counterclockwise, how far).

These features can also be used to characterize controls, which are important components of products used to command and control mechanical processes, such as on/of, speed, direction, etc.

The aim of this study was to establish relationships between controls and the way they are handled, given the arm constraints. Since the three features seem to be of great importance, they will be used to describe the control. Moreover, the effects of changes in a property on the handling of the control will be examined.

In daily life countless controls can be found. It is, however, impossible to explore the effect of all the possible variations on the way the control will be used. Therefore, a selection of controls has to be made.

Most of the controls used in daily life are operated by (a part of) the hand. Only a few are used by the foot, for instance the pedals in a car. Therefore, for our research project, we were interested exclusively in controls operated by the arm. Since the exact registration of finger motions is difficult, we decided to study only controls that are grasped by the hand and fingers but are controlled by forearm and upper arm movements. This criterion leaves us with a significantly smaller collection of controls. This collection, however, still contains a variety of controls. For this study the next choice was continuous, non-multirotational controls, like the doorknob etc. But these controls occur in many forms with numerous details. In this study we intentionally chose to offer non-existing controls, i.e. abstractly styled, especially constructed controls. Furthermore, it was decided that rotational arm movements should be measured in an experimental situation. The basis for these two choices was that otherwise cognitive influences, such as habits evoked by the design (Gelderblom, in press), can be expected to influence the way in which a control is handled.

For these experiments three different kinds of control were used: the O-, T- and L-knob as already explained in Chapter 1. These knobs differed mainly in their shape. In the next section the physical characteristics of the three controls will be described. Later on in this chapter the location of the controls will be described. In almost all experiments the location remained the same, only the orientation of the control, the shape of the control, and the rotational task will be varied systematically. This part will be described in chapters 5 and 6.

The O-knob was a cylindrical knob (see figure 4-1a). The dimensions were: diameter 4 cm, height 2.5 cm. The diameter of the axis was 1.5 cm. These dimensions enable the subjects to grasp the knob in a comfortable grip; they could also easily grasp the knob with the whole hand (see figures 4-1b and c). This knob was made of hard rubber. The main property of this knob was that, due to its shape, the orientation of this knob did not alter when the knob was rotated.

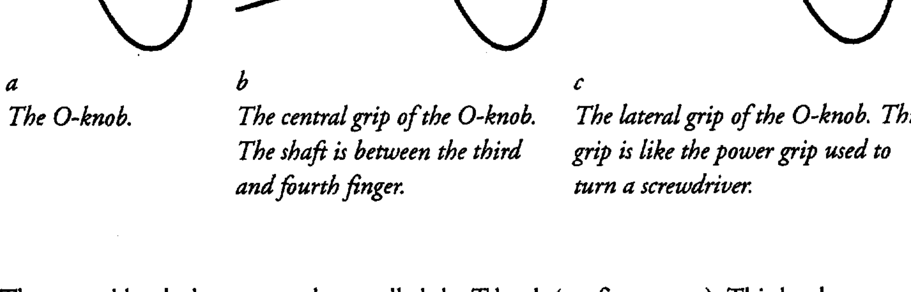


figure 4-1: a *The O-knob.*

b *The central grip of the O-knob. The shaft is between the third and fourth finger.*

c *The lateral grip of the O-knob. This grip is like the power grip used to turn a screwdriver.*

The second knob that was used was called the T-knob (see figure 4-2a). This knob, or handle, was also cylindrical, but the cylinder was perpendicular to the axis. The length of the knob was 10 cm, the diameter 2.5 cm. The axis of rotation was placed in the middle of the knob, the diameter of the axis was 1 cm. The knob was PVC-coated. Since the axis of rotation was perpendicular to the cylindrical part of the knob, any rotation altered the orientation of the knob. A rotation of 180°, either clockwise or counterclockwise, resulted in the same orientation.

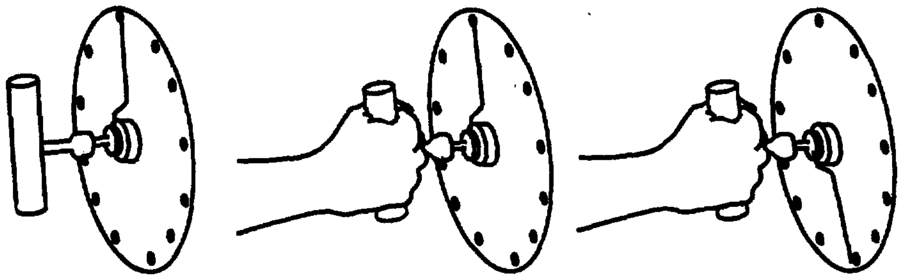


figure 4-2: a
The T-knob.

b
The way in which the T-knob had to be grasped: the shaft is between the third and fourth fingers. This grip is called the thumb-towards grip; the thumb is directed towards the tip of the pointer.

c
The thumb-away grip; the thumb is directed away from the tip of the pointer.

Thirdly, the L-knob was used (see figure 4-3a). Like the T-knob, this handle was perpendicular and cylindrical. The length of the knob was 10 cm (from the centre of rotation to the end). The diameter was 2.5 cm. This knob too was PVC-coated. Due to the position of the axis this knob was also sensitive to direction; in this case a rotation of 360° was necessary to regain the same orientation.

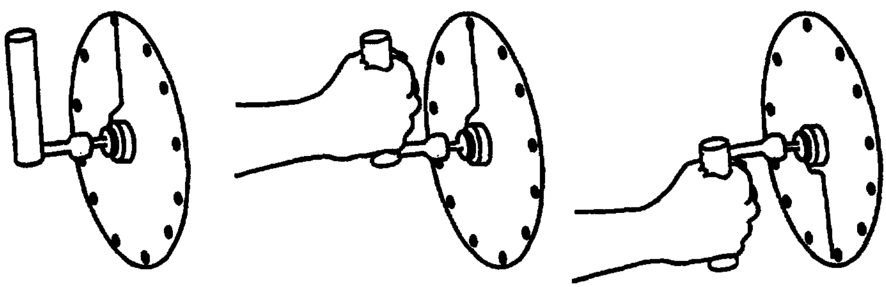


figure 4-3: a
The L-knob.

b
The thumb-towards grip of the L-knob; the thumb is directed towards the tip of the pointer.

c
The thumb-away grip of the L-knob.

The dimensions of these knobs were such that adults could easily grasp them and hold them firmly. The three knobs could be grasped in several ways. The subjects were, however, instructed to grasp the knobs in a specific way.

Napier (1956) divided all kinds of grasps into two categories: the power grip and the precision grip (Landsmeer, 1962, called the latter precision handling, since a static phase does not exist). In other publications a more comprehensive classification of hand postures has been described, see for instance Grieve and Pheasant (1982), or DIN 33 401 (figure 1-1). They classified all possible grips according to two nominal axes: -1- the degree to which the hand is held in a closed or open chain configuration, and -2- the degree of contact of the hand with the object held. In our experiments subjects were asked to use a closed chain grip, and make as much hand-skin contact with the knob as possible. In such a case manipulation of the knob, within the hand, is not possible; the task of the grip was to immobilise the knob relative to the hand.

The O-knob was grasped in two different ways: the central grip and the lateral grip. To accomplish the central grip the subject had to grasp the knob with the axis between the third and fourth fingers (see figure 4-1b).The second way in which the knob could be grasped was the lateral grip (see figure 4-1c). For this grip the subjects had to grasp the knob like a screwdriver. The T-knob could only be grasped with the axis between the third and fourth fingers (see figure 4-2b). The subjects had to grasp the knob tightly without changing their grip nor letting go. The L-knob had to be grasped like the T-knob, only now the axis was lateral to the little finger (thumb-away grip, see figure 4-3b) or the index finger (thumb-towards grip, see figure 4-3c). Subjects were instructed to use only one of these five grips, according to instructions. Via a video camera, directed toward the subject's arm, the investigator could check the grip used.

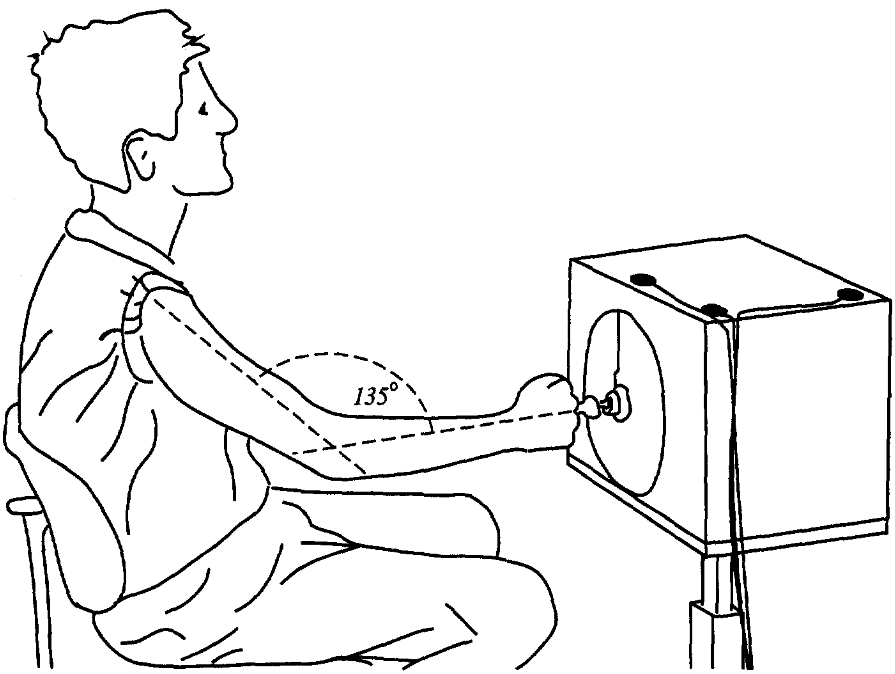


figure 4-4: The position of the subject relative to the knob.

4.2 Subjects

In all experiments young healthy adult volunteers, male and female, served as subjects. In almost all cases the subjects performed the rotation task with their preferred hand; in the event of an exception this is mentioned. Subjects who had any problems with their arm were intentionally excluded from the experiments. None of the subjects was previously informed about the purpose of the experiments. Most of the subjects were students from the Faculty of Industrial Design Engineering.

4.3 Apparatus

In the experimental situation subjects had to rotate the knob, that was mounted on a box (see figure 4-4). A shaft ran through this box (40 × 30 × 30 cm). This shaft turned on ball-bearings. The knobs could be mounted on the shaft. For the L-knob, a counterweight was attached to the shaft to balance the mass of the knob. A simple friction device (see figure 4-5) determined most of the rotational resistance, which was about 0.15 Nm. Resistance was induced by pressing on the shaft. The shaft passed through this resistance device, which consisted of a cylinder of POM (Polyoxymethyl). Perpendicular to the shaft was an opening. In this opening a small piece of POM was pressed against the shaft by a screw; in between the screw and the small piece of POM small diaphragm springs were placed. By turning the screw, the rotational resistance could be increased to more than 5 Nm.

On the subject's side the (O-T-L) knob was attached to the shaft. When the knob was rotated, a pointer (14 cm), which was also mounted on the shaft, indicated the magnitude of the angle of rotation (see figures 4-1, 4-2, and 4-3). For the T or the L-knob the pointer was placed parallel to the knob. Behind this pointer was a scale, with numbers analogous to a clock. This scale was used to indicate the magnitude and direction of the required rotation. In all experiments clockwise rotations were defined as positive, whereas counterclockwise rotations were called negative.

To assess the angle of rotation of a shaft, an encoder was used. Via a pulley the encoder was connected to the shaft. When the axis of the encoder rotates, the encoder produces pulses every 0.5°. These pulses were sent to a device that transduced these pulses to a voltage. A rotation of 360° equalled a voltage of 1.76 V.

4.4 Experimental situation

The subjects were seated behind the box (see figure 4-4). The chair and box could be moved independently of each other. The height of the seat of the chair could be adjusted in the range 50 to 75 cm. The vertical position (height) of the shaft to which the knob was attached could be varied between 85 and 110 cm from the ground. The box was positioned such that, when the subjects grasped the knob (without intending to rotate it), the forearm was horizontal and the upper arm was about anteflexed 45°. In all of the experiments the location of the control, relative to the subject, was kept constant.

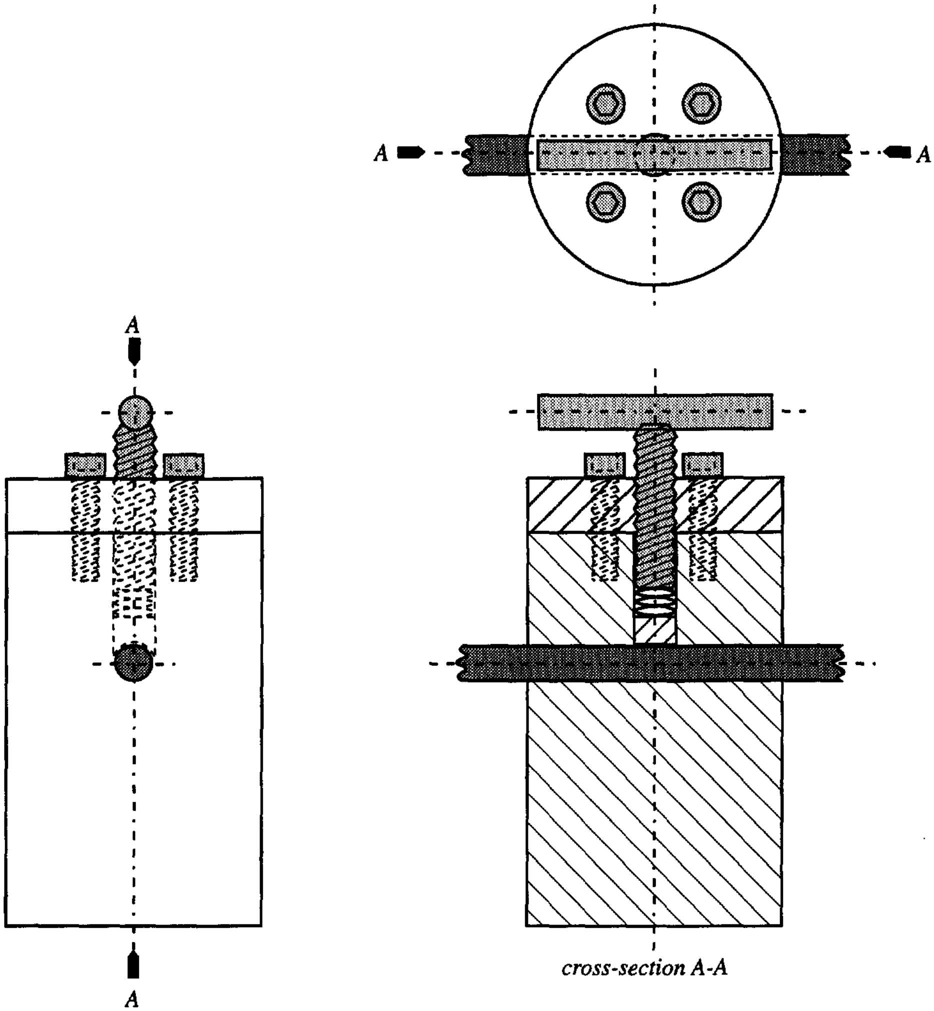


figure 4-5: The friction device used to regulate the rotational resistance. See text for further explanation.

The subjects were asked to sit back against the back of the chair. Their feet were supported. The shoulder joint of the active arm and the shaft were in the same sagittal plane. The frontal plane of the box was parallel to the subject's frontal plane.

4.5 Registration equipment

The system used was the OPTOTRAK 2010 (Northern Digital Inc., Waterloo, Ontario, Canada) 3D opto-electronic motion registration system (see fig 4-6). This consists of a system unit (a), two cameras (b), markers (c) and strobers (d). The system unit is the central controlling, interfacing, and processing unit of the OPTOTRAK system. Essentially it links the markers, cameras, and host together. The minimum system requirements for proper operation of the OPTOTRAK are an IBM compatible PC (Intel 286 processor or higher) and a minimum of 640 Kbytes RAM memory.

The system uses 'active' markers, meaning that the markers are placed on a subject and controlled by the system unit. The markers are connected to the strobers, which are placed on or near the subject. The strobers are connected to the system unit. The markers (IREDs: InfraRed Emitting Diodes) radiate infrared light which can be detected by the cameras. The system unit controls the markers, which are activated in serial order. Since each marker is only momentarily active, two position sensors observe the marker as a point source of light. The processor uses a weighted gravity algorithm to locate the image of the point source of light. When the position of the two cameras in a previously calibrated space is known, the system is able to calculate the 3D positions of the markers.

To calibrate the position of the two cameras, the calibration frame (64 × 64 × 73 cm), see figure 4-6e, must be used. Within this rigid frame 20 markers are placed at precisely known positions, the frame marker locations are presurveyed to an accuracy of 0.1 mm in 3D. Depending on the relative positions of the cameras and the calibration frame the RMS will be less than 0.25 mm. This RMS can be calculated by determining the distances between the measured positions of the 20 frame markers and the previously known positions of these markers. Each of these distances will be squared. Then the mean value of these 20 squared distances will be determined, and the square root will be extracted. In the event that a calibration exceeds 0.25 mm, the position of the cameras can be altered slightly, and a new calibration can be made. The 3D distance error is always less than 0.5 mm at a camera distance of 4 m. Due to the position of the cameras, which were at the same height in this experiment, the 3D distance error for the vertical position will be greater than the 3D distance error for the horizontal plane. For the horizontal plane this error is less than 0.3 mm, for the vertical plane less than about 0.45 mm (specifications according to the manufacturer).

To assess the motion of an object or subject, IREDs have to be fixed to it. The 3D positions of these markers are sampled by the system, at a chosen sample frequency and duration. As a consequence, the motion is divided into several consecutive frames, each containing the position of the markers in one sample.

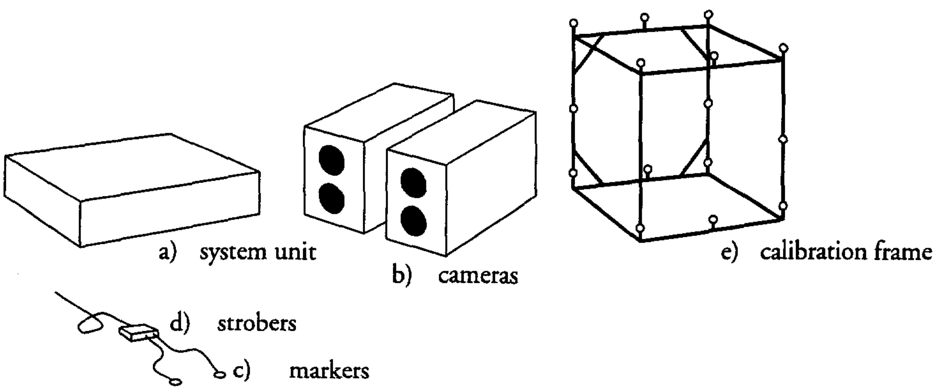


figure 4-6: The opto-electronic motion registration system, OPTOTRAK 2010.

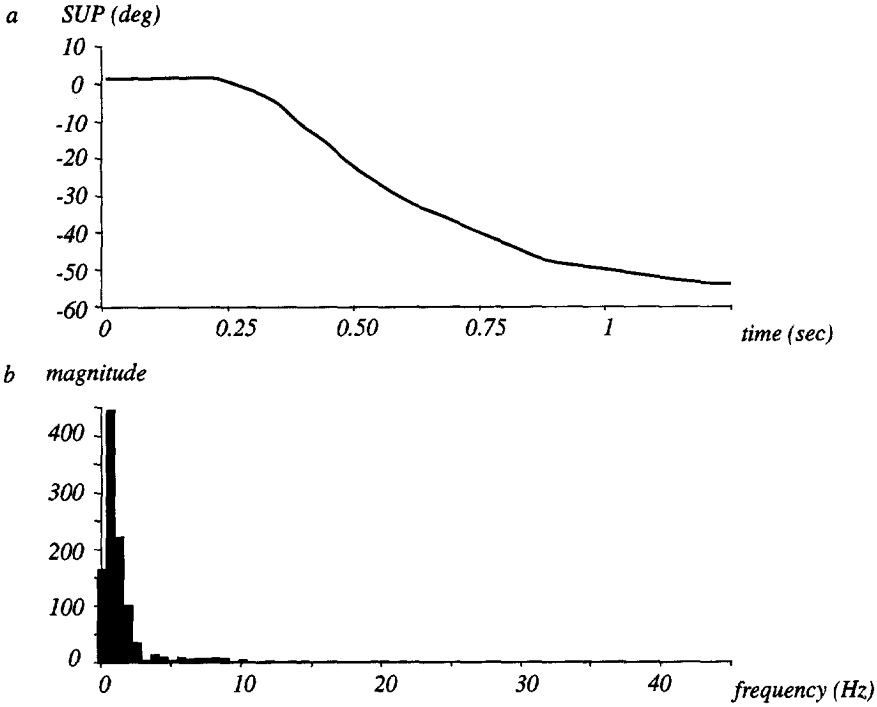


figure 4-7: The Fourier transformation of supination data (a) to the frequency spectrum (b).

The maximum sample frequency is directly coupled to the number of markers used: the number of markers (plus one) times the installed sample frequency must be less than the maximum sample rate (2500 Hz). Therefore, the sample frequency can be set between 0 and about 1200 Hz, depending on the number of markers used. In this project 28 markers were used (3 on the box, see figure 4-4, and 25 on the subject; for the placement on the subject, see paragraph 3.5.2 and 3.5.3). Due to this number of markers the sample frequency could not exceed 86 Hz. In a pilot experiment data were collected at a frequency of 80 Hz. The original data (see figure 4-7a) contained the angle of supination for each sample. The results were analysed by Fourier transformation (figure 4-7b). The horizontal axis contains the frequencies, the vertical axis the magnitude of the components of these frequencies in the original data. The results show that the important frequencies were below about 5 Hz. These frequencies turned out to be the most important components of the original signal. To preserve the original signal as clearly as possible, the sample frequency was set at 25 Hz (i.e. five times oversampling).

The two cameras were installed on tripods, at a height of approximately 1.70 m, next to the subject on the side of the active arm. The distance between subject and cameras was about 4 m. The cameras were placed such that their optical axes formed an angle of about 60° (see figure 4-8). In this way all necessary marker positions could be recorded. As mentioned before, the video camera was placed such that the grip used could be monitored.

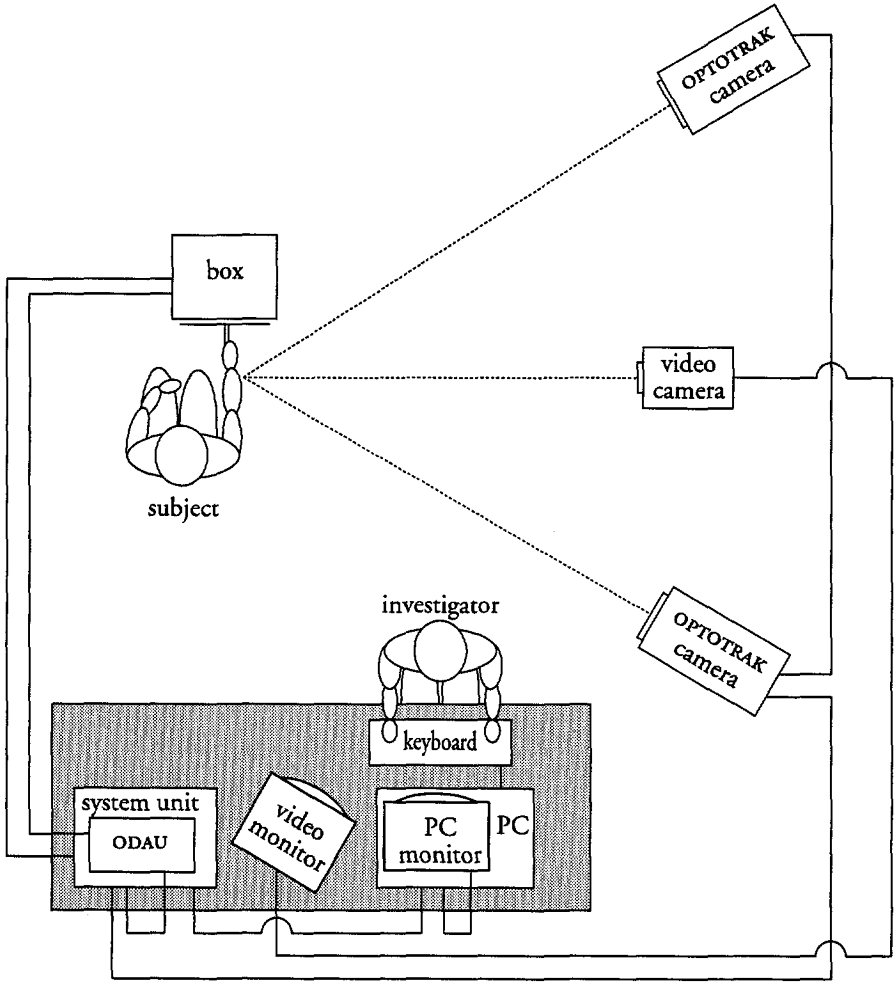


figure 4-8: The experimental conditions seen from above.

On the box with one of three handles, three markers were placed to indicate the position of the handle. Since the frontal plane of the subjects was parallel to the frontal plane of the box, these markers on the box could also be used to determine the orientation of the subject in space. In paragraph 3.5 the positioning of the markers on the subjects was described in detail.

To collect additional analog signals, the system was expanded to include the OPTOTRAK Data Acquisition Unit (ODAU). The ODAU is used to collect the output of the encoder, which was fixed to the shaft through the box (see paragraph 4.2) and expresses the angle of rotation of the knob. The sample frequency of the ODAU was equal to that of the OPTOTRAK system: 25 Hz. Therefore, within each frame the positions of the markers and the angle of the shaft were known. The accuracy of the determination of the angle of rotation was 0.5°, due to the resolution of the encoder.

4.6 Data processing

To collect data, we used the programme COLLECT.EXE (Northern Digital). This programme controlled the OPTOTRAK system. With this program, among other things, the sample frequency and number of markers could be chosen. This program was also used to determine the start and the duration of data collection. Before collection of the actual data, the subject had to perform pure supination (see paragraph 3.5.4). This motion was observed by the system, resulting in the first floating point file, named: R#001.ext ('R' means rough data file, '#001' stands for the first trial, and 'EXT' stands for three unique letters to indicate the subject and experiment). This file contained the numeric output of both of the cameras, for all 28 markers.

During the experiment, trials of each of the tasks were collected and named in a consecutive order (R#002.EXT to R#NNN.EXT). At the same time, the ODAU delivered rough data containing the output of the shaft encoder (see paragraph 4.5). These data were stored in a file named 01#nnn.ext. All of these files were sampled at a frequency of 25 Hz.

After the experiment was ended, the data of the 01#-files were converted to V1#-files, containing a voltage between 0 and 1.76V. These voltages could later be linearly transformed into the angle of rotation of the control.

Next, the data were processed to calculate the supination and combined arm rotation angles. First, the initial trial was processed. The R#001.ext file was used to determine for each frame the transformation matrix for the wrist bracelet and the 'butterfly' attached to the elbow. For this transformation the program RIGID.EXE (Northern Digital) was used in a subroutine. The output, i.e. the transformation matrices, was stored in a file called RIG#001.ext. Simultaneously, the rough data file (R#001.ext) was converted to a file containing the 3D positions of the markers attached to the box as well as the position of the shoulder marker (this file was named C#001.ext). The transformation matrix of the bracelet was used to determine the position of the axis of supination (see paragraph 3.5.4). Knowing the position of the axis of supination and the position of the plane of the wrist bracelet, as defined by the 1st, 7th and 13th markers, the four parameters describing the position of the wrist points in the local coordination system of the wrist bracelet (λ_1, λ_2, μ_1, and μ_2 , see paragraph 3.5.5) could be determined. These were stored in a log-file, called EXT.LOG. These four parameters will be needed for determination of the two wrist points in all subsequent trials.

After processing the initial trial, which resulted in the four wrist parameters, the rest of the trials were processed. Each rough data file (R#NNN.EXT) was used to make a file containing the transformation matrices (RIG#NNN.EXT). Also the rough data were converted to 3D positions (C#NNN.EXT). This file already contained the 3D position of the shoulder marker. The transformation matrices of the 'butterfly' could be made when only three of the markers were in view of both cameras (e.g., only one of the wings). The origin of the rigid body, containing the relative position of the seven markers attached to the 'butterfly', was placed in the centre marker. This part of the 'butterfly' was placed over the lateral epicondyle of the subject's elbow and represented the position we wanted to know. Consequently, the translation part of the transformation matrix equals the 3D position of the elbow. Next, only the two wrist points remained to be determined. Since in each frame at least three markers of the bracelet were in view of both cameras, RIG#NNN.EXT file contained the transformation matrix of the bracelet for each frame. Consequently, the 3D position of the 1st, 7th and 13th marker of the bracelet could be determined. Knowing these positions, and the four parameters describing the position of the two wrist points in the local coordinate system of the bracelet, the 3D position of the two wrist points could be calculated (see paragraph 3.5.5). At this point the 3D positions of the shoulder, the elbow, and the two wrist points were known. By using the formulas describing the angles of supination and combined arm rotation (see paragraphs 3.3.2 and 3.4.2), the SUP and CAR angles could be calculated for all frames. These data were stored in a file called ROT#NNN.EXT.

The ROT#NNN.EXT contained all SUP and CAR data collected during one trial. The control was rotated only for a short period of time. The file containing the rotation angle of the shaft (VI#nnn.ext) was applied to determine the first and last frames of the rotation. The first frame of rotation was defined as that in which the angle of the shaft differed by more than 4° from the initial angle at the start of the trial. The last frame of rotation was defined as that in which the angle of the shaft was equal to the final angle at the end of the trial. Knowing the first and last frames, the corresponding joint angle values could be determined. These values were stored in an ASCII-file, named EXT.PRN.

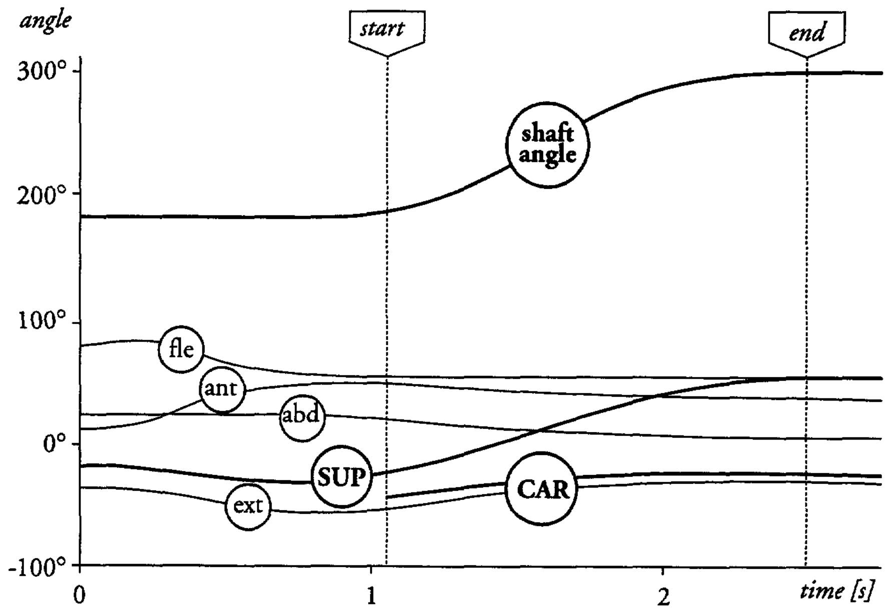


figure 4-9: The joint and shaft angles during a trial (rotation task was 120° clockwise). 'Start' means the onset of rotation of the axle, ending at 'end'. The joint angles shown are: abd(uction), ant(eflexion), ext(ernal rotation), fle(xion), SUP *(ination), and* CAR. *See text for more detailed information.*

In figure 4-9 an example of the joint angles in one trial is shown. Data collection was started about one second before the start of rotation of the shaft. Right from the start the joint and shaft angles (abduction, anteflexion, external rotation, flexion, and supination) were determined. It must be kept in mind that the angles of abduction, anteflexion, and external rotation cannot be considered to be independent of each other (see paragraph 3.4.1). To determine the actual position of the upper arm from the anteflexion, abduction, and external rotation angle, the arm must first be anteflected (starting from the anatomical position). The sagittal axis, in the shoulder joint, around which abduction takes place, must rotate in conjunction with the arm, around the frontal axis. Then abduction must be carried out, around *the temporary* sagittal axis. Remember that the sagittal axis is not horizontal anymore. Finally external rotation is performed along the longitudinal axis of the upper arm. This longitudinal axis also is no longer vertical; it remains in line with the upper arm. CAR was only assessed from the start of rotation of the shaft, since CAR is not defined when the hand is not connected to the control.

4.7 Conclusion

For these experiments the rotation tasks were conducted in a strictly experimental setting. No previously existing controls were offered to the subjects, only the O-, T- and L-knobs were used. The protocol also prescribed the way the knob had to be handled; in all cases the subjects were not allowed to manipulate the knob inside their hand. The experimental setting was systematically varied by changing the properties of the control and the tasks.

To monitor the movements made by the subject, the OPTOTRAK motion registration system was used. This system assessed 3D points with an accuracy of less than 0.5 mm in each direction. The sample frequency was 25 Hz. In addition to the movements of the subject, the angle of the shaft was also assessed by the OPTOTRAK system.

5 Non-directional rotary control

5.1 Introduction

In the next two chapters the results of our experiments will be described and discussed. As mentioned before, the rotary controls used in the experiments were the O, the T, and the L-control. First the experiments with the O-control will be described. In the next chapter the experiments with directional controls, i.e. the T- and L-controls, are reported.

In the first group of experiments the round O-control was used. This control can be grasped in the palm of the hand by means of either the central or the lateral grip (see paragraph 4.1 for a detailed description of the control and the grip). Other sorts of grasp were excluded from the experiments. The most important characteristic of this control is the directional indifference. The view of the control remains the same, irrespective of the angle of rotation of the control. The consequence is that when the control is being held, the orientation in the frontal plane of the hand and the wrist is not imposed by the control.

To grasp the control, the subject has to reach towards the control by using upper arm movements and adjusting elbow flexion. Once the subject has hold of the control, he has to rotate it; he is only allowed to use supination and combined arm rotations (SUP and CAR, see chapter 3). Subjects were instructed not to use other kinds of movement, such as sidewards flexion of the trunk or manipulation with the fingers. The total range of possible rotations is the sum of the range of SUP and the range of CAR. This total range is about 330°, SUP and CAR each contributing about half of the total range.

In chapter 2 the problem of the degrees of freedom was considered. Analysis of the ways to control the O-knob reveal that when the user rotates the knob, his degrees of freedom (which are two, namely SUP and CAR) exceed the degree of freedom required for the control (only rotation of the control). In such a case, automatically the theoretical number of performances to rotate the control will be infinite, as long as the magnitude of the rotation task is not close to the maximum value.

In all experiments, the subjects had to rotate the control in a specified direction and through a certain angle. For rotation of the O-control, the initial and final directional wrist angle was not imposed on the subject. Comparing our rotation task to pointing tasks (e.g. Lacquaniti et al., 1982; Soechting and Lacquaniti, 1982 and 1983; Cruse, 1986), the rotation task seems to be more indeterminate than the pointing tasks. In pointing tasks the initial and final positions of the hand are determined beforehand. In the experiments with the O-control, the initial and, consequently, the final position are not known. This makes the problem more difficult: not only the degree of the two degrees of freedom in each wrist position but also the initial wrist position is free. The only restriction is that the difference between the final

SUP and CAR angles and the initial SUP and CAR angles must be equal to the angle of rotation of the knob. When, for instance, the task is to rotate the knob 90°, the initial SUP angle may be -27° and the initial CAR angle -46°. After rotation of the knob, the SUP angle might be 40° and then the CAR angle must be -23°. But all four angles can be different, as long as the difference between the final angles and the initial angles equals the magnitude of the rotation task, and all four joint angles are within the range of possible joint motion. It is even possible, although we do not expect this to occur, that while rotating the knob in a clockwise, i.e. positive, direction the change in the CAR angle will be negative, i.e. in the counterclockwise direction. In that unexpected case, the change in the SUP angle has to be larger than the required angle of rotation, namely the size of the rotation task added to the change in the CAR angle. We also do not know whether the rotation task will be performed, for instance by means of SUP only or a combination of both SUP and CAR. Only when the rotation task is larger than the individual range of movement of SUP or CAR can we be sure that both movements will be used.

In conclusion, it can be said that for rotation of the O-control, very little is imposed on the subjects. A large range of variations, even for one and the same rotation task, is possible.

5.2 Experiments

In the first subparagraph the standard experiment will be described. The experiments in the next six subparagraphs are characterized by slight alterations in this standard situation. First, we changed the grip used to the lateral grip. After that, we used left-handed subjects. In the next experiment we excluded any visual information. Then the angle of elbow flexion was changed. In the last variation we increased rotational resistance.

5.2.1 Standard experiment

In the literature we found that in experimental situations in which the number of degrees of freedom of the user exceeded the degrees of freedom required for the task, subjects tend to move in a constant way although performance of the task is essentially not determined by hard constraints (see chapter 2). We therefore expect that, in our experiments too, subjects will move in a constant way, i.e. some constraints or synergies will be introduced to diminish the variation.

In 1988 Rosenbaum et al. described how subjects grasped and rotated a handle. Their aim was to understand why a particular movement is selected, given the fact that a finite number of movements can in reality achieve the goal: grasping the handle with the thumb or the little finger to a specified end of the handle. They concluded that the movements which the subjects selected spontaneously ensured that the muscle torque at the joints of the hand-arm system was minimal at the end of rotation. In another experiment Rosenbaum and Jorgensen (1992) studied the way subjects grasped a bar to move it to a target position. In this task subjects had to transport and rotate the bar. Subjects had to choose between two different, imposed initial hand positions (i.e. overhand and underhand grip). Again they concluded that the choice of hand orientation depended on how comfortable the arm would be at the end of the transport movement, which they called the optimization of end-state comfort.

The idea of optimization of end-state comfort, which possibly can be applied in our experiments, could result in an explanatory model. Due to the length-force relationship of each muscle, it is expected that the arm will be in a comfortable end-state when the joints involved are all in about the middle of their range of motion (Rosenbaum and Jorgensen, 1992; Cruse et al., 1990). It must, however, be noted that the optimum length of a muscle, i.e. the length of the muscle when it can produce maximum force, is not always achieved in the middle of the range of motion. Heslinga (1992, p.88) showed that the optimum length of a muscle immobilized in a shorter position becomes shorter. When the range of motion of CAR is taken into consideration, it is clear that in daily life the upper arm is in a neutral or anatomical position. From this it can be expected that the optimum length of the muscles involved in CAR, and therefore the comfortable joint position, will be near this neutral position. Therefore, if end-state comfort is a constraint for control of the O-knob, it is to be expected that the final SUP angle will be near the middle of the range of motion and the final CAR angle somewhere near 0°. In this situation, each subject has to start in a more uncomfortable position to end in a comfortable one. The size and direction of the anticipatory movements will depend on the rotation task the subject has to perform. The explanatory model does not predict the way the anticipatory movements are made: they can consist of SUP and/or CAR rotation. In the first column of table 5-1, this model is given schematically for positive tasks (in case of negative tasks, the signs must be reversed).

table 5-1: Three models for predicting the initial and final angles of both SUP *and* CAR *For each model the tasks are divided into small and large rotation tasks, all tasks are assumed to be positive. Explanation of signs: 0 = comfortable joint angle, - = decreased joint angle, + = increased joint angle. See text for further explanation.*

	1 (Rosenbaum et al.)	2 (Bullinger & Solf)		3 Combination	
	small large	small	large	small	large
initial SUP	- / 0	- / 0	- / 0	-	-
initial CAR	- / 0	0	- / 0	0	-
final SUP	0	0 / +	+	0	0
final CAR	0	0	0 / +	0	0

The second model, see the second column of table 5-1, is that of Bullinger and Solf (1979). They state that, when using the hand to rotate a control, rotation will first take place at the distal end of the arm; only when necessary will the more proximal rotation possibilities be used (see figure 2-7). When this idea is applied to our experiments, the following tactic can be predicted: depending on the magnitude and direction of the rotation task and the initial angle of the subject, the subject will first use SUP movements and, only when necessary, will CAR movements be used. Whether a task can be performed in its entirety by SUP movements depends on the magnitude and direction of the rotation task and the joint angles at the start. Small rotation tasks are expected to be performed by SUP only. The subject will either anticipate SUP, resulting in a decreased initial SUP, or the subject will end at an increased SUP angle. A combination of the two is also possible. In any case, the subject is not expected to use CAR. Only for the larger rotation tasks will some change in the CAR angle towards the comfortable position occur, i.e. in the initial and/or the final joint angle. Here the SUP angle will be near maximum.

The ideas of Rosenbaum and colleagues and Bullinger and Solf can be combined. This will lead to a third kind of prediction model (table 5-1, the third column). In this case the final positions are expected to be near the comfortable joint angles. When the magnitude and direction of the task allow only SUP, no CAR movements are expected. Only in case of a task in which the SUP movements are not enough to perform the rotation task will CAR movements be used.

Until now we have only considered the initial and final joint angles. Depending on the model, certain expectations for the initial and final joint angles exist. In between the final and the initial positions, the SUP and/or the CAR angle will change. The relationship between these alterations in joint angle is not predefined by the task, nor do any of the models predict a relationship between the changes in SUP and CAR. In literature (see chapter 2) we see that in 2D pointing tasks (e.g. Soechting and Lacquaniti, 1981) and circular drawings (Soechting et al., 1986), the changes in the angle of anteflexion of the arm and the angle of flexion of the elbow are coupled. For these pointing and drawing tasks, the hand must be moved by applying two degrees of freedom: anteflexion of the shoulder and elbow extension. When rotating the knob in our experiments, the same situation exists for CAR and SUP. As in the above-mentioned motor tasks, the degree of freedom of the upper arm, i.e. CAR rotation, forms the base for a more distal degree of freedom, namely SUP rotation (see paragraph 3.2). We expect, therefore, that for our rotation tasks too a fixed linear coupling between these two degrees of freedom will apply.

Method

Thirteen subjects (6 males, 7 females, aged 18-40 years old) participated in the experiment. All subjects were right-handed and had no problems in using their arm. They were all unaware of the purpose of the experiment.

The general experimental conditions were described in chapter 4. For all rotation tasks the subjects had to use the central grip (see figure 4-1b). At the start of the trial, the pointer attached to the shaft of the knob pointed towards 12 o'clock. In each trial, the subject was given one of the nine target positions (8, 9, 10, 11, 12, 1, 2, 3 and 4 o'clock), i.e. rotate the knob -120°, -90°, -60°, -30°, 0°, 30°, 60°, 90° or 120° using the right hand. When the target was 12 o'clock, the subject only had to grasp the knob and not rotate it. The experiment contained five series of nine targets each. In each series the targets were given in a random sequence. Subjects were instructed to rotate the pointer towards the target within an accuracy of about 10°. In particular there were no special requirements as to the speed of movement. They were asked to make one smooth movement; if they overshot or undershot the mark they were asked not to correct it. Subjects were not allowed to change their grip during rotation of the knob. The investigator instructed the subjects by calling the target position in clock-code. Then the OPTOTRAK system started to collect the data, i.e. the 3D coordinates of the IREDs and the angular position of the axis of the box, for about 3 seconds. To get acquainted with the experimental conditions, one full experiment was conducted before the actual experiment.

Results

What is the contribution of SUP *and* CAR *to the rotation task?*

For all subjects the contribution of joint rotations (i.e. SUP and CAR) to the rotation task was determined. In all cases a perfect linear relationship existed between the magnitude of the actual rotation of the knob and the change in joint angles (minimal $r^2 = 0.98$). Table 5-2 shows the outcome of linear regression analysis ($\hat{y} = \hat{\beta}_0 + \hat{\beta}_1 x$). The estimated constant ($\hat{\beta}_0$), although significant ($p<.01$) for eight subjects, changed only a little from zero. The estimated task parameter ($\hat{\beta}_1$) was significant for all subject sessions ($p<.01$). The range was 0.73 to 0.93, the median 0.85. This indicates that about 85% of the knob rotation can be explained by the joint rotations SUP and/or CAR. The rest of the knob rotation must be attributed to other movements. In an extra test we checked the residuals for normality. For all subjects the 'normal P-P plot' resulted in a distribution along the 45°-line, showing that the residual variance was distributed normally.

table 5-2: The outcomes of the simple linear regression analysis of the differences in joint angles with respect to the magnitude of the task. Each subject performed 45 trials ($df = 43$). The constant and variable factor, residual variance, and r^2 value are listed for all thirteen subjects. All variable factors exhibited significant differences ($p<.01$). For subjects 1, 2, 4, 7, and 10 the constant factor was not significant ($p>.01$).

subject	constant parameter estimate	task parameter estimate	residual variance	r^2
1	0.80	0.83	2.46	1.00
2	-0.35	0.86	2.77	1.00
3	-3.16	0.91	3.57	1.00
4	1.59	0.82	6.70	0.99
5	-0.97	0.84	2.27	1.00
6	4.47	0.73	4.98	0.99
7	-1.74	0.75	4.44	0.99
8	1.46	0.86	3.46	1.00
9	4.52	0.87	3.86	1.00
10	0.82	0.81	2.71	1.00
11	2.45	0.85	2.94	1.00
12	1.83	0.87	1.92	1.00
13	7.04	0.93	11.43	0.98

Is there an effect of repetition on the performance?

Next we analysed the initial and final values for both SUP and CAR by using an analysis of variance (ANOVA). First, we wanted to know whether there was any effect of the number of repetitions. We analysed the data for all four variables by separate ANOVA's. In our model it is presumed that the effect due to the subjects is random, since the thirteen subjects must be considered as a sample from a larger population. The effects due to task and repetition are fixed. Since we only have one sample in each cell, it is not possible to estimate the residual variance. Therefore we assumed that a three-way interaction between subject, task, and repetition does not exist. In the null hypothesis it was assumed that there is no effect due to the number of repetitions (α=.01). The results of ANOVA showed that there was no significant effect due to the number of repetitions: initial SUP $F(4,48)=0.91$, $p=.47$; initial CAR $F(4,48)=0.36$, $p=.83$; final SUP $F(4,48)=0.36$, $p=.84$; and final CAR $F(4,48)=1.04$, $p=.40$. The results indicate that the subjects were constant in their performance of the rotation tasks.

Was there an interindividual difference, and what is the effect of the task on the rotation?
We wanted to know whether there was any variation between subjects or an effect of the task on the initial and final joint angles. Again we analysed the data for each of the four variables using ANOVA. In our models we now have five replica's in each cell. Again the effect of subjects is presumed to be random. The results of this ANOVA showed that for all four variables (initial SUP, initial CAR, final SUP, and final CAR) there was a significant variation between subjects ($F(12,468)=132$, $p<.01$; $F(12,468)=274$, $p<.01$; $F(12,468)=168$, $p<.01$, and $F(12,468)=295$, $p<.01$, respectively) and an effect on task ($F(8,96)=23$, $p<.01$; $F(8,96)=5.6$, $p<.01$; $F(8,96)=39$, $p<.01$, and $F(8,96)=18$, $p<.01$, respectively). In a separate ANOVA the initial and final orientation of the wrist, i.e. the sum of the SUP and CAR angles, was taken as the dependent variable. This analysis too showed a significant variation between subjects ($F(12,468)=132$, $p<.01$; $F(12,468)=158$, $p<.01$, respectively) and an effect on the task ($F(8,96)=15.9$, $p<.01$; $F(8,96)=32.6$, $p<.01$, respectively).

Next we checked whether the data were adequately described by the model used, and that the errors were normally and independently distributed with a mean μ and constant variance σ^2. To check the underlying assumptions of the analysis of variance, we used some primary diagnostic tools which are based on residuals (Montgomery, 1984 p.85/86). First, we constructed a normal probability plot of the residuals for each of the four response variables, i.e. initial SUP, initial CAR, final SUP, and final CAR. This should result in a straight line for each of the variables. The plots showed only slight deviations from a straight line, indicating that the residuals were distributed normally. Next we plotted the residuals versus the fitted values. In case of a correct model and if all assumptions are satisfied, the residuals should be structureless. For all four variables the plots did not reveal any structure. In the last diagnostic analysis we plotted the residuals versus factor levels. For the factor rotation task, the four plots showed no structure. The plots for the factor subject, however, revealed discrepancies in the distribution of the residuals for the diverse subjects, although we assumed that there was no relationship between the residuals and the subjects. In general we conclude that the underlying assumptions of ANOVA are satisfied.

End-state comfort?
Since the results of the ANOVA showed an effect of the task on the final wrist orientation and even on the final joint angles, it can be concluded that the models for prediction based on Rosenbaum and colleagues (see table 5-1: model 1 and 3) cannot be confirmed. The hypothesis based on the concept of end-state comfort, i.e. that there will be no difference between a small positive rotation task (30°) and large positive rotation task (120°), could not be confirmed for either the final SUP value ($F(1,468)=1327$, $p<.01$) or the final CAR value($F(1,468)=263$, $p<.01$). Subjects do not always end up in the same joint position. Consequently, the comfortable end-state cannot be used to predict the movements subjects will make while performing rotation tasks.

Do subjects use CAR *only when* SUP *is no longer possible?*

The effects of each task on the four variables were also estimated. The results are presented in figure 5-1. From this we can see that the effect of the rotation task on the joint angles changes as the magnitude and direction of the task change, whether small or large, negative or positive. In model 2 of table 5-1 we predicted that small tasks would not have an effect on the initial and final CAR values; CAR was not expected to be used in small rotation tasks. In figure 5-1 we can see that for small positive rotation tasks (30° and 60°) the effect of the task on the initial SUP and CAR angles is nearly constant. There is, however, a clear change in the effect on the final CAR angle due to the magnitude of the task. From this we may conclude that the CAR movement is also applied for small rotation tasks. In a separate ANOVA we analysed the ratio between the uses of SUP and CAR. We determined delta for each rotation trial:

$$\delta = \arctan\left(\frac{CAR_{final} - CAR_{initial}}{SUP_{final} - SUP_{initial}}\right)$$

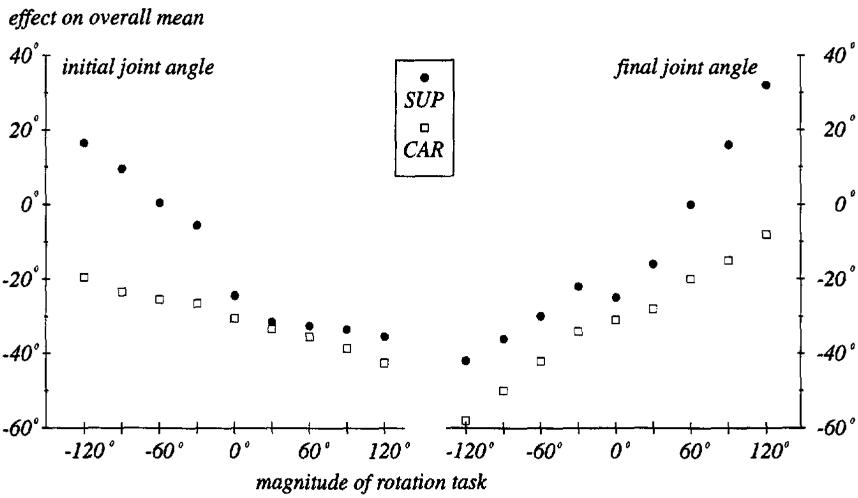


figure 5-1: The effect of the task on the initial and final values of both SUP *and* CAR, *in degrees, relative to the overall mean value.*

By determining the arctan value comparison of the use of SUP and CAR is possible, i.e. which part of the rotation was conducted by CAR and which part of the rotation was the result of a SUP movement. The result was used as the dependent variable in the next ANOVA. The analysis showed that there was no significant effect on task ($F(7,84)=1.23$, $p=.30$), which indicates that the ratio of the use of CAR to that of SUP is not dependent on the magnitude and direction of the rotation task. Figure 5-2 shows the distribution of deltas for all rotation tasks performed by all subjects. The figure reveals that there is no clear effect of the task on delta. Although there is a remarkable variation in delta within each task, the general tendency of all subjects was to use twice as much SUP as CAR (the overall mean arctan value was 28°), independent of the magnitude and direction of the rotation task. Therefore model 2, based on Bullinger and Solf (1979), also cannot be confirmed.

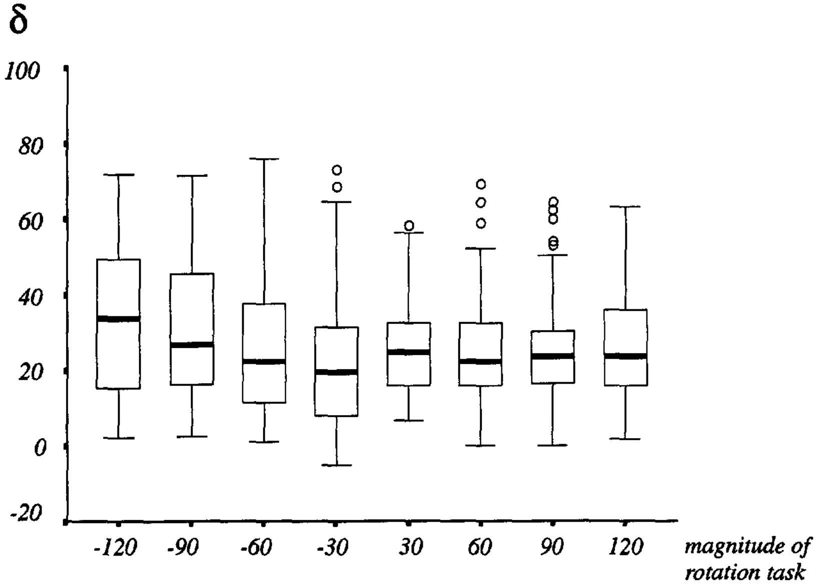


figure 5-2: Boxplot of the deltas for all subjects in the standard experiment. The dark line in the box represents the median value, the upper and lower ends the 25th and 75th percentiles. The lines on each side of the box indicate the range of the data. When they measure more than 1.5 times the length of the box, these data are called outliers and are indicated by small circles.

Are there more ways to perform the set of rotations?

The analysis described above showed that there is a significant influence of the subjects on the initial and final joint angles. It was concluded that not all subjects performed the rotation tasks in the same way. The raw data, however, showed that some subjects performed the rotation tasks in nearly the same way, i.e. they used the same tactic to solve the problems, such as which initial angle to choose and what ratio should be used between SUP and CAR.

To gain some insight into the existence of groups of subjects we used the hierarchical cluster analysis technique (Ward's Clustering Method, see e.g. Romesburg, 1984 p.129-135). Since we are not primarily interested in the individual values of the initial and final joint angles, but rather in the use of the two degrees of freedom in relation to the magnitude and direction of the rotation task, we used the difference between the final and initial joint angles as input for this analysis. In a cluster analysis, extreme values influence the outcome considerably. To diminish this sensitivity of the analysis, we used only the median values of the differences between the final and the initial joint angles.

The outcome of the cluster analysis can be seen in figure 5-3. The subjects were divided into two subgroups: A and B. Gender is concluded to have no influence on the separation into the two groups. Group A consists of three females and two males. In group B the number of females equals to the number of males. When the original data are considered, it appears that subjects 4, 5, 6, 9, and 13 (i.e. group A) behave almost identically. These subjects exhibited almost the same initial arm position for every rotation task, i.e. the initial SUP and CAR angles were similar for all tasks (see figure 5-4 for a typical example).

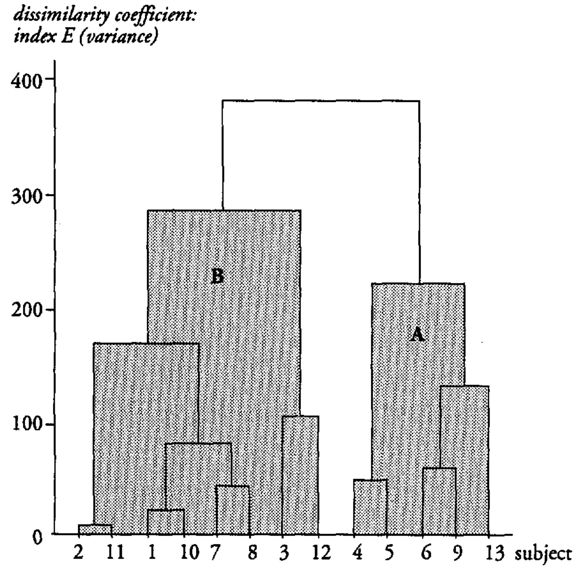


figure 5-3: Dendogram for cluster analysis (Ward's Clustering Method).

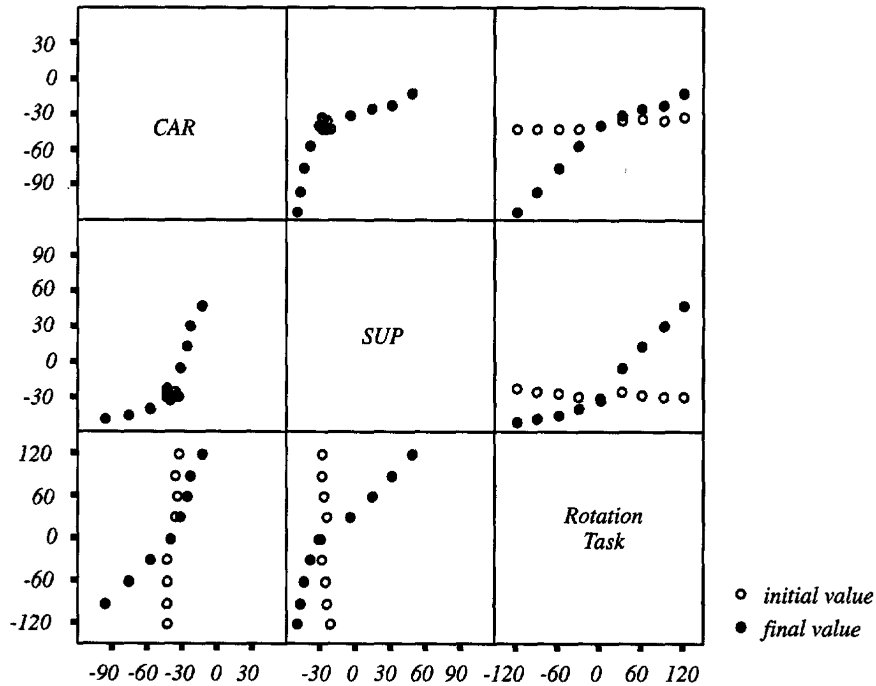


figure 5-4: Tactic A (subject 5). A matrix plot of the CAR × SUP × *Rotation Task data. In this plot, the mean initial (open dots) and mean final (filled dots) joint angles for all nine tasks are plotted against each other, i.e. from left to right, and from top to bottom* SUP × CAR, *Rotation Task* × CAR, CAR × SUP, *Rotation Task* × SUP, CAR × *Rotation Task, and* SUP × *Task.*

Depending on the direction and the magnitude of the task, these subjects altered the arm position in a specific way. For positive tasks, the subjects used relatively more SUP and only a little CAR; for negative tasks, only a little SUP was used and most of the movement was performed by CAR. This approach to the total set of tasks is called tactic A. It should be clear that for this tactic the relationship between SUP and CAR, i.e. the delta value, cannot be independent of the magnitude and direction of the rotation task. In case of a minimal SUP angle (which is found for negative tasks), the ratio of CAR to SUP changes in favour of CAR.

Group B cannot be characterized by an overall constant initial arm position. This position depended on the direction and sometimes the magnitude of the rotation task. In figure 5-5 the data on one of the subjects from group B (subject 11) are presented. This subject used mainly SUP movements. CAR movements were used only for some of the positive rotation tasks. This subject's performance is characterized by relatively constant initial positions; rotation tasks were initiated from one of two different initial positions: one for the negative and one for the positive rotation tasks. Since this subject applied only a little CAR, the differences in the initial position between the two directions involved mainly the SUP angle. Performances by this subject can be characterized as adaptation of the initial SUP angle to the direction of the task. We call this combination of task performances tactic B1. Subjects 7, 10, and 11 performed the rotation tasks by applying tactic B1.

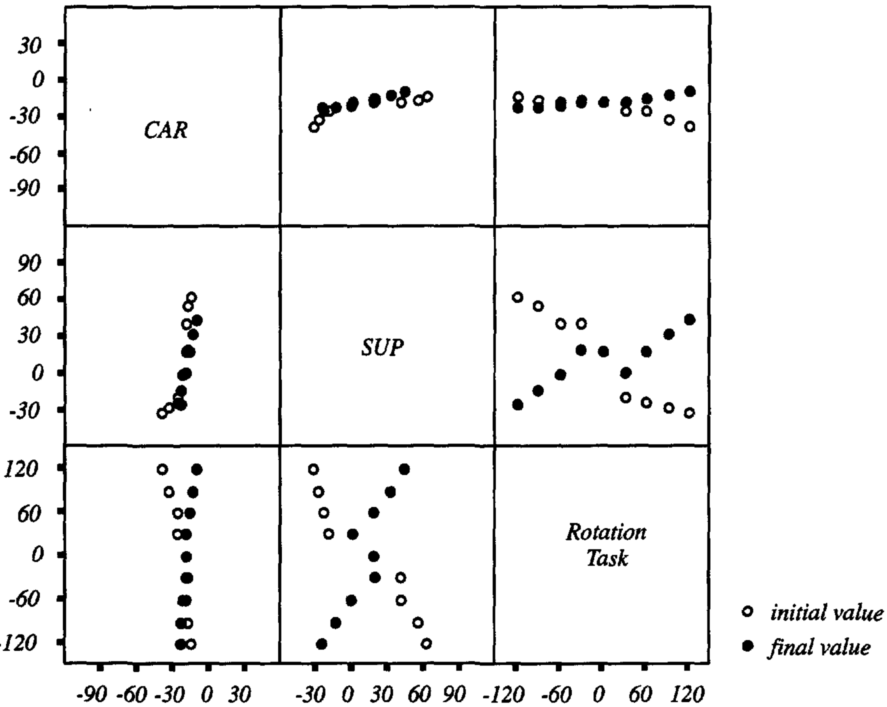


figure 5-5: Tactic B1 (subject 11). A matrix plot of the CAR × SUP × *Rotation Task data. See figure 5-4 for further explanation.*

Not all subjects in group B performed the rotation task as described above. Another approach to the rotation tasks is illustrated by subject 1 (see figure 5-6). In this figure it can be seen that this subject anticipated the direction as well as the magnitude of the rotation tasks. It is clear that this subject used more CAR movements than subject 11, who applied almost only SUP movements. The graph Rotation Task × SUP shows that for positive rotation tasks the subject started the tasks from an almost constant SUP angle, as in tactic A. The final SUP position of the arm changed linearly according to the magnitude of the rotation task. The data on the negative rotation tasks are the reverse of those on the positive tasks. In the former, the final angle of SUP was almost always constant. The initial SUP angle changed linearly with the magnitude of the rotation task. This subject can be described as having a relatively constant initial position for the positive rotation tasks and a relatively constant final position for negative rotation tasks. This combination of approaches is called tactic B2 and was used by subjects 1, 2, 3, 8, and 12.

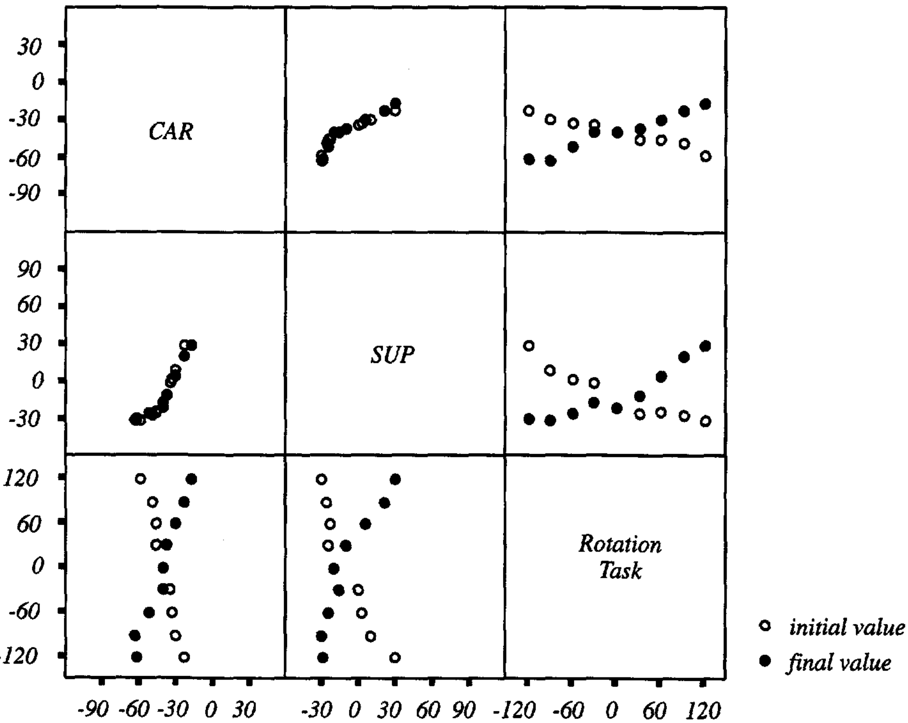


figure 5-6: Tactic B2 (subject 1). A matrix plot of the CAR × SUP × *Rotation Task data. See figure 5-4 for further explanation*

Comparison of the three tactics (A, figure 5-4; B1, figure 5-5; and B2, figure 5-6) showed that the positive rotation tasks were performed in almost the same way. The initial position of the SUP and CAR angles was almost constant for all positive rotation tasks. Depending on the magnitude of the tasks, the subject changed his arm position mainly by altering the SUP angle with little change in CAR. The differences between the subjects become manifest particularly when negative rotation tasks were performed.

Are all possible combinations of sup *and* car *used?*

Another striking resemblance between the subjects is the limited use of combinations of sup and car. In principle all combinations of sup and car are possible, as long as they are within the range of movement. Subjects, however, do not use them all. In figure 5-7 we divided the area sup × car into squares of 10° × 10°. For all thirteen subjects we determined the number of initial and final combinations that occurred in each square. The relative number for each square is given on the vertical axis (in percentages). In essence the full ranges of the sup and car movements were used. In no case, however, was there an initial or final combination of a large positive sup and a large negative car. Moreover positive car angles rarely occurred in the initial and/or final positions. The initial and final combination most frequently encountered was about -20° sup × -20° car (+/- 10°).

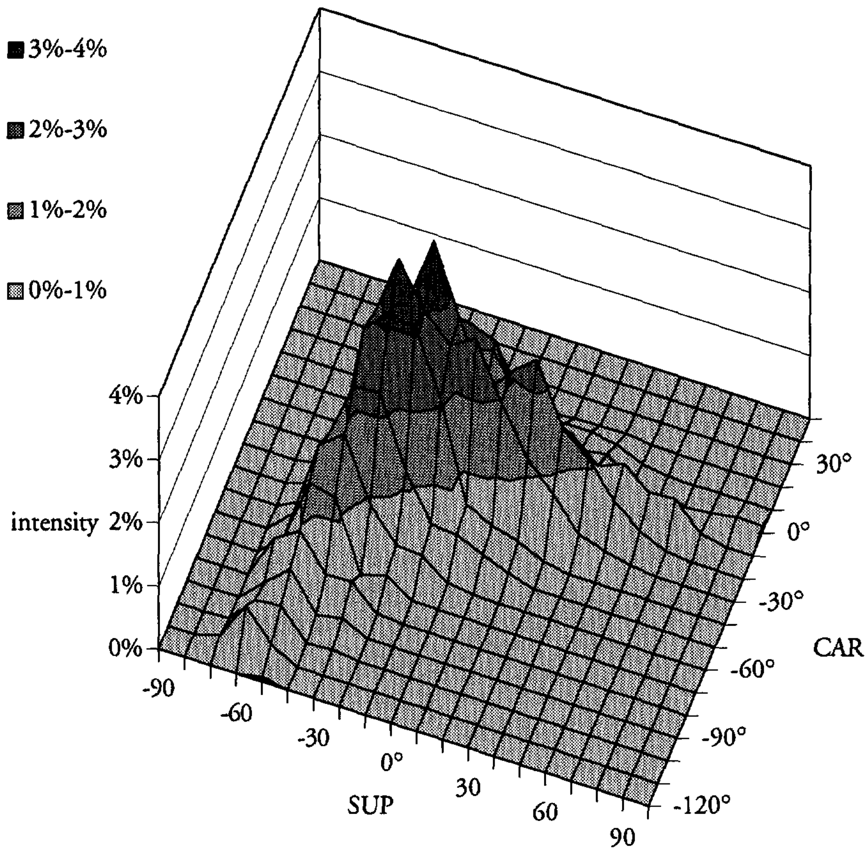


figure 5-7: Graph of the use of initial and final combinations of sup × car *for all thirteen subjects. The vertical axis represents the percentage samples in each of the 10° × 10° squares.*

Discussion

The results of the experiments showed that the complete rotation task cannot be explained by sup and car. Although we asked the subjects to perform the rotation tasks only by means of SUP and CAR, subjects must have used other additional movements to perform the tasks. Since we only measured arm movements, we cannot say which part of the body provided the rest of the rotation. We suspect that shoulder and trunk movements were responsible. The major part of the rotation was, however, indeed performed by SUP and CAR movements. Therefore, we believe that the most important part of rotation can be described by SUP and CAR movements.

The results of ANOVA showed that each subject was constant in his performance of the set of rotation tasks, i.e. the number of repetitions had no effect on the initial and final joint angles. There were, however, differences between subjects. The results of the experiment show that there are at least two ways to perform the set of rotation tasks. The outcome of cluster analysis indicated a separation into an A-group and a B-group. As mentioned before, the A-tactic can be characterized as starting all rotation tasks from a constant initial position, independent of the direction and magnitude of the task. The B-tactic, on the other hand, can be characterized as anticipating the movements needed to achieve rotation, the initial position changing as the task is changed. A remarkable outcome of the experiments is that all subjects (independent of the tactic used) performed the positive rotation task in nearly the same way.

Our separation of the subjects into the two B groups was not supported by the results of the cluster analysis. The reason for this is that cluster analysis depends strictly on quantitative data. With this method the dissimilarity coefficient is determined for all subjects. Then two subjects, later on two groups of subjects, with the smallest increase in the index *E* were clustered together (see Romesburg, 1984 p.129-135). For this analysis we used the median values of the difference between the final and the initial joint angles, because we were not interested in the exact initial and final joint angles but in the relationship between the two (i.e. two subjects who exhibit the same relationship between initial and final joint angles but one uses angles which are all 10° larger can be considered as applying the same tactic). This also explains why this method did not distinguish between groups B1 and B2. When the differences between the final and initial angles for all tasks are examined the B1 and B2 tactics will not exhibit a clear difference. For the separation into groups we used the same data as for the cluster analysis. But we were able to use filters which are hard to quantify. For example the position of all initial and final joint angles relative to one another was used. This resulted in subdivision of the B-tactic into B1 and B2. Moreover, it must be noted that when we use the word constant to describe, for example, the initial SUP angles for tactic B1, this means that the data showed that this subject tended to start with the same SUP angle, although each of the initial angles varied somewhat with the magnitude of the tasks. It is arbitrary to discriminate between an overall constant joint angle and joint angles dependent on the magnitude of the rotation task.

In the introduction of this chapter the problem of performing rotation tasks with the O-control was mentioned. In that case the only restriction, imposed by the investigator, is the amount of change between SUP and CAR. No starting positions were imposed. The subject was allowed to choose any position. The subjects in group A, however, always started from the same arm position, i.e. constant SUP and CAR angles.

This is in direct contrast to expectations, according to Rosenbaum and colleagues, of a constant final position for all rotation tasks (see table 5-1, column 1 and 3). The concept of end-state comfort cannot therefore be used to explain or predict the outcomes of our rotation tasks. A remarkable finding is the fact that the constant initial position is not 0° SUP and 0° CAR. For four of the five subjects in group A the constant initial position was about -20° for the SUP angle as well as the CAR angle (subject 13 showed a constant initial SUP angle of about 20°). Consequently, these subjects had a larger SUP range for the positive rotation tasks than for the negative rotation tasks. The result is that the positive rotation tasks could be performed with relatively more SUP; for negative rotation relatively more CAR had to be used because the required range of movement cannot be supplied by the same ratio of SUP to CAR as used for the positive tasks. This constant initial position was also found for the subjects who used tactic B1 and 2; in this group too the initial position was about -20° SUP and CAR for all positive rotation tasks. The constant values found for the SUP and CAR angles were not what we expected to find. But when one looks at people in daily life, one can see that most of the time the arm does not hang down vertically and the hand is not in the sagittal plane. Most of the time, the upper arm is slightly abducted, in many cases the palm of the hand faces downwards. In light of this the constant joint angles found become more logical.

Group B showed that there is, in fact, no general constraint on the initial position of the arm. From this we may conclude that the subjects in group A performed the rotation tasks by applying their own restrictions. Bernstein (1967) noted that when people learn movements, they freeze a certain number of degrees of freedom during the initial learning phase (see also chapter 2). The result is a less complex situation, in which fewer degrees of freedom have to be controlled. This might be the case for the subjects in group A. They might have frozen the freedom to choose an initial position, which was always a constant combination of SUP and CAR, independent of the magnitude and direction of the tasks. These subjects did not anticipate the task, making the initial phase of the task easier to control since the starting point could be used as a general reference point.

In a small extra experiment we asked two young girls (aged 3 and 5 years old) to perform the rotation tasks. Although the two girls performed the rotations with a large degree of variation within each task, both tended to perform the task by applying the A-tactic. This is what we expected, because it was assumed that these children would perform the rotation task in the simplest manner, i.e. without anticipating either the magnitude or the direction of the task and by assuming an overall constant reference point.

The subjects in group B altered the initial position for the diverse tasks, depending on either the direction or the direction and the magnitude of the rotation. The consequence of this kind of adaptation to the task is that all rotation tasks can be performed essentially by using only SUP. When a negative rotation task is to be performed, the subject can anticipate by performing a SUP while reaching for the knob. In this case the range of SUP, when the knob is grasped, is enough to perform the rotation task. For positive rotation tasks too this kind of adaptation can be applied. In that case the anticipatory movement consists of negative SUP.

By using anticipatory SUP movements, the contribution of CAR can be minimized. Group B can be characterized as the group that anticipated the task. Group B, however, could be divided into more than one tactic. Some used both SUP and CAR movements, while others used almost only SUP. Comparing the overall results with predictive model 2, based on Bullinger and Solf (1979), we concluded that the theory of Bullinger and Solf cannot be confirmed by our data either. On the other hand, the data showed that in all cases most of the rotation tasks involved more SUP than CAR. When the performances of group A are examined, one can see that the positive rotation tasks were performed mainly by SUP, with only a little CAR, although CAR could also have been used. Whenever the range of SUP is not enough to perform the tasks mainly by SUP (e.g. the negative rotation tasks in group A), then (and only then) extensive CAR movements will be used. From this we may conclude that these subjects prefer the use of SUP above the use of CAR. Analysis of tactic B1 (see figure 5-5) also showed that these subjects prefer the use of SUP. They almost never used CAR movements. Therefore, we can conclude that, when performing rotation tasks, subjects prefer to use the more distal movements (SUP) above the more proximal movements (CAR), which tends to confirm Bullinger and Solf. It is, however, not correct to say that in the case of small rotations only the more distal movements will be made and that the more proximal movements will be reserved for the larger rotation tasks. Almost every subject applied SUP movements as well as CAR movements for all rotation tasks; however the ratio in most cases was in favour of the SUP movement. ANOVA yielded an overall delta of 28°, i.e. the rotation movements contained twice as much SUP as CAR. However, we have seen that this relationship depends on the tactic used. For instance subjects who used tactic B1 used almost only SUP and hardly any CAR. When the delta for tactic A was analysed it appeared that as the negative rotation tasks increased in magnitude the contribution of CAR increased at the expense of SUP.

Therefore it can be concluded that subjects prefer SUP over CAR. This preference seems to be independent of the magnitude of the rotation task. Still, most of the subjects used SUP as well as CAR movements. In general, subjects used distal SUP movements twice as often as proximal CAR movements. However when the limit of the range of movement of SUP is reached, the ratio between SUP and CAR will change in favour of CAR.

In all cases it is remarkable that only a small part of the SUP × CAR joint space was used. A possible reason for this phenomenon could be the passively imposed joint movements of the wrist. When rotation was performed, the task was conducted by using SUP and/or CAR. Due to the position and orientation of the forearm, a change in wrist angle will be imposed passively.

To determine the effect of the CAR and SUP angles on the wrist angles, the arm is represented as a wire frame (like that used to determine the SUP and CAR angles, see paragraphs 3.3 and 3.4). Figure 5-8a shows the wire frame in the global coordinate system of the shoulder. To determine the joint angles of the wrist, one can transform the arm and shaft to the local coordinate system of the forearm, see figure 5-8b. In this coordinate system it is easy to determine the wrist joint angles. Since, also for wrist angles, joint motion is defined as starting from the anatomical position (see figure 3-2), it is, in fact, not possible to use the terms abduction and flexion for most postures. Given a position of the hand relative to the forearm (see figure 5-8), dorsal flexion is defined as:

$$\arctan\left(\frac{a_y}{a_z}\right)$$

and ulnar abduction as:

$$\arctan\left(\frac{a_x}{a_y}\right)$$

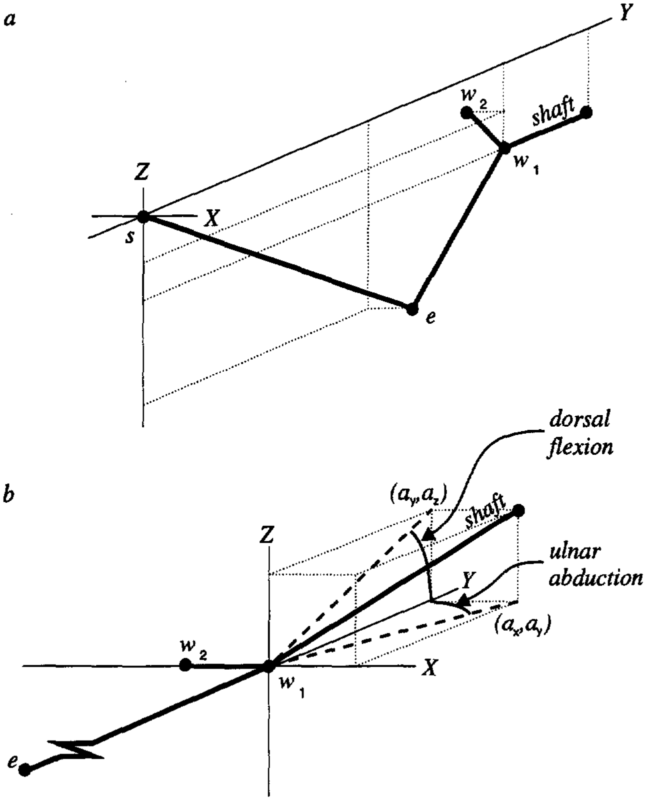


figure 5-8: The arm represented as a wire frame. In a) the position of the elbow (e), wrist (w_1 and w_2) and shaft (a_{xyz}), relative to the shoulder joint (s). b) The transformation to the local coordinate system of the forearm, which was used to determine the wrist angles.

The effect of the CAR and SUP angles on the wrist angles depends on the angle of flexion of the elbow and the lengths of the upper arm and forearm. In our calculations elbow flexion was 45°, as applied in the experimental situation. The length of the upper arm was 30 cm and the length of the forearm 25 cm, both being rough estimates.

In figure 5-9 the imposed wrist angles are shown. Figure 5-9a and 5-9b, respectively, show dorsal flexion and ulnar abduction as a result of the combination of SUP and CAR. This combination determines the imposed wrist angles. In table 3-1 the ranges of motion of the various joints are given. According to AAOS ulnar abduction is possible between -20° and 30°. The range of motion for dorsal flexion is larger: -80° to 70° (radial abduction and palmar flexion are both indicated by negative values). It must however be stated that the two degrees of freedom of the wrist are not fully independent of each other. Savelberg (1992 p. 87) has shown that when the maximum excursions of the hand for the different movement directions are plotted in a 2D picture, a kidney-shaped plot of wrist joint movements with the concavity on the radial side is obtained. The consequence is that the combination of a maximum or minimum abduction and a maximum or minimum flexion will be less than expected for the separate ranges of motion.

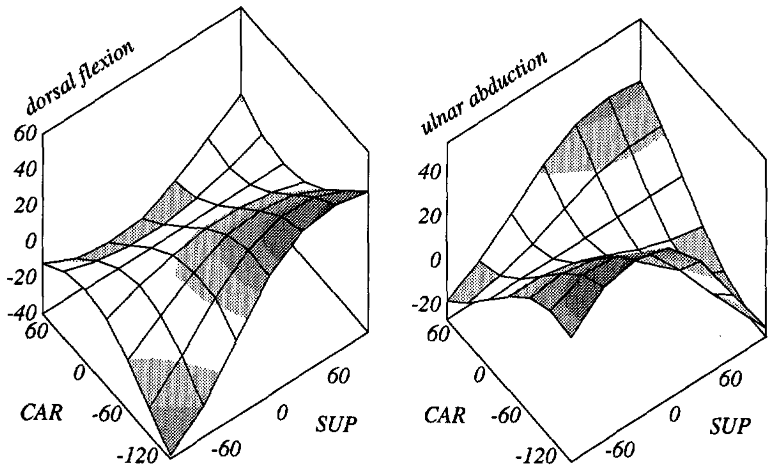


figure 5-9: The effect of the combination of SUP *and* CAR *on the passively imposed wrist angles. On the left (a) is dorsal flexion and on the right (b) ulnar abduction (palmar flexion and radial abduction are both indicated by the negative sign).*

It can clearly be seen that arm postures with a CAR angle of 0° do not impose a change in wrist angle, independent of the SUP angle. When the CAR angle is not 0°, the wrist will exhibit an abduction and/or flexion angle. The sizes of these wrist angles depend on the size of CAR and the size of SUP. From figure 5-9 we can conclude that some combinations of SUP and CAR are impossible, since these combinations require wrist angles which are outside the range of motion. Ulnar abduction in particular limits the possible combinations of SUP and CAR: an extreme negative CAR angle combined with a negative SUP angle requires ulnar abduction angles of more than 30°. From this it is concluded that movements performed in combination with a CAR of nearly 0° are to be preferred. This is in agreement with the data found (see figure 5-7).

Another reason for a preference for SUP above CAR could be the physical cost of holding the arm posture. When the CAR angle is near 0° no remarkable muscular activity is needed to maintain this posture. Both negative and positive CAR angles, however, require muscular activity, because gravity will automatically pull the arm back to zero. When the SUP angle exceeds zero gravity will not cause a change in effect. From this it can be concluded that an alteration in CAR angle will cost relatively more than an alteration in SUP angle, and therefore subjects will prefer to use SUP. Moreover, comparison of the number of muscles involved (see table 3-2) and the total mass indicates that a change in CAR angle from the neutral position costs more energy than a change in SUP.

5.2.2 Lateral grip

In the next five subparagraphs (5.2.2 to 5.2.6), some variations in the standard experiment will be described. In these experiments, the grip, left-handed subjects, visual information, elbow flexion angle, and rotational resistance were investigated.

Method

The first variation was the grip used. In the standard experiment, subjects had to use the rather cumbersome central grip (see figure 4-1). The shaft of the control had to be grasped between the third and fourth fingers. Most of the subjects had to get used to this grip. A more natural approach to a rotation task is the lateral grip (see figure 4-1). This grip is preferred, for instance, when performing such tasks as holding a screwdriver. With the lateral grip the knob is held in the palm of the hand. The hand is placed in ulnar abduction, since the shaft of the knob lies between the thumb and the index finger, which forms one line with the forearm.

Six right-handed subjects (3 males, 3 females, aged 22-40 years old) participated in the experiment. All six subjects had also participated in the standard experiment. Except for the change in grip, nothing was changed in the experimental situation. Subjects had to perform nine rotation tasks (-120° to 120°), five times in random order. Initial orientation of the control was always 12 o'clock.

Results

Is there an effect of the grip used on the rotation performances?

The results of this experiment were analysed by means of an analysis of variance. As in the standard experiment, the variable subject was assumed to be random. The outcomes of ANOVA indicated that the grip had no significant effect on either the initial or final SUP and CAR angles ($F(1,5)=0.13$, $p=.12$; $F(1,5)=1.38$, $p=.29$; $F(1,5)=1.63$, $p=.26$; $F(1,5)=8.75$, $p=.03$, respectively). Moreover the grip had no significant effect on wrist orientation either at the beginning or the end of rotation ($F(1,5)=5.83$, $p=.08$; $F(1,5)=3.38$, $p=.13$, respectively). When the relationship between CAR and SUP is examined by determining delta, i.e. the arctan of the ratio of CAR to SUP, we found a significant effect of grip ($F(1,5)=20.51$, $p<.01$). The interaction between magnitude of rotation task and the grip appeared to be not significant ($F(7,35)=2.62$, $p=.03$). In figure 5-10 the effect of grip on the deltas for each of the rotation tasks is shown. This figure illustrates clearly that a change to the lateral grip causes a decrease in the overall delta, indicating that a larger part of the rotation task is performed by SUP. The effect of the central grip on the mean delta was 33 degrees, whereas the effect due to the lateral grip was only 9 degrees, which is significantly less. This effect becomes clear when we examine the tactics in more detail. None of the subjects who used the lateral grip performed like group A, i.e. an overall constant initial position (see figure 5-4), although three of them (subjects 4, 5, and 13) were considered members of this group in the standard experiment. When using the lateral grip, all subjects anticipated the direction of the rotation task. When CAR was observed, it could be seen that the six subjects used hardly any CAR for the rotation tasks. The six subjects performed according to tactic B1 (see figure 5-5). This tactic is the use of almost only SUP with hardly any CAR. The consequence is that the overall relationship between these two degrees of freedom yields a reduction of delta.

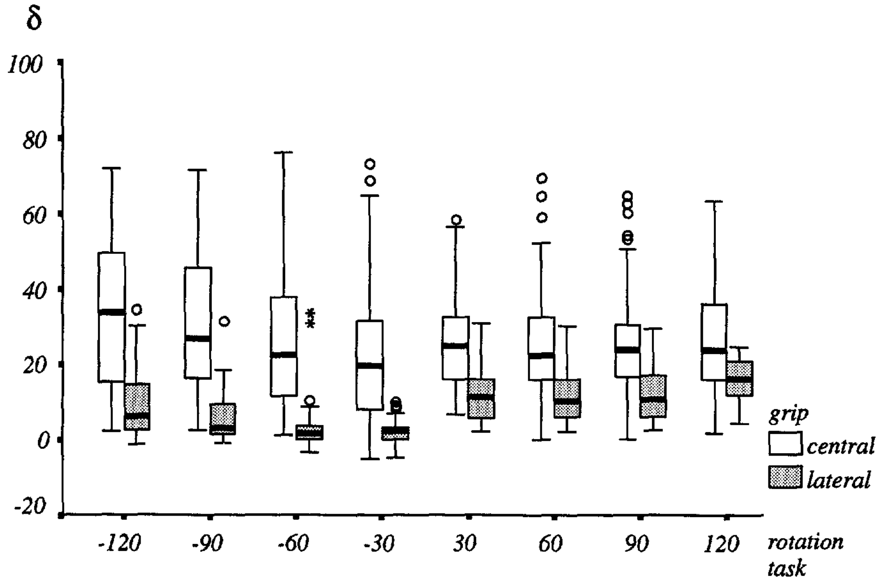


figure 5-10: A boxplot of the delta values for each of the rotation tasks. The grip for the open boxes was the central grip, for the shaded boxes the lateral grip.

Discussion

Possibly this alteration in tactic can be explained. When grasping the control in the lateral grip, the hand is in ulnar abduction. Extensive CAR movements would require an ulnar abduction angle beyond the boundary of the range of movement. By anticipating the task, the subjects could prevent this.

Another possible explanation could be the fact that the lateral grip was less awkward than the central grip. The consequence may be that subjects experienced this task as being less difficult. Introduction of the central grip, even for simple rotation tasks, is experienced as something new and perhaps therefore as a difficult motor task. When performing difficult motor tasks, people tend to freeze a number of degrees of freedom in the initial phase. Only when they have adjusted to the new situation will they release some restrictions; eventually they will use all degrees of freedom. For our rotation tasks, use of the central grip could possibly be the reason for restriction of the freedom to choose the initial wrist orientation, resulting in the A-tactic. When the same subjects are placed in a more natural environment, simply by changing the imposed grip to the lateral one, they no longer experience the situation as being difficult; consequently they do not feel the urge to freeze some of the freedoms offered by the task. As a result they performed the rotation tasks in the optimum manner. Now, subjects can anticipate the direction of the rotation tasks, which is the characteristic aspect of the B-tactic. As a result rotation is composed merely of SUP.

5.2.3 Left-handed subjects

The environment of the human being can be characterized as being designed predominantly for right-handed people. In most cases the left-handed subjects have to adjust: they simply have to use their right hand (Garonzik, 1989). However in many situations they will use their preferred left hand in a right-handed environment. Then the motor output of the left hand must resemble the motor output of the right hand. If this concept is applied to our rotation tasks, one would expect left-handed subjects to perform the rotation tasks in a direction opposite to that of right-handers. Left-handed subjects will use -SUP and -CAR instead of SUP and CAR. Therefore those applying the A-tactic will exhibit a constant initial position of about 20° for all tasks instead of the negative SUP angle found for right-handed subjects. The positive tasks will be performed mainly by using -SUP, and the negative tasks will consist of relatively more -CAR. This applies when the motor output plays the most important role in the achievement of the tactic.

Another idea may be that the tactics are based mainly on anatomical constructions. In this case left-handed subjects perform negative rotation tasks like right-handed subjects perform positive rotation tasks. Therefore the A-tactic will still result in an overall constant initial position of about -20°; however now the negative tasks will be performed mainly by SUP, instead of the positive tasks as for right-handed subjects.

Method

In the next variation we investigated whether the tactics are based mainly on output, i.e. SUP and CAR are replaced by -SUP and -CAR, or on anatomy, i.e. the negative task was performed like the positive task for right-handed subjects. Therefore, left-handed subjects were asked to perform the rotation tasks. Seven subjects (4 males, 3 females, all students) served as volunteers. These subjects used their left hand for most of their daily tasks. Rotation tasks, such as holding a screwdriver, were performed only with the left hand.

This experiment consisted of two subexperiments. Subjects had to perform the rotation tasks by means of the central grip and the lateral grip. In each subexperiment the nine different rotation tasks were repeated five times. The order of the two experiments was randomized. To determine the joint angles for left-handed subjects, we rotated the subject 180° in the experimental situation so that the left side of the subject would be towards the cameras.

Results

What is the difference between left-handers and right-handers?

In the first part of the analysis we only used data from the experiment with the central grip; this data was compared with data from the standard experiment. We compared the two data sets in two ANOVA's. Since the subjects were not the same, i.e. left-handed versus right-handed, the factor subject (random) was nested within the factor 'hand used'. In the first ANOVA we changed the values of the joint angles, i.e. SUP becomes -SUP and CAR becomes -CAR. The outcome of this ANOVA showed a significant effect of the factor 'hand used' on all the initial and final joint angles: initial SUP $F(1,12)=36.9$; initial CAR $F(1,12)=51.5$; final SUP $F(1,12)=62.8$; and final CAR $F(1,12)=40.3$. All p-values were below .01. In the second analysis we inverted the sign of the task. For the initial SUP, initial CAR, final SUP, and final CAR, the outcome showed no significant effect on the hand used ($F(1,12)=.13$, $p=.73$; $F(1,12)=.85$, $p=.37$; $F(1,12)=1.13$, $p=.31$; $F(1,12)=.32$, $p=.58$, respectively). From these results it is concluded that left-handed subjects performed the rotation tasks in an inverted way, i.e. the anatomy plays an important role in the achievement of tactics. For left-handed subjects, the motor outcome was inverted just like the anatomy.

Also, the matrix plots for the subjects revealed that the left-handed subjects performed rotation tasks in the opposite fashion; they did not convert SUP to -SUP and CAR to -CAR. Two of the seven subjects (14 and 15) performed in a way that can be compared with the A-group of the standard experiment. These two subjects approached the rotation tasks by starting every task from a constant initial position (SUP and CAR). In the case of negative rotation tasks they generally used SUP with only some CAR. For the positive rotation tasks, however, the amount of SUP available to perform the task was not enough; consequently a large amount of CAR had to be used. This was also observed for the negative rotation tasks in the standard experiments, in which only right-handed subjects took part. The other five subjects performed rotation by using tactic B2, like subject 1 in the standard experiment (see fig. 5-6). Of course, here too the sign of the tasks must be changed to compare left-handed and right-handed subjects.

The results of this part of the experiment lead us to conclude that performances are determined, to a significant degree, by the anatomy of the arm. When, however, the B1 tactic is analysed it appears that the performances could be reflected either in the task, i.e. the positive tasks of the right-handed must be compared to the negative tasks of the left-handed, or in the joint angles, i.e. positive SUP and CAR values are replaced by negative joint angles. The two cases will result in the same outcome. This relationship does not, however, apply for the A and B2-tactics. When, for instance, the joint angles for tactic A are reversed, we should get a constant initial position of about +20° SUP and +20° CAR. This is not what we found. Left-handed subjects who applied the A-tactic also had an overall constant arm position of about -20° SUP and CAR. We, therefore, conclude that the tactics applied reflect the tasks and not the sign of the joint angles.

What is the effect of the grip on the used tactic?
In the experiments that focussed on the central grip, none of the subjects performed the rotation task according to tactic B1 (see figure 5-5). When, however, the grip was altered to the lateral grip, all seven subjects performed the rotation task by applying tactic B1. The outcome of ANOVA, in which the delta value or the relationship between CAR and SUP was the dependent variable, also showed a significant effect of the grip used ($F(1,6)=39$, $p<.01$). For all positive rotation tasks the initial position was almost constant, i.e. close to the maximum angle of supination. For negative rotation tasks too, a constant initial position was found, only now this position was near the minimum angle of supination. The contribution of CAR, to both positive and negative rotation tasks, was negligible.

From this we may conclude that for left-handed subjects too the sequence of the change in tactics was similar to that for the standard experiment and that for the experiment in which the central grip was altered to the lateral grip. Insisting on the rather cumbersome central grip may result in tactic A (see figure 5-4). When the grip is changed to the more common lateral grip, the tactic used will change to B1. This latter tactic can be described as anticipating the direction of the rotation, which means less CAR and thus a more efficient tactic.

5.2.4 No visual information

In the standard experimental situation, there was ambient light. Subjects could easily see the position and orientation of the control, the position of the arm, and the position of the target. These perceptions are expected to be used when performing the rotation tasks. In addition to visual information other aspects of somaesthesia will provide information about the position and orientation of (parts of) the body, for instance via proprioception. If there is no visual information, it is expected that the rotation tasks will become more difficult. Then, the subjects have to determine the orientation of the wrist by establishing the SUP and CAR angle by means of only proprioception. If no visual information is available, it will be more difficult to assess the actual orientation of the wrist. When, however, the initial position can be used as an overall constant reference point, the task will be easier to control. This indicates that subjects will perform rotation by means of tactic A, i.e. they will freeze the initial freedom by using a constant initial position, independent of the magnitude and direction of the rotation task.

Method

In the experiment seven subjects (4 females, 3 males, aged 18-24 years old) served as volunteers. All subjects were also participants in the standard experiment. The subjects were blindfolded during the experiment; no feedback was given. The rest of the experimental situation was the same as for the standard experiment.

Before the actual experiment started, the subjects were allowed to practice the rotation tasks. The investigator called a target position in clock-code, and the subject grasped and rotated the control. By giving knowledge of result, the subject could improve his performance. Practice consisted of eight targets (the 0°-task was not practiced), each repeated five times.

Results

Is there a significant effect of the factor vision on the performances?

The results of the experiment were analysed by ANOVA. Again, the subject was assumed to be a random factor. Contrary to expectations, the results of ANOVA revealed no significant effect of the factor vision. For the initial SUP and CAR and the final SUP and CAR the results were $F(1,6)=6.47$, $p=.04$; $F(1,6)=6.05$, $p=.05$, $F(1,6)=3.83$, $p=.10$, and $F(1,6)=2.39$, $p=.17$, respectively. There was no significant effect on initial and final wrist orientation $(F(1,6))=2.31$, $p=.18$; $F(1,6)=4.95$, $p=.08$). Delta, which indicates the ratio between CAR and SUP, showed no significant effect ($F(1,6)=2.39$, $p=.17$).

When the matrix plots of the results are examined visually, it can be concluded that three of the seven subjects used tactic A during the non-visual experiment. Tactic B2 was used by the rest of the subjects. During the standard experiment only two subjects used tactic A. One of them, however, used tactic B during the non-visual variation. Two subjects who used tactic B during the standard experiment used tactic A for the non-visual variation.

From these results little can be concluded about the visual component as a factor for the choice of tactic. Although two subjects changed to the A tactic, one subject also switched to the B tactic.

5.2.5 Distance to control

In the discussion in paragraph 5.2.1 it was noted that the passively imposed wrist angle may constrain the use of combinations of the joint angles. When the imposed wrist angles were determined, it became clear that a CAR angle near 0° would be preferable, because this angle does not impose a change in wrist angles. In the discussion of paragraph 5.2.1 it is stated that the effect of the SUP and CAR angles will be different when the elbow is not bent 45°. Figures 5-11 and 5-12 show the effect on the wrist angle of an elbow flexion angle of 10° and 90°, respectively (note that in figure 5-12 some data were out of range and therefore not displayed). These two figures illustrate clearly the effect of the elbow angle on the imposed wrist angles. Also it can be seen that when the arm is nearly extended, hardly any change in wrist angle will occur. But, when the angle of flexion is increased to 90°, the wrist angles will be large when the CAR angle increases only slightly from the 0° position. These facts suggest that the angle of elbow flexion may influence the choice of various combinations of SUP and CAR.

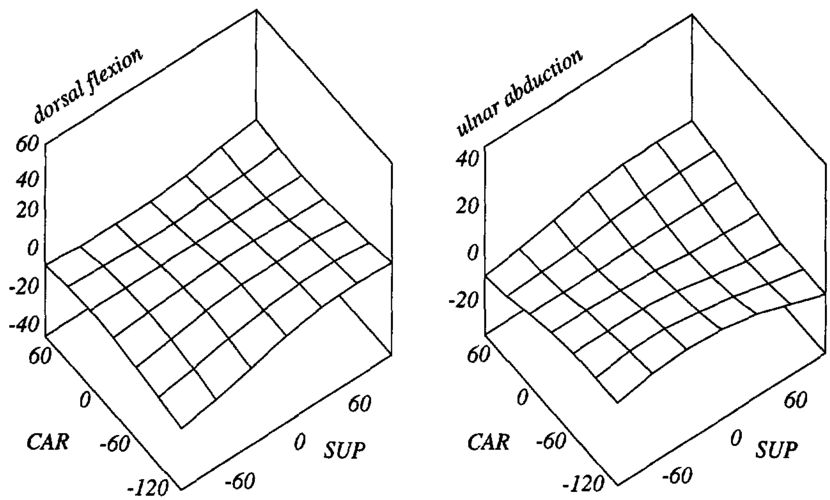


figure 5-11: The effect of the combination of SUP *and* CAR *on the passively imposed wrist angles. On the left is dorsal flexion, on the right ulnar abduction (palmar flexion and radial abduction are both indicated by the negative sign). The angle of flexion of the elbow is 10°.*

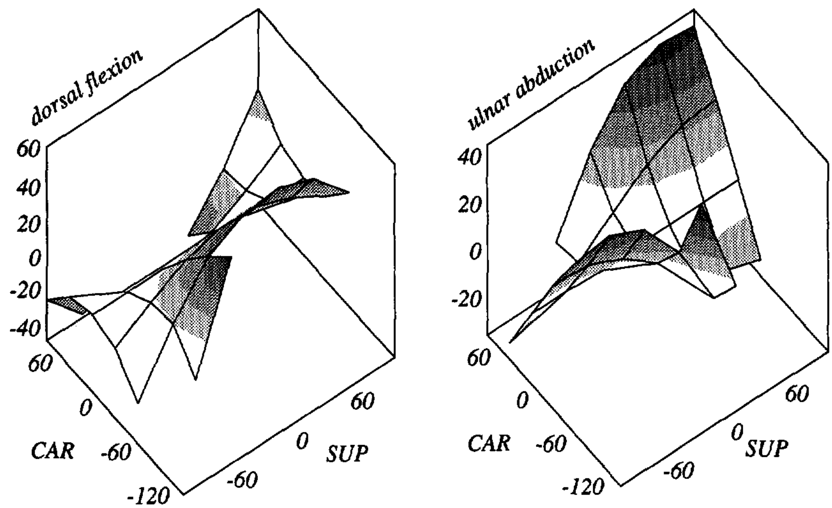


figure 5-12: The effect of the combination of SUP *and* CAR *on the passively imposed wrist angles. On the left is dorsal flexion, on the right ulnar abduction (palmar flexion and radial abduction are both indicated by the negative sign). The angle of flexion is 90°. The combinations of minimal* CAR *with maximum or minimum* SUP, *and maximum* SUP *with minimum* SUP *resulted in angles outside the range of the axis and are therefore not presented in the figure.*

As mentioned in the discussion of paragraph 5.2.1, gravity may also be relevant in the choice of combinations of SUP and CAR. In case of an extended arm in line with the shaft of the control, alteration of both SUP and CAR will have almost no effect on the local centre of gravity of the arm. Consequently, the effort to hold the arm in that posture will not change. From this it can be concluded that when the arm is extended, rotation tasks will be performed by both SUP and CAR. Neither will be superior to the other. When, however, the arm is flexed 90°, an alteration in the CAR angle will have a marked influence on the local centre of gravity of the arm. In this latter case, the subjects will use little CAR to rotate the control.

In addition to these two possible causes of the limited use of combinations of SUP and CAR, which can be described as hard constraints, soft constraints may also be responsible. In chapter 3 it was shown that fewer muscles are involved in SUP than in CAR (see table 3-2). Not only the number of muscles but also the total mass is less. From this we may conclude that SUP is more economical than CAR. This may mean that a soft constraint is involved: the use of distal movement possibilities first (SUP) and the more proximal possibilities, which are more expensive, only when necessary. In this latter case a change in the angle of flexion will have no influence on the combinations of SUP and CAR.

Method

Therefore, in the next variation of the standard experiment, we changed the position of the subject relative to the O-control. Seven students (3 males, 4 females) served as subjects in this experiment. All seven also took part in the standard experiment. Subjects were asked to use the central grip. In this variation the position of the subject relative to the control was altered. In one experiment the subject was asked to grasp the control (without intending to rotate it) with the forearm in line with the shaft and the elbow flexed 90°. In the other experiment the control was placed almost at shoulder height. When the subject grasped the control, the forearm again was in line with the shaft, but now the elbow was flexed only 10°. It was essential that the elbow should not be fully extended, since then the SUP angle could not be distinguished from the CAR angle (see paragraphs 3.3.2 and 3.4.2). The order of these two experiments was randomized among subjects.

Results

What is the effect of the angle of the elbow on the performances?

ANOVA revealed that the angle of flexion of the elbow had no significant effect on initial CAR and final CAR values ($F(2,12)=4.9$, $p=.03$; and $F(2,12)=1.9$, $p=.19$, respectively). The effect on the SUP angle, both at the start and at the end, was significant ($p<.01$). When, however, the effect on the initial and final wrist orientations is analysed, it was not significant in either case ($F(2,12)=5.8$, $p=.02$; $F(2,12)=5.9$, $p=.02$, respectively). From this it is concluded that there is no pronounced effect due to the change in angle of flexion. Remarkable is that when delta is analysed the ANOVA revealed a significant effect ($F(2,12)=18.0$, $p<.01$). Figure 5-13 shows the delta values for each of the rotation tasks under standard conditions and after changes in elbow flexion (10° and 90°). This figure shows that, in contrast to our expectations, the delta value is lower for the 10° variation than for the standard and the 90° situation ($F(1,662)=369$, $p<.01$). The change caused by flexion of the elbow from 45° to 90° is less clear but still significant ($F(1,662)=10.4$, $p<.01$). The interaction between magnitude of the rotation task and the angle of flexion was not significant ($F(14,84)=.68$, $p=.78$).

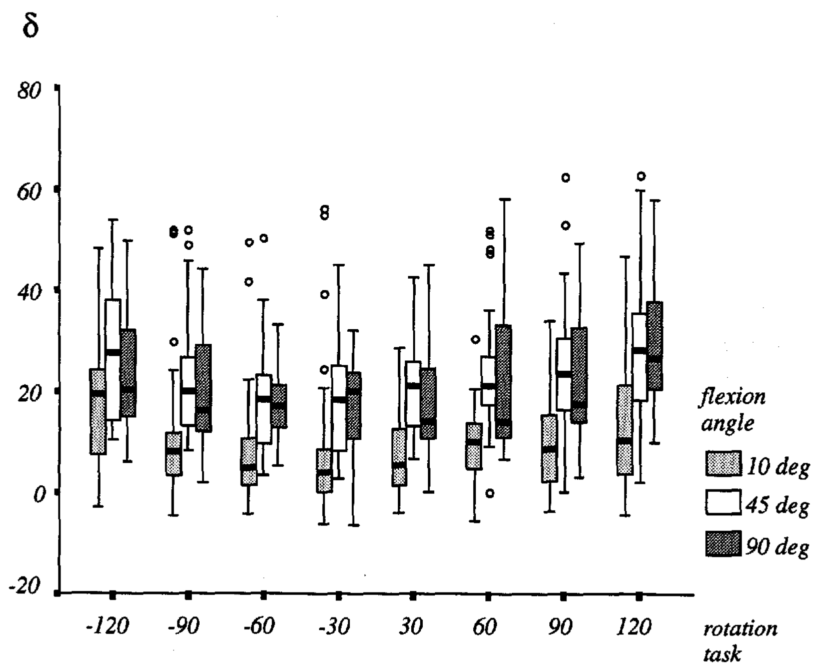


figure 5-13: The deltas for the three variations of elbow flexion. In the standard experiment elbow flexion was 45°.

Visual examination of the data on the subjects, presented in the matrix plots, suggests that systematic differences between the three experimental situations do not exist. In all cases (elbow flexed 10°, 45°, and 90°), the subjects used SUP and CAR. Even in the experiment in which the elbow was flexed 90°, the subjects used a substantial amount of CAR. This, however, applied only in the case of a nearly minimum SUP angle. In the experiment in which 10° flexion was used, the same kinds of rotation occur. If the above-mentioned hard constraints are the cause of the limited use of SUP and CAR combinations, this should not have occurred. In this situation the use of CAR would be as attractive as the use of SUP (since there is no effect due to either gravity or the passively imposed wrist angles). The limited use of combinations of SUP and CAR is therefore not caused by the hard constraints, i.e. either the imposed wrist angles or the influence of gravity. The limited use of combinations of SUP and CAR is presumed to be the result of a soft constraint: subjects prefer the use of SUP over CAR. But it should be noted that for almost every movement a subject will use some CAR. The question of why subjects in the 10° experiments used relatively more SUP remained unanswered.

5.2.6 Increased rotational resistance

In the standard experiments the rotational resistance was nearly negligible (about 0.15 Nm). In this last variation the rotational resistance was increased up to 50% of the maximal isometric moment subjects could deliver to the O-control. The resistance was increased by adjusting the force pressing against the shaft of the control (see paragraph 4.3). Now, subjects had to impart a greater momentum to the control. In this case subjects will use relatively more CAR. CAR movement is induced by the relatively stronger shoulder muscles, compared to the forearm muscles which induce SUP movement. The total momentum of CAR, however, has to be transmitted via the forearm, and therefore the forearm muscles also need to be able to deliver a large force (see paragraph 3.2). When the speed of the SUP movement is slow, zero or even negative, i.e. in the opposite direction to the CAR movement, it can deliver large forces which may be necessary to transmit the forces induced at the shoulder (compare the relationship between contraction velocity and force; see e.g. Schmidt and Thews, 1983, p.44).

Method

Seven students served as subjects (4 females, 3 males). Four of them also participated in the standard experiment. According to the subjects themselves, they did not suffer musculo-skeletal disorders of the arm. Since rotation of the control requires an optimum grip of the control, we asked the subjects to use the lateral grip. In this experiment, subjects performed the same tasks as in the standard experiment.

At the start of the experiment the maximum moment was determined for each subject. At the other end of the shaft on which the O-control was mounted, we placed a digital static torque gauge (AMETEK, model TC6000-15, 0-6 Nm, +/-5%). Subjects were asked to deliver maximum static torque in both the positive and the negative direction. The maximum torque was applied according to the procedure of Caldwel et al. (1974). The subjects were asked to increase the torque up to maximum force within four seconds and to hold this maximum torque for four seconds. The subjects were not encouraged and there was no visual feedback on their performance. In between two measurements the subjects were allowed to rest for two minutes. Subsequently, the investigator adjusted the friction device in order to increase the rotational resistance to 50% of the average maximum torque. The maximum static isometric torque varied between subjects. Therefore, the rotational resistance varied within a range of 2.1 to 2.8 Nm.

Results

Does the increased resistance affect the choice of tactics?

Only four of the seven subjects had also participated in the standard experiment, and only these four were included in the statistical analysis. The results of ANOVA (the factor subject was assumed to be random) revealed that there was no significant influence on the initial and final SUP values ($F(1,3)=2.63$, $p=.20$; $F(1,3)=2.56$, $p=.21$). The hypothesis that an increase in force would not affect the initial and final CAR values was valid at a significance level of .05. When, however, the initial and final wrist orientations were analysed, neither showed a significant effect ($F(1,3)=9.17$, $p=.06$; F91,3=9.58, $p=.05$). Moreover the effect on the ratio of CAR to SUP, i.e. delta, was analysed. The outcome of this ANOVA revealed no significant effect due to increased resistance ($F(1,3)=9.58$, $p=.06$). It was therefore concluded that increased rotational resistance has no influence on the way subjects perform the rotation tasks.

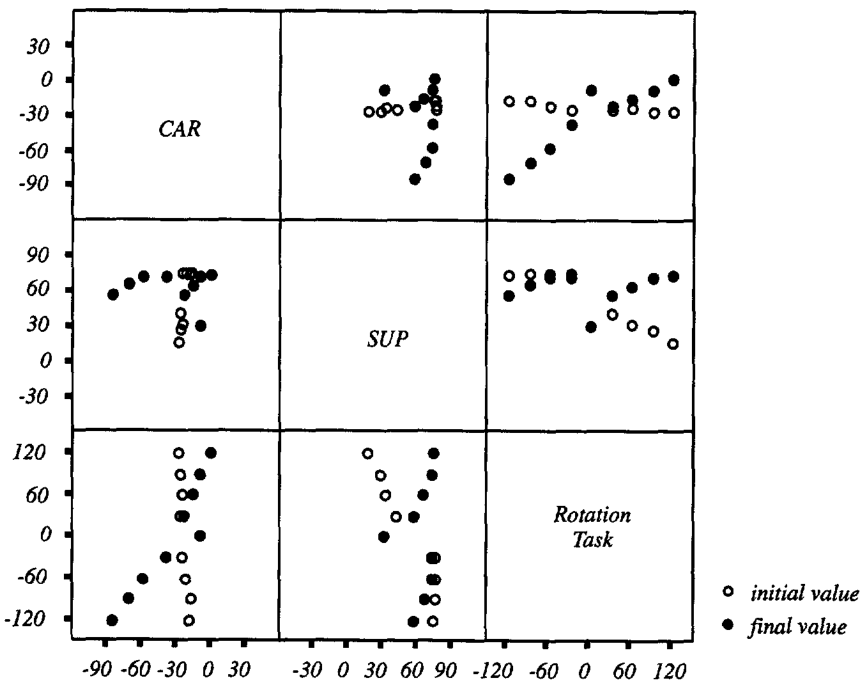


figure 5-14: A matrix plot of the CAR × SUP × *Rotation Task data (subject 13). See figure 5-4 for further explanation*

When, however, the matrix plots for the subjects are examined, it is apparent that subject 13 performed the rotation tasks in a completely different way (see figure 5-14). Examination of the sub-graph SUP × CAR reveals that this subject used an entirely different part of the joint space. The negative rotation tasks in particular were performed in a unique way. This subject started negative rotation tasks by adjusting the arm to the nearest maximum SUP angle; the task was then performed by using almost only CAR. Meanwhile, the subject maintained the maximum SUP angle. This maximum SUP angle will remain maximum, without any muscular effort, because the negative CAR movement automatically induces a maximum SUP angle. Here no distal muscular forces are needed to maintain the SUP angle, since the proximal forces are transmitted by passive elements such as bone, fibrous capsule, and ligament. The performance of positive rotation tasks resembled more closely the performance by other subjects. It is still considered remarkable that this subject started all positive tasks from a positive SUP angle, in contrast to most other subjects. This subject also exhibited the same difference with respect to standard rotation tasks. Then the subject used tactic A, starting all rotation tasks from a positive SUP angle.

All other subjects exhibited a B1-like tactic, i.e. depending on the direction of the rotation tasks, the subjects started from one of the two constant SUP angles. Depending on the direction of rotation, the subjects started from the nearest maximum SUP angle for negative rotation tasks and from the nearest minimum SUP angle for positive rotation tasks. All tasks were performed mainly by changing the SUP angle; the contribution of CAR remained small.

According to analysis, we may conclude that the rotational resistance has no influence on the motor performances of the subjects. A striking result is that almost all subjects used tactic B1 to perform the rotation tasks. This might be attributed to the increased resistance, but it could also be explained by the lateral grip.

5.3 Conclusion

This chapter focusses on the O-control. In the introduction it was noted that an abundance of degrees of freedom can lead to an infinite number of possible ways to perform rotation. Not only the ratio between the two degrees of freedom but also the initial orientation is in principle free. The results, however, show that people rotate in a constant way. When one and the same rotation task had to be performed five times, data analysis showed no significant influence of the number of repetitions. In addition to the constant motor behaviour exhibited by each subject, we also found constant behaviour between some of the subjects.

Nevertheless, it appeared that the tasks were never performed in just one way. In the experiments we identified at least three different tactics. We called them A, B1 and B2. The A tactic can be described as an overall constant initial wrist orientation (about -20° for both joint angles), which was independent of the magnitude and direction of the rotation tasks. According to this tactic subjects use both SUP and CAR movements. The overall ratio of the two degrees of freedom was 1 to 2. When, however, a large negative rotation task had to be performed, the range of SUP movement was not sufficient to perform the task in the same way as all other tasks were carried out. The subjects reached the limit of the range of SUP. Consequently, they had to use more CAR for this rotation task.

Characteristic of the other two tactics is the fact that the subjects anticipated the task. When tactic B1 is further analysed, it can be seen that the subject used a relatively constant initial wrist orientation for both directions. This orientation was different for the positive and negative rotation tasks. For the positive tasks, the initial position was characterized by an almost minimum SUP value. In contrast, for negative rotation tasks, this constant initial position was nearly equal to the maximum SUP value. For all rotation tasks the contribution of CAR was almost negligible. The movement consisted predominantly of SUP.

For the other B tactic (B2) we found that the negative rotation tasks exhibited a nearly constant final position. Subjects, who used this tactic, anticipated the negative rotation tasks by adjusting the initial wrist orientation to the magnitude of the required task. The positive rotation tasks were conducted in the same way as for tactic A.

Remarkable is that the differences among the three tactics almost always became manifest in the negative rotation tasks. All subjects performed the positive rotation tasks in nearly the same way, i.e. they started from an almost constant initial position and depending on the magnitude they altered the SUP (and sometimes CAR) angle. This does not agree with expectations based on literature. Rosenbaum and colleagues mentioned the end-state comfort effect. Subjects were presumed to perform rotation tasks such that they would end up in a comfortable position. In our experiments there were few final angles that were the same for more than one task.

Another concept was based on the ideas of Bullinger and Solf (1979). In their view subjects will first use SUP movements; when the range of movement of SUP is not sufficient, then CAR movements will be used. This too was not confirmed by our experiments. Subjects almost always used SUP movements as well as CAR movements in a fixed ratio (this had also been found for instance for pointing tasks, see Lacquaniti et al., 1982; Soechting and Lacquaniti, 1982 and 1983; Cruse, 1986). Depending on the tactic used, the ratio between the two degrees of freedom may change. There is nevertheless indeed a general preference for the usage of distal SUP movement. In most cases subjects used relatively more SUP than CAR movements. The mean ratio between these movements was 2 : 1. This ratio depended on the tactic used. With tactic B1, for instance, the subjects used hardly any CAR. The other two tactics, A and B2, included CAR. Also, when tactic A is further analysed, it can be seen that for right-handed subjects the larger negative rotation tasks were performed with relatively more CAR. The reason for this is the limit of SUP. During these tasks the subjects reach the limit of SUP and consequently have to use more CAR to achieve the required rotation.

The experiment with the left-handed subjects showed that the anatomical structure of the arm of the subject is of major importance as far as tactics are concerned. For left-handed subjects the tactics were not simply transferred to the left hand but also reflected the tactics of the right-handed subjects, in analogy to the anatomy of the arm.

A remarkable finding was the limited use of combinations of SUP and CAR. It was rare for subjects to use a combination of a large positive SUP and a large negative CAR (only subject 13 in the experiment with increased rotational resistance proved to be an exception to this rule). By changing elbow flexion, we studied whether hard constraints such as gravity and passively imposed wrist angles could cause such limitations. The results of these experiments, however, do not support such a concept. We assume that the limited use of combinations of SUP and CAR is due to soft constraints; subjects prefer the more economical distal movements (SUP) to the more expensive proximal movements (CAR). The most common wrist orientation was about -40°. This wrist orientation was frequently seen at the start of the rotation task (for all tasks executed via the A-tactic; for all initial orientations of the positive tasks executed via tactics B1 and B2), as well as the end of negative rotation tasks performed according to the B2 tactic. We expect that this wrist orientation is the most neutral one.

The experiments revealed three different tactics for the approach to the rotation tasks. The A tactic is expected to be the simplest way to perform the set of tasks (two little girls also used this tactic). For every task one and the same position of the wrist is considered as the initial posture. Depending on the magnitude and direction of the task, subjects altered the SUP angle and to a lesser degree the CAR angle. For the larger negative rotation tasks (for right-handed subjects), the limits of SUP were reached and, consequently, the subjects used relatively more CAR than SUP for these tasks. In fact, these subjects reduced the amount of freedom, because they did not anticipate at the start of their task. The B group, on the other hand, can be described as anticipating either the direction or the direction and magnitude of the rotation task (B1 and B2, respectively). These tactics, therefore, require a more complex control. Upon changing the cumbersome central grip to the more common lateral grip, we found that subjects changed their tactic. When using the lateral grip people generally used the B1 tactic. This could, however, be due to the imposed ulnar abduction of the wrist, which is induced by the lateral grip. In the experiment in which the distance to the control was changed, the change in the passively imposed wrist angle had no influence on the performance of the set of rotation tasks. It is, therefore, concluded that the change in tactic which accompanies the switch to the lateral grip is not caused by changes in the wrist angle. It seems more likely that the change in tactics was caused by the fact that this lateral grip is more common. This tactic is presumed to be the most economical, since in this way subjects used only the distal SUP movements; hardly any CAR movement was necessary.

6 Directional rotary controls

In this chapter the directional rotary controls (the T- and L-control) will be discussed. As described in chapter 4, these directional controls are sensitive to the orientation, i.e. the frontal view of the control changes in appearance with rotation of the control. The difference between the T- and the L-control is the position of the shaft relative to the handle. The experiments with the L-control will be described in paragraph 6.2. First we will deal with the T-control.

6.1 T-control

6.1.1 Introduction

The T-control is mounted in the centre of the cylinder to the shaft, so that a rotation of 180° gives the same frontal view. The position of the hand, relative to the shaft, is analogous to that for the O-control; the control is grasped with the axis between the third and fourth fingers (see figure 4-2). The experimental conditions, such as the position of the control relative to the subject, the rotational resistance, etc., were the same as in the standard experiment with the O-control. Also in this experiment a pointer was attached to the shaft of the box. This pointer was placed parallel to the orientation of the control. For a general description of the experiment see chapter 4. A more detailed description of the experiment with the T-control is presented in paragraph 6.1.2.

When this control is compared with the O-control, one must conclude that for the task of rotation the O-control has fewer degrees of freedom than the T-control. Subjects were asked to use SUP and CAR while performing rotation, as in the O-control experiments. When rotating the T-control, the orientation of the wrist at the start and the end of rotation is imposed by the control. For each position the sum of the SUP and CAR angles must be about equal to the orientation of the control. The ratio of SUP to CAR, while rotating the control, however, is not imposed by the control. When grasping the control which has a specific orientation, there is no continuous choice of initial wrist orientation. In most cases wrist orientation is imposed by the control. Sometimes there are two discrete ways to grasp the control. Then subjects have to choose (most likely subconsciously) whether to grasp the control by the thumb-towards grip or the thumb-away grip (see figures 4-2b and c). In the event of the thumb-away grip the orientation of the wrist changes 180° with respect to the orientation of the control, as indicated by the pointer on the shaft.

Rosenbaum and colleagues (1988 - 1993) conducted several rotary experiments which can be compared with our rotary task. From their experiments (see paragraph 2.2.3 for an overview) they concluded that subjects, who have to perform a rotation task, will grasp a bar such that the final position of the rotation will be more comfortable than the initial position. They call this the 'end-state comfort effect'. However, they did not measure any of the joint angles involved. They only scored the way the bar or handle was grasped, comparing this to ratings of awkwardness ascertained for every static posture.

In 1992 (see also Rosenbaum et al., 1988; and Rosenbaum, 1992 p. 10 and 11), subjects had to rotate a handle through 180°, starting in one of eight orientations (see figure 6-1). It appeared that the final position was significantly related to the grip with the thumb directed towards the pointer. They tried to explain the end-state comfort effect by means of several ideas, concluding that the effect reflects an attempt to maximize precision; in fact however they had no evidence for this hypothesis.

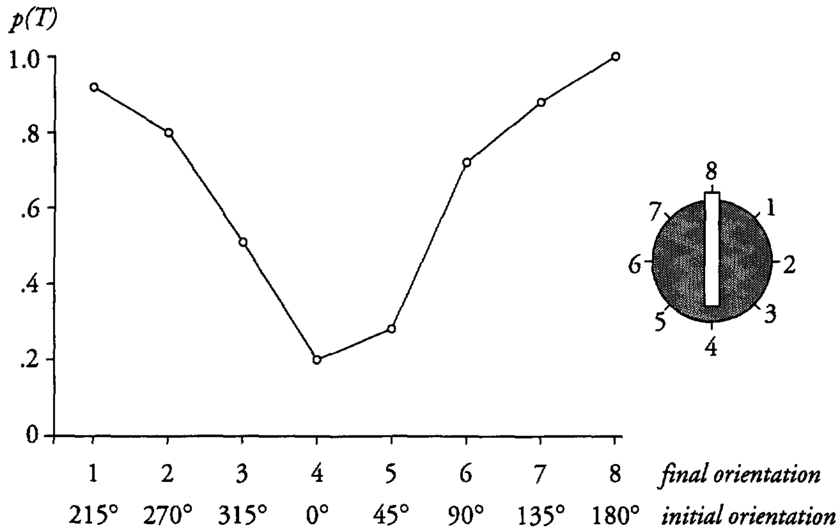


figure 6-1: Probability, p(T), of grabbing the handle with the thumb towards the pointer as a function of the pointer's final orientation. The rotation task was 180°, and no direction was imposed. The second scale indicates the initial orientation in degrees, 12 o'clock is 0 degrees (after Rosenbaum et al., 1992a).

In chapter 5 we concluded that rotation by the subjects of the O-control cannot be characterized by an overall constant final position. Only for negative rotation tasks performed by subjects who used tactic B2 was there a constant final joint angle. In most cases, however, the final position varied. It could be that the final status is more important when a directional control is involved. Therefore, in the experiments with the directional controls, the final comfort concept may still play a role.

The experiments of Rosenbaum and colleagues involved only rotation through 180° with free choice of direction of rotation. If the end-state comfort effect is a general constraint on rotation tasks, it can be hypothesized that the magnitude of the rotation task will have no influence on the way the handle has to be grasped. Therefore, in our experiments, the subjects were asked to rotate the T-control through nine different angles. The angles varied from -120° to 120° in increments of 30°. The initial orientation of the T-control varied between 1 o'clock and 12 o'clock. In our experiment the changes in the joint angles induced by rotating the T-control were measured (see chapter 3). In addition the kind of grip used to perform the rotation task was recorded.

In our kinematic study, we first analysed the movements that had to be performed by the subjects theoretically. Due to the range of movements of both SUP and CAR, it is possible to predict the way the control will be grasped. Let us consider the joint space in which the rotations have to be performed, see figure 6-2. On the horizontal axis we find the range of SUP, the range of CAR is found on the vertical axis. On each of these axes the range of movement is indicated by the minimum and maximum joint angle. The space between these values, between the dashed lines, represents all possible combinations of SUP and CAR. The range of wrist orientation lies between the summation of the maximum values of SUP and CAR (in figure 6-2 about 150°) and the summation of the minimum values (about -170°). The oblique lines in the joint space represent all combinations which yield the same orientation of the wrist. These lines are called iso-lines. All combinations of SUP and CAR on an iso-line will produce the same wrist orientation.

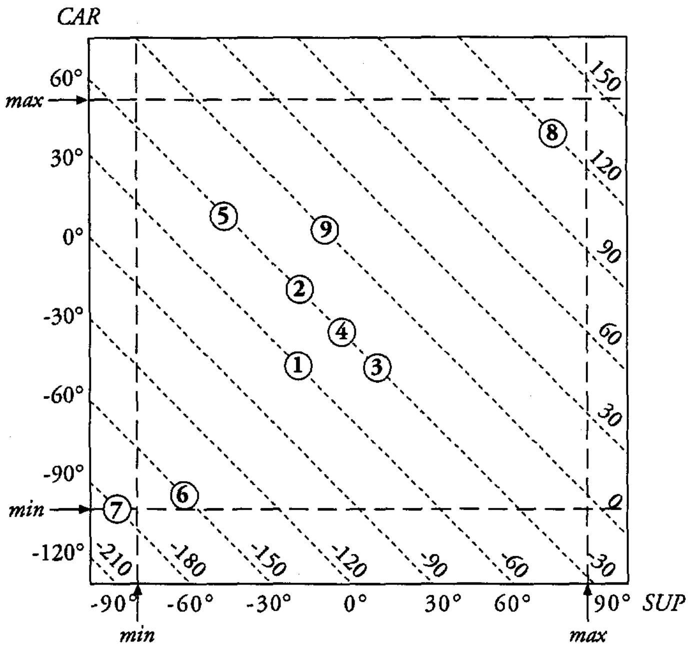


figure 6-2: The joint space, formed by the SUP *and* CAR. *The dashed lines indicate the minimum and maximum joint values. The oblique lines, called iso-lines, represent combinations of* SUP *and* CAR *resulting in the same wrist orientation. See text for detailed information.*

When the initial orientation of the T-control is -60°, i.e. the control is pointing towards 10 o'clock, the subject is allowed to use one of the joint combinations indicated by iso(-60), indicating the iso-line which represents a wrist orientation of -60°. A subject, for instance, assumes posture 1 (see figure 6-2). The given task is to rotate the T-control 30°. The final wrist orientation is therefore -30°, i.e. 60°+30°. The subject can perform this rotation in many ways. One of the possibilities is for the subject to end in posture 2. In this case the subject has only used some CAR movements and no SUP movements. Another possibility is to assume posture 3. Now the subject need only alter the SUP angle, while the CAR angle remains constant. Another possibility is posture 4. The subject has altered the SUP angle as well as the CAR angle. In chapter 5, it was mentioned that we do not expect subjects to use the joint movements that counteract each other, i.e. to perform a rotation task with CAR acting opposite to SUP. This would be the case when the subject moves his arm from posture 1 to posture 5. The CAR angle then would have increased, while the SUP angle decreased. Here we can see that the change in CAR is larger than the magnitude of the required rotation task. In this situation CAR is induced by concentric muscle activation, while the muscles inducing SUP are activated eccentrically; these muscles elongate but deliver force to prevent free, uncontrolled elongation. It is expected that this kind of movement will not be used to rotate a control.

Figure 6-2 shows whether a task can be performed or not. When, for instance, the task is to rotate the T-control from 10 o'clock to 7 o'clock (i.e. -90°), it appears that the number of possible final positions has decreased remarkedly, since iso(-150) is very small within the joint range. This task, however, can still be to performed. If the task were to rotate the knob from 10 o'clock towards 6 o'clock (-120°), the final position must be somewhere on iso(-180). This iso-line is no longer within the possible range of the subject. The solution is to change grip. The T-control can be grasped in two different ways: thumb-towards, and thumb-away. For the above-mentioned rotation tasks the subject always grasped the control in the thumb-towards grip, because the orientation of the wrist is then the same as the orientation of the pointer of the control. By using the thumb-away grip, the subject can grasp the knob which is pointed towards 10 o'clock. Now the orientation of the wrist has to be 120°, i.e. -60°+180°. The subject assumes a posture corresponding to iso(120), for instance posture 8, to grasp the knob. Now he can perform the rotation task from 10 to 6 o'clock, he moves his arm towards iso(0), for instance at position 9.

When one knows the range of movement of a subject, the grip that will be used to perform many of the rotation tasks can be predicted. In figure 6-3 the performance of all rotation tasks is depicted. The horizontal axis, at the top of the figure, represents the value of SUP+CAR. The figure contains 6 blocks, each block contains an initial position of *i* and *i*+6 o'clock (*i* =1 to 6), which is indicated to the left of the block. The initial positions are indicated by circles, open for the thumb-towards grip (T) and closed for the thumb-away grip (Ŧ). The magnitude of the rotation is indicated by the length of the arrows; an arrow pointing to the left means a negative rotation task, to the right a positive task. It is obvious that when the initial orientation is changed 180° the same solutions are possible, but the thumb-towards and thumb-away grips are interchanged.

Sometimes there will be multiple solutions to the problem of performing a task. When, for instance, the task is to start at 2 o'clock and to rotate 30°, it is possible to use a thumb-towards as well as a thumb-away grip. In the first case the subject has to assume a posture corresponding to iso(60) and rotate towards iso(90). For the thumb-away grip the initial position will lie on iso(-120), the final grip on iso(-90). All four iso's, i.e. -120, -90, 60, and 90, are within the range of movement possibilities since the range extends from -180° to 150°. In these cases the subjects have to choose between the two possibilities. Table 6-1 can be used to predict the grip used. In this table the range of motion extends from -180° to 150°. One can see that in 30%, i.e. 32/108, of all cases there are two ways to grasp the control. Depending on the range of motion of the joints, the number of tasks for which a choice has to be made will change. The larger the range of motion, the larger the number of tasks for which a choice must be made.

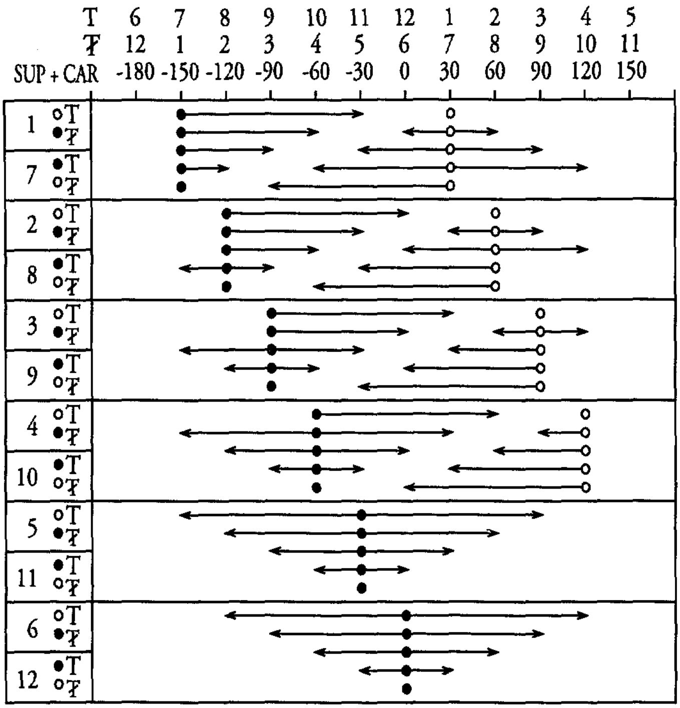


figure 6-3: Possible performances of the rotation tasks, when the possible range of movement of SUP +CAR *is -180° to 150°. For detailed information see the text.*

table 6-1: For each initial position (1 o'clock - 12 o'clock), and each magnitude of the rotation task (-120° to 120°) the way the T-control will be grasped is predicted. Minimum SUP +CAR *is -180°, maximum* SUP +CAR *is 150°. 1 = thumb-towards grip, 0 = thumb-away grip, 1/0 = both grips are possible. See text for further explanation.*

magnitude of rotation	initial position 1	2	3	4	5	6	7	8	9	10	11	12
-120°	1	1	1	1	0	0	0	0	0	0	1	1
-90°	1	1	1	1/0	0	0	0	0	0	1/0	1	1
-60°	1	1	1/0	1/0	0	0	0	0	1/0	1/0	1	1
-30°	1	1/0	1/0	1/0	0	0	0	1/0	1/0	1/0	1	1
0°	1/0	1/0	1/0	1/0	0	0	1/0	1/0	1/0	1/0	1	1
30°	1/0	1/0	1/0	0	0	0	1/0	1/0	1/0	1	1	1
60°	1/0	1/0	0	0	0	0	1/0	1/0	1	1	1	1
90°	1/0	0	0	0	0	0	1/0	1	1	1	1	1
120°	0	0	0	0	0	0	1	1	1	1	1	1

There are several ways to choose between 1 and 0. One possibility is to prefer the thumb-towards grip. Rosenbaum and colleagues described the thumb-towards bias for rotation tasks; subjects prefer to grasp the bar with the thumb directed towards the pointer. In literature on controlling human movements (e.g. Wing and Fraser, 1983) the thumb is considered to play a guiding role in grasping. In this model if the subject has a choice he will always choose the thumb-towards grip. Therefore, this model is not the same as the thumb-towards bias but represents an extreme extension of the bias towards an over-all preference for the thumb-towards grip. In table 6-2, this concept is indicated by *thumb-towards* in the first column for initial positions from 1 to 4 o'clock.

table 6-2: Four possible methods for choosing between the thumb-towards and thumb-away grips. The numbers indicate the probability of grasping with a thumb-towards grip. See text for detailed information.

initial	thumb-towards				avoid extreme				final comfort				linear approximation			
orientation	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
-90°				1				0				1				1/2
-60°			1	1			1	0			1	1			2/3	1/3
-30°		1	1	1		1	0	0		1	1	0		3/4	2/4	1/4
0°	1	1	1	1	1	1	0	0	1	1	0	0	4/5	3/5	2/5	1/5
30°	1	1	1		1	0	0		1	0	0		3/4	2/4	1/4	
60°	1	1			1	0			0	0			2/3	1/3		
90°	1				0				0				1/2			

Another way to choose between 1 and 0 is based on the concept that people will avoid extreme joint angles. Depending on the initial and final positions, one will choose an approach in which both the initial and final joint angles are least awkward. This will be the case when the middle point of the movement lies close to the centre of the range of movement, in this case between the minimum and maximum SUP+CAR values. This approach yields the second column of table 6-2 (*avoid extreme*).

In the third column (*end comfort*), the comfortable end-state concept of Rosenbaum is applied. People will choose the grip which ensures a final position which is free of maximum joint angles. Here maximum joint angles at the start of rotation do not play a role in deciding which grip to use.

The last way, column four (*linear approximation*), is simply to draw a line connecting the surrounding initial positions. To determine the predicted grasps for, for instance, rotation task -60°, at 3 and 4 o'clock, the grips predicted for initial positions 1 and 2 o'clock (thumb-towards) and initial positions 5 and 6 o'clock (thumb-away) are found in table 6-1. Between the two sets the probability that the thumb-towards grip will be chosen changes linearly from 1 to 0. In other words, the probability that for the -60° task the T-control will be grasped with the thumb towards the pointer will be ⅔ for final position 3 o'clock and ⅓ for initial position 4 o'clock. For the prediction model the predicted numbers are rounded off to integers.

The four methods described above can be used to fill in the block in which there are two ways to perform the rotation task. There are, however, two such blocks (see table 6-1). To fill in the other block (initial positions 7 to 10 o'clock) one has to use the complementary values, i.e. 1 becomes 0, ⅔ becomes ⅓ , 0 becomes 1, etc. For the first model, of course, the predicted values remain 1. Now the prediction table contains only the probabilities for grasping the knob with the thumb towards the pointer.

Until now only the way the T-control will be grasped has been predicted. For most of the wrist orientations a large number of combinations of SUP and CAR exists (the iso-lines are only short for the extreme ranges of the joint angles). In the previous chapter it was shown that the combinations of SUP and CAR used for rotation tasks only encompass a relatively small part of the joint space. When rotating the O-control, subjects used the full range of SUP, while the CAR angle remained close to the neutral position. In case of a significant increase in CAR angle, the SUP angle was always close to the minimum value. It was shown that neither the imposed wrist angles nor the effect of gravity can explain the limited use of the joint space. Changes in the standard experiment, wherby the flexion angle was altered (see paragraph 5.2.5), indicated that even when the elbow is nearly extended subjects will still use aproximately the same combinations of SUP and CAR (cf. figure 5-13). From this, we concluded that the limited usage of SUP and CAR combinations was attributed to a soft constraint: subjects prefer the more economical distal SUP over CAR. Therefore it is to be expected that for the T-control too, significant CAR movements will only be used when the SUP angle is close to the minimum value.

If the aim is only to grasp the T-control in one of the 12 initial orientations, the whole range of SUP+CAR need not be used. One can, for instance, use the range iso(-90) up to iso(60). Then, when the full range of SUP has been used, the CAR angle need only change between -30° and 0°; in this way maximum wrist angles will not be imposed, see figure 6-2. It is, however, not possible to perform all rotation tasks without using the full range of SUP+CAR. Sometimes one simply has to start or end with both the SUP and the CAR angle at a maximum, e.g. start at 6 o'clock and perform a rotation task of 120°.

Therefore, the full ranges of SUP and CAR have to be used to perform the rotation tasks with the T-control. However, it is not likely that all possible combinations of SUP and CAR will be used. Similar to rotation of the O-control, we expect that only in the case of maximum or minimum SUP will a significant CAR movement be needed to rotate the T-control. Consequently the ratio of SUP to CAR movement will depend on the initial and final orientations of the wrist, i.e. the SUP+CAR value. In case of a large negative SUP+CAR value relatively more CAR will be used; the ratio will change in favour of SUP as the initial SUP+CAR value increases.

6.1.2 Method

Six subjects (3 males, 3 females, aged 20-34 years old) participated in the experiment. All subjects were right-handed; none of them suffered musculo-skeletal disorders of the arm. The subjects were not aware of the purpose of the experiments.

The position of the subject, relative to the control, was as described in chapter 4. The grasp could be either the thumb-towards grip or the thumb-away grip. The investigator did not impose one of these two grips. He explicitly asked the subject to perform the rotation tasks in a comfortable way and not to change grips during the rotation. Subjects were also instructed not to react too quickly but to take the time to perform the task.

Since the frontal view of this control changes with the angle of rotation, we used different initial positions. At the start of the trial, the pointer pointed towards 1, 2, ..., 12 o'clock, i.e. 12 start positions. For each initial position there were nine different rotation tasks: from -120° to 120° in increments of 30°. This resulted in 108 different rotation tasks. Each of them was repeated three times. The total session, therefore, consisted of 324 rotation tasks. The order of the rotation tasks during the three subsessions was random.

During the experiment the investigator instructed the subject first to change the direction of the control to the new initial position by calling out the clock code. This adjustment of the control had to be performed with the left hand, to prevent any influence of the grasp used on the actual rotation task to be performed afterwards. When the control was adjusted, the investigator instructed the subject to rotate the control towards a new target position, again by calling out in clock code. Subjects were allowed to place the control within an accuracy of about 10°. Before the subject performed the rotation task, the investigator ran the OPTOTRAK system for about three seconds to collect the 3D data and register the orientation of the control. Also, the grip used was noted by the investigator.

To get acquainted with the rotation tasks, about twenty rotation tasks were performed before the actual experiment started. The range of movement of SUP+CAR was also determined. For this purpose the subjects had to grasp the control (with the pointer at 12 o'clock) and rotate the control through the maximum range to the left and to the right. For this task the subjects were asked to use their full range of movement, SUP as well as CAR. The investigator stopped the subject from using other than SUP and CAR, e.g. sidewards flexion of the trunk.

6.1.3 Results

Does the magnitude, direction, and initial position of the task affect the choice of the grip?
For each subject a matrix was completed using the empirical data. In figure 6-4 the number of thumb-towards grips for each combination of initial position - magnitude of the rotation task is presented for one of the subjects. The number of thumb-towards grips in each cell was used as the dependent variable in an ANOVA. In the ANOVA model the effect of the subject is assumed to be random. The other three factors, rotation task, initial position, and repetition, are assumed to be fixed. The outcomes showed a significant effect of the interaction between task and initial position ($F(88,440)=20.8$, $p<.01$), indicating that the combination of initial position and magnitude and direction of the rotation task does influence the number of times the thumb-towards grips is used. The result of the analysis of variance was that there was no significant variation between subjects ($F(5,440)=2.38$, $p=.04$). From this we conclude that for all subjects the same distribution of the two grips over all tasks applies.

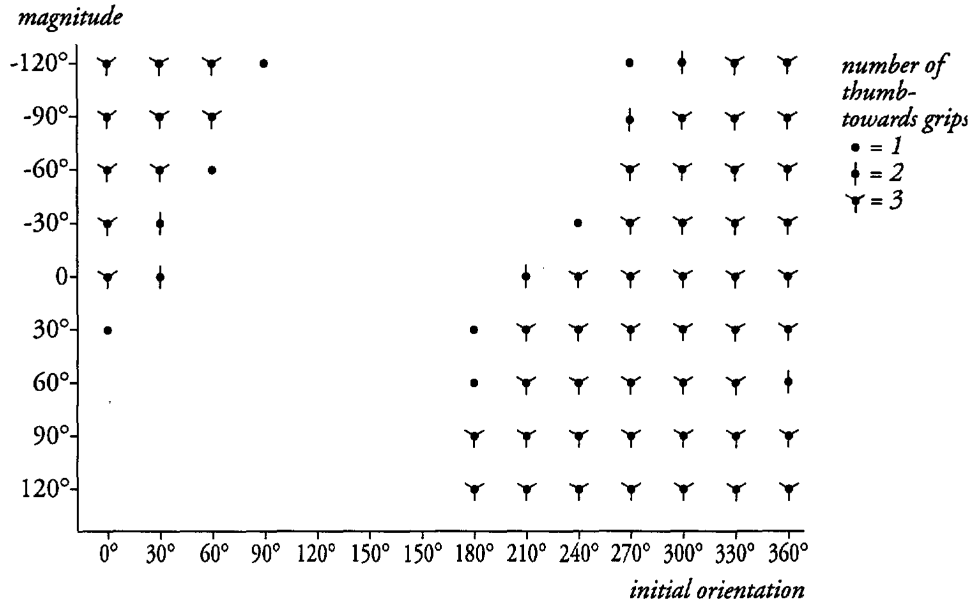


figure 6-4: The number of thumb-towards grips for each combination of initial position and magnitude of rotation task (subject 21). Each combination was repeated three times.

Is there a thumb-towards bias?

When figure 6-4 is further analysed, it can be seen that when subject 21 performed the rotation from the initial positions in the lower half of the initial positions, i.e. 90°, …, 240°, the grip was usually the reverse of that for the upper half. In the introduction, we mentioned that the initial positions i and i+6 (i=1…6) result in the same orientation of the control. In a separate ANOVA we analysed the influence of the position of the pointer, i.e. the initial positions i and i+6 were compared. For this purpose the number of thumb-towards grips in the upper half of the initial positions was compared with the number of thumb-away grips in the lower half. The results showed that there was a significant effect of the position of the pointer relative to the control: $F(1,6)=164$, $p<.01$. Thus, when the orientation of the control remained the same, for instance orientation from 8 to 2 o'clock, the position of the pointer, i.e. towards 8 or 2 o'clock, had a significant effect on the grip used. In the case of no effect, the subject would use the thumb-towards grip 162 times, i.e. 50% of 324. The number of thumb-towards grips, however, differs significantly from 162 ($t(5)=7.54$, $p<.01$). The mean number of thumb-towards grips was 187, range 178 to 195. Therefore, in more than 50% of cases subjects used a thumb-towards grip, indicating the existence of the thumb-towards bias.

Do the models predict the way of grasping accurately?

Next, we wanted to analyse whether the previously described models predict the number of thumb-towards grips correctly. Since the prediction models depended on the range of movement of SUP and CAR, the four prediction models were adjusted to fit each subject. In case of a correct prediction, the value for each cell of the prediction models should equal the actual number of thumb-towards grips. In both the prediction model and the matrix of the empirical data, the value could lie between 0 and 3, due to the repetitions.

For each subject a frequency table was made. This frequency table contained four columns and four rows, indicating the empirically determined number of thumb-towards grips ($i = 0$ to 3) and the predicted number ($j = 0$ to 3), respectively. If the prediction was correct, the cells on the main diagonal ($i = j$) were filled and the remaining cells were empty.

To quantify the agreement between the prediction model, and the empirical data, we used the estimate of the weighted kappa ($\hat{\kappa}_w$, Wilkens, 1989 p. 238-243). This measurement of agreement can vary between 0 and 1; 0 indicates total disagreement and 1 complete agreement. One can use , i.e. not the weighted kappa, but then all cases outside the main diagonal, i.e. $i \neq j$, indicate complete disagreement. When, however, the model predicted, for instance, 3, and the subject performed the task by using the thumb-towards grip twice and the thumb-away grip once ($i = 2, j = 3$), this prediction is better than when the subject had not used the thumb-towards grips at all ($i = 0, j = 3$). Therefore we chose the weighted kappa; the weighting factors, indicated in table 6-3, are a monotonic function of the magnitude of the differences between i and j. Now cells adjacent to the main diagonal indicate slight agreement, the next cell slight disagreement, and only cells ($i = 0, j = 3$) and ($i = 3, j = 0$) indicate complete disagreement.

table 6-3: The weighting factors used to estimate the weighted kappa. The columns indicate the empirical number of thumb-towards grips, the rows the predicted number.

predicted number of T	emperical number of T 0	1	2	3
0	1	⅔	⅓	0
1	⅔	1	⅔	⅓
2	⅓	⅔	1	⅔
3	0	⅓	⅔	1

In figure 6-5, the estimated weighted kappas are presented for the six subjects. All of these kappas differ significantly from 0 ($p<.01$), so it can be concluded that each of the four models predicts the choice of the grasp very well. Although the kappas for the *thumb-towards* model are in most cases lower than the others, the difference for each subject was not significant ($p>.05$). None of the models, however, resulted in a kappa of 1. The reason for this is probably the fact that the thumb-towards bias (!), which is known to exist, results in an unbalanced distribution of the thumb-towards and thumb-away grips. The models used, apart from the thumb-towards model, do not include this thumb-towards bias; consequently the kappas can be expected to be less than 1.

From this we can conclude that the grip can be predicted fairly accurately from the range of movement of SUP + CAR. In the event of two possible grips, one can easily predict the choice by linear approximation. The theoretical models (thumb-towards, avoid extreme, and end comfort) do not result in a better prediction. One, however, must keep in mind that the thumb-towards bias affects the prediction in a negative way. This bias is not incorporated in the above-mentioned prediction model.

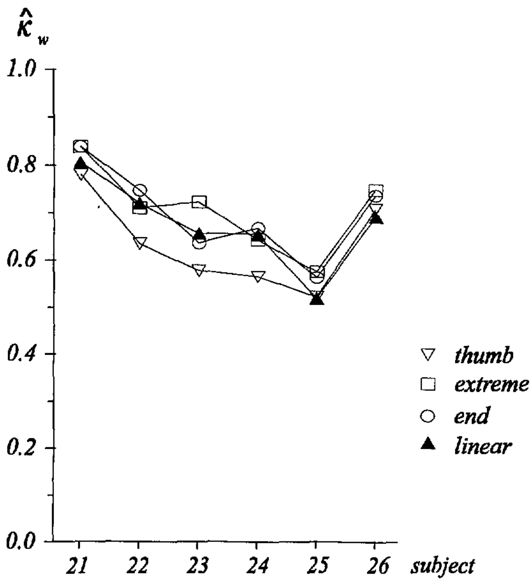


figure 6-5: The estimated weighted kappa's for each of the four prediction models for each of the six subjects.

How about the joint angles?
In the preceding paragraph we analysed the prediction of the grip used. To grasp the T-control with one of the two grips, one has to alter the SUP and CAR angles to achieve the correct wrist orientation. When the control is grasped, one has to change the wrist orientation, depending on the magnitude and direction of the rotation task. The ratio of the changes in SUP and CAR is not imposed by the experiment. ANOVAS were used to analyse the use of SUP and CAR in the initial position as well as the final position.

To use a simple ANOVA, one has to have a balanced matrix, filled with data. Due to missing values (for instance because of a missing IRED at a crucial moment) the data matrix becomes unbalanced, and the simple ANOVA analysis cannot be performed. In our data only 8 observations (of the 1944, i.e. 6 subjects × 12 initial positions × 9 rotation tasks × 3 repetitions) were missing. Montgomery (1984, p. 238-240) advises estimating the missing data by minimizing the residual sum of squares, which results in taking the average value for a cell. The consequence will be that the number of degrees of freedom for the residual values will decrease by the number of estimated values.

First the effect of repetition was determined. For this analysis there is only one observation in each cell. The consequence is that the residual variance cannot be estimated. To solve this problem, the 4-way interaction between subject, task, start, and repetition was used instead to estimate σ^2.

For all initial and final values of both SUP and CAR, there was no significant effect of the repetition: initial SUP $F(2,10)=2.90$, $p=.10$, initial CAR $F(2,10)=0.66$, $p=.54$, final SUP $F(2,10)=0.91$, $p=.43$, and final CAR $F(2,10)=2.33$, $p=.14$. These results indicate that the subjects were constant in their performance.

In the second analysis the three repetitions formed the values for one cell (since there was no effect of repetition). In this analysis the variance between subjects, and the effects on the initial and final values of both SUP and CAR of the rotation task and initial position were assessed. The results of the second ANOVA were: for subjects $F(5,1288)=65$; $F(5,1288)=119$; $F(5,1288)=89$; $F(5,1288)=102$, for tasks $F(8,40)=139$; $F(8,40)=40$; $F(8,40)=47$; $F(8,40)=63$, and for initial positions $F(11,55)=9.3$; $F(11,55)=10.9$; $F(11,55)=6.4$; $F(11,55)=9.7$. For all four response variables, all main sources of variation yielded a p-value of less than .01. Also the interaction between task and initial position was found to be significant ($p<.01$) for all four variables: initial SUP $F(88,1288)=7.8$; initial CAR $F(88,1288)=7.9$; final SUP $F(88,1288)=6.8$; final CAR $F(88,1288)=7.8$. The general conclusion is, therefore, that the initial and final joint angles (SUP and CAR) seem to be dependent on the rotation task, the initial position, and the subject performing the rotation tasks.

In the introduction to this chapter, we showed how we could predict the grasp of the T-control. The model used took into account only the range of possible SUP+CAR values. Therefore an initial position *i+6* resulted in the complementary number of expected thumb-towards grips. In several supplementary analyses we tested the hypothesis that the initial and final joint angles recorded at initial positions i and i+6 are the same. It should be noted that for these analyses only the effect of the initial position was taken into account. Effects, such as the subject or task, had no influence on the outcomes of these analyses.

The results of these analyses showed that for all four joint angles there were no significant differences between the initial positions 150° and 330° (initial SUP $F(1,1288)=0.16$, $p=.67$, initial CAR $F(1,1288)=0.22$, $p=.64$, final SUP $F(1,1288)=0.90$, $p=.34$, and final CAR $F(1,1288)=0.82$, $p=.36$). The five other comparisons yielded significant differences ($p<.01$). These findings led us to conclude that only for rotation tasks performed with the control pointing initially to 150° or 330° was the control always grasped in the same way, i.e. the wrist orientation was always -30°, and the task performed with the same rotation movements, i.e. the initial and final joint angles were the same. According to the five other analyses, the position of the pointer relative to the control influenced the grip used. Consequently, these performances differed with respect to each other.

Still it is possible that the performances at initial position *i* with the thumb-towards grip - i.e. the way SUP and CAR were employed - were similar to the thumb-away performances at *i+6*. This, however, could not be tested due to the unbalanced matrix, since the number of thumb-towards grips depended on the task and the initial position.

Does delta depend on the task?

Until now, we have only analysed the initial and final positions of the two joint angles. The contribution of the two degrees of freedom to the rotation has not been considered yet. In chapter 5 the contribution of the two degrees of freedom to the rotation of the O-control was discussed. It was shown that only a small part of the possible joint space is used by a subject, and consequently that the ratio of SUP to CAR depended on the orientation of the wrist. Therefore, it seems likely that for rotation of the T-control, a relationship also exists between wrist orientation and the ratio of SUP to CAR movement.

In figure 6-6 the horizontal axis represents mid-orientation between the initial wrist orientation and the final wrist orientation, i.e. the orientation of the wrist half-way through the range needed to perform the rotational task. These orientations are determined by the initial position, magnitude and direction of the rotation task, and the grip chosen. When, for instance, the task is to rotate the control from 7 to 10 o'clock, and the subject grasps the control with the thumb-towards grip, the initial wrist orientation has to be -150° and the final orientation -60°. When, however, the grip used is the thumb-away grip, the initial wrist orientation has to be 30° and the final orientation 120°. In the first case, the mid-orientation will be -105°, in the second case 75°. The vertical axis, in figure 6-6, is delta (see paragraph 5.2.1). A delta of 90° indicates a rotation achieved only by CAR, whereas a delta of 0° means a movement consisting only of SUP. When delta is 45°, the amount of CAR rotation equals the amount of SUP rotation.

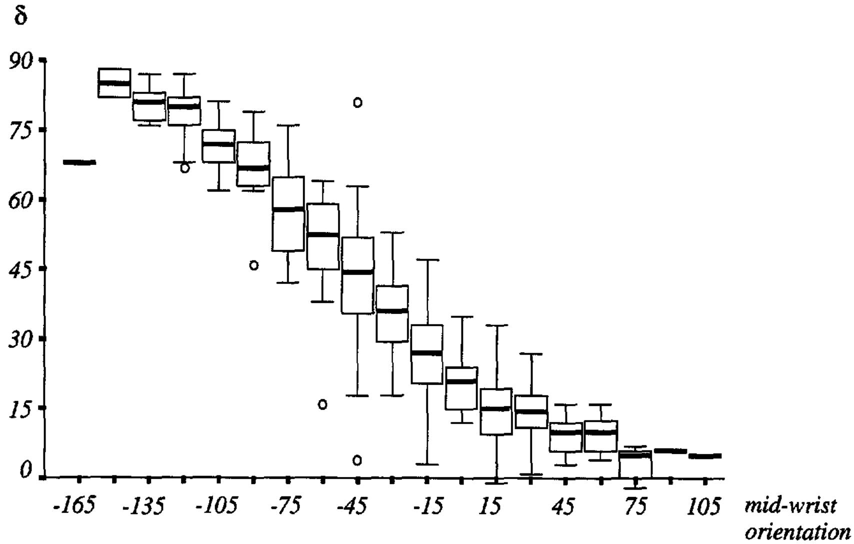


figure 6-6: A boxplot of the mid-wrist orientation versus delta, subject 22. See text for a description of these variables. The boxplots shows the median, upper and lower values (25th and 75th percentiles). The lines indicate the range of values which were less than 1.5 times the length of the box. Outlying values are indicated by circles.

In figure 6-6 we can see that, for subject 22, delta depends on the mid-wrist orientation. In the case of a large negative mid-wrist orientation CAR rotation exceeds SUP rotation, i.e. delta is close to 90°. For large positive mid-wrist orientations the contribution of CAR is negligible; in this case rotation is performed mainly by SUP. The delta value was always between 0° and 90°. This indicates that the muscles inducing SUP and CAR are always concentrically (or sometimes isometrically) activated. At no time were eccentric contractions of the muscles induced. For all other subjects the same tendency was found. These results agreed well with our expectations.

6.1.4 Conclusion

The results of our experiment show that we can predict the grasp used very accurately. The prediction of the grasp can be based only on the range of movement of SUP+CAR. When our predictions are compared with the findings of Stelmach et al. (1994, see figure 2-2), there appears to be reasonable agreement for the 0° rotation task. In the experiment of Stelmach et al. the subjects had to grasp an elongated object between the pads of the thumb and the index finger. When the orientation of the object was 70°, grip orientation was about -20°, i.e. 70°-90°. Stelmach et al. showed that the subjects changed grip between 90° and about 120°. In our study this equals a grip orientation between 0° and 30° or initial orientations at 12 o'clock and 1 o'clock. We, however, predicted that the grip would be changed between 12 o'clock and 5 o'clock, and this was affirmed by our data. The discrepancies between the findings of Stelmach et al. and our results may be due to the orientation of the plane. In our experiments the control was mounted in the vertical plane, whereas Stelmach et al. placed the object on a horizontal plane.

In the event of two possible ways to rotate the control, one can simply make the choice by linear approximation of the probability of using a thumb-towards grip. This method yields a prediction as accurate as one based on other theories, for instance the end-state comfort idea. So, in contrast to Rosenbaum et al. (1992a), we can state that for most of the tasks, i.e. when no choice has to be made, physics alone is sufficient to predict the way the control will be grasped. Rosenbaum and colleagues, however, needed the concept of end-state comfort and thumb-towards bias to explain the results of their rotation experiments. If their experiments are to be evaluated by means of our prediction model, not only the initial orientation and magnitude of the rotation but also the direction of rotation must be known. Due to the range of movement possibilities of SUP+CAR (from about -180° to 150°), one can predict that for negative rotations starting from initial positions 1 to 4 (see figure 6-1), the T-handle will be grasped in the thumb-towards grip. For the other initial positions (5 to 8) the predicted grip will be the thumb-away one. For positive rotations, the predicted grip will be the opposite: instead of thumb-towards one will predict thumb-away, and vice versa. We can see that for each of the initial positions, both grips are possible. Since, in the experiments of Rosenbaum and colleagues, the direction of rotation is not imposed and the positive and negative directions require the same amounts of rotation, an interesting question arises. Why do people choose one grip instead of the other?

If the concept of end-state comfort is applied to the rotation tasks, one would expect the subject to use that grip which will end near the mid-point of the range of SUP+CAR, i.e. -15°. In table 6-4 the distances to the mid-point are listed for the thumb-towards grip as well as the thumb-away grip. On the basis of this table, one would expect the subject to use the thumb-towards grip in start positions 3, 4, 5, and 6, and the thumb-away grip in the remaining positions. This almost agrees with the findings of Rosenbaum and colleagues; see the last row of table 6-4. In conclusion, the fact that the direction of rotation is not imposed in the experiments of Rosenbaum means that a concept such as end-state comfort is needed to predict the grip that will be used.

table 6-4: The distance (in degrees) of wrist orientation from the mid point of the range SUP +CAR, *when performing the rotation task (+/-180°) with the thumb-towards* (T) *or thumb-away* (Ŧ) *grip. The initial positions are as indicated in figure 6-1. The p(T) values are extracted from figure 6-1.*

	initial position							
	1	2	3	4	5	6	7	8
grip	0°	45°	90°	135°	180°	225°	270°	315°
T	165°	120°	75°	30°	15°	60°	105°	150°
Ŧ	15°	60°	105°	150°	165°	120°	75°	30°
p(T)	.29	.72	.88	.96	.95	.86	.47	.19

In our prediction models, we used the thumb-towards bias to help when both grips were in principle possible. The results of the experiment showed that this approach did not improve the prediction. When, however, the number of thumb-towards grips used by each subject was counted, it appeared that relatively more thumb-towards grips were used than thumb-away grips. From this it can be concluded that, as Rosenbaum and colleagues mentioned, there is a thumb-towards bias, meaning that subjects tend to use the thumb-towards grips relatively more often than the thumb-away grips.

A remarkable finding is that the grip used for each task did not significantly vary between subjects. Initial positions 5 and 11 o'clock, in particular, are characterized by extremely constant performances. All subjects, in all repetitions, grasped the control with a wrist orientation of -30°. When, however, the joint angles for all other rotation tasks were analysed, there was a significant variation between subjects. On the other hand, each subject performed each rotation task in a constant way. In spite of the variations between subjects, it was not possible to perform the set of rotation tasks differently, as seen in the previous chapter. The direction of the control restricted the performances of the subjects to such an extent that the tactic used could not vary between subjects.

One aspect of the tactic was that all subjects used nearly the same limited combinations of SUP and CAR. The variation between these combinations was greater than that found for the O-control, but still a combination of a large SUP value and a small CAR value did not occur. The consequence is that the ratio of SUP to CAR, i.e. delta, depended on the mid-wrist orientation. Therefore, in addition to the initial position and the magnitude of the rotation task, the grip used also influenced delta.

6.2 L-control

The second directional control used in our experiments was the L-control. In contrast to the T-control, the L-control is mounted on the shaft at the end of the cylinder (see figure 4-3). The frontal view of this control also depends on the angle of rotation of the shaft. The frontal view of the L-control changes throughout the entire 360°. In case of a rotation of 180°, the orientation of the control remains the same, but the position of the control relative to the subject changes. A change of 180° results in a translation of the control, so that the 'other' side of the handle is now located at the position of the shaft. For the purpose of rotation the L-control can also be grasped in two different ways: the thumb-towards and the thumb-away grips, i.e. towards the tip of the pointer and away from the tip of the pointer, respectively.

The change in the position of the handle relative to the shaft means that extra arm movements are needed to rotate the control. When the O-control or T-control is grasped the centre of the control is in line with the forearm. Due to the cardan construction of the wrist joint, the subjects could use SUP and CAR to rotate the control. For rotation of the L-control, these two degrees of freedom still apply. However, an extra imposed arm movement is needed. To perform the rotations with SUP and CAR only, the axis of rotation of both movements must lie near the shaft of the control. This is not always the case with an L-control. When, for instance, the control points towards 7 o'clock and the task is to rotate it towards 4 o'clock, the subject can grasp the control in the thumb-away grip, i.e. the thumb is pointing away from the pointer (see figure 6-7, position 1). When the control is grasped, wrist orientation has to be about 30°; after rotation the required wrist orientation is -60°. Since wrist orientation is the result of the addition of SUP and CAR, one can easily see that wrist orientation has to change by -90°. This -90° may be composed of SUP and CAR. When, however, the subject rotates his arm to reach the initial posture by performing SUP and CAR, one can see that the position of the hand will be wrong (see figure 6-7, position 2). Therefore extra arm movements will be needed to translate the hand to the required position (see figure 6-7, position 3). This will only be the case when the subject grasps the control in the thumb-away grip. In case of the thumb-towards grip the centre of rotation of SUP and CAR will be sufficiently close to the centre of rotation of the control. The amount of translation needed in that case is negligible. Whether the translation is only the passive result of SUP and/or CAR movement or forms an active part of the arm movements is not relevant. The translation movements are directly linked to the SUP and/or CAR movements, so one only needs to determine the SUP and CAR components to describe the characteristics of the performance of a particular task.

Therefore not all arm movements made when performing a rotation task starting from initial positions 1 to 11 o'clock with the thumb-towards grip can be compared with those performed with the thumb-away grip and starting from initial positions 7 to 5 o'clock. The thumb-away grip requires extra arm movements. The rotation component, however, still has to be performed by SUP and/or CAR. In paragraph 3.2 it was mentioned that the range of CAR depends on the direction of the axis of rotation relative to the subject. In fact the axis of CAR changes position during rotation of the L-control. The change in position of the axis of CAR does not, however, affect the actual range of movement of CAR. Therefore, we can use the same procedure as we did for the T-control to predict the way the L-control will be grasped, depending on the initial position and the magnitude and direction of the rotation task (see table 6-1). This prediction will be either the thumb-towards grip, the thumb-away grip, or both possibilities. In case of both possibilities, it was shown in the experiment with the T-control that the linear model yields an accurate prediction of the grip. So, for the L-control the linear model will also be used to predict the number of thumb-toward grips for each combination of initial position and magnitude of the task.

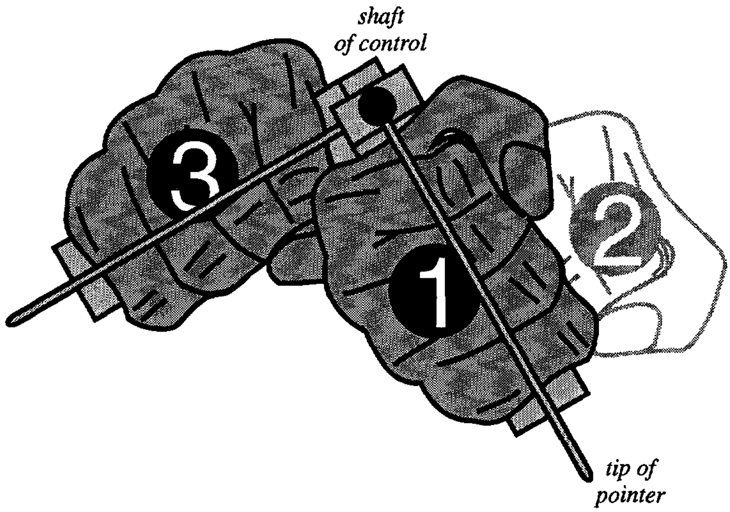


figure 6-7: Rotation of the L-control with the thumb-away grip. In the initial position (1) the pointer is directed towards 7 o'clock (remember that the hours of the clock are reversed because of the frontal view). When the knob has to be rotated towards 4 o'clock (position 3), one can rotate the wrist towards position 2; extra translation movements are then necessary to translate the hand from position 2 to 3. The rotation and translation components are, of course, not performed consecutively but at the same time.

In the next three subparagraphs, the experiments conducted with the L-control will be described. The first experiment resembles the experiment with the T-control. In this kinematic study the grip used and the application of SUP and CAR are assessed. In the next experiment, a time experiment, the reaction times and movement times found for subjects performing rotation tasks with the L-control were determined. In the last subparagraph it is shown how a slight alteration of the handle influences the distribution of the thumb-towards grips among the rotation tasks.

6.2.1 Kinematic study

It is presumed that the results of the experiment with the L-control will be similar to the findings for the T-control. Moreover the distribution of the thumb-towards and thumb-away grips is expected to be the same as that determined for the T-control.

Method

In this experiment eight students served as subjects (5 females, 3 males). All subjects were healthy and right-handed. Four of these subjects also participated in the experiment with the T-control. The experimental conditions resembled those for the T-control. Each subject had to perform 324 rotation tasks: 12 initial positions, 9 different rotation tasks (-120°, -90°, ..., 120°), and 5 repetitions. Before each performance we recorded the 3D positions of the IREDs and the rotation of the shaft of the control. In this experiment too subjects were asked to adjust the control to the initial position with the left hand.

Results

What aspects affect the choice of grip?
The numbers of thumb-towards grips for each of the rotation tasks, i.e. a combination of an initial position and magnitude of the rotation task, were analysed by ANOVA. The results of the ANOVA showed that, again, there was no significant variation between subjects ($F(7,616)=.9$, $p=.50$). There was, however, a significant effect of the task, initial position and the interaction between the two ($F(8,56)=4.81$, $p<.01$; $F(11,77)=24.52$, $p<.01$; and $F(88,616)=16.69$, $p<.01$), which is in agreement with our expectations.

What about the thumb-towards bias?
As indicated by the results for the T-control, when rotating the L-control the subjects used the thumb-towards grip significantly more often than the thumb-away grip ($t(7)=10.95$, $p<.01$). This was also demonstrated by an ANOVA comparing the upper half of the initial positions with the lower half. The results showed a significant effect on the number of thumb-towards grips ($F(1,7)=30.9$, $p<.01$).

Can we predict the grip?
For each subject we calculated the estimated weighted kappa: $\hat{\kappa}_w$ (Wilkens, 1989 p. 238-243, see also paragraph 6.2.3) as a measurement of agreement between the predicted number of thumb-towards grips and the actual number. Again the monotonic function of the magnitude of the differences between the predicted and the actual number of thumb-towards grips is used to determine the weighting factors (see table 6-3). For all subjects, the kappas were significantly different from 0 ($p<.01$). The range of kappa was .63 to .81; the mean estimated weighted kappa was .73. Therefore for rotation tasks performed with the L-control the predicted grip agreed closely with the grip actually used.

Does the difference between the L- and the T-control affect the choice of grips and the performances?
Since four subjects participated in the experiment with the T-control and also in that with the L-control, we could compare the use of grips in the two experiments. The control was taken as one of the independent variables, while the grip was taken as the dependent variable. The results revealed no significant effect of the type of control, $F(1,3)=1.14$, $p=.36$. From this we can conclude that the extra arm movements imposed by the L-control do not influence the distribution of the thumb-towards grips over the combinations of initial position and magnitude of the rotation.

In addition to the grip used, we also recorded the joint angles made while performing the rotation task. The results of analysis were similar to those found for the T-control. Again the ratio SUP to CAR when rotating the L-control depended on the mid-wrist orientation. In case of a small mid-wrist angle the contribution of CAR exceeded that of SUP. This ratio changes in favour of SUP as the mid-wrist orientation increases.

6.2.2 Time study

In the experiments with the T- and L-control it was seen that the grip could be predicted quite accurately. To predict the grip, one only needs to know the initial orientation, the magnitude of the rotation task and the range of movement of the combination SUP+CAR.

However, for some combinations of the initial orientation and magnitude of the task two possible grips are predicted. In the experiment with the T-control we showed that we do not need any extra theory, such as avoiding extreme joint angles, to make a choice. A linear approximation between the area in which the thumb-towards grip is used and the area in which the thumb-away grip is used produces a good prediction. In this area the probability of using a thumb-towards grip p(T) alters from 1 to 0 or vice versa. At the point where the p(T) is 0.5, the chances of a thumb-towards and a thumb-away grip are equal. This should have an effect on the reaction time of the subject. When p(T) is 1 or 0, there is no point in questioning, and therefore, the subject will react faster when p(T) is 1 or 0 than when p(T) is 0.5.

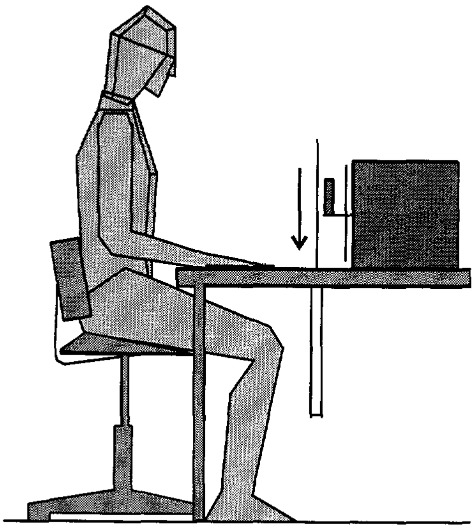


figure 6-8: The experimental conditions under which the reaction and movement times were determined. The screen, in front of the control, dropped into the table.

Method

In the next experiment, we measured the reaction time and movement time of subjects performing the rotation tasks. The experimental conditions are depicted in figure 6-8. The subjects sat in front of the control, the position of the control was the same as in former experiments. The box, to which the control was attached, sat on a table. The subject placed his hand on a micro switch on this table. Between the subject and the control was a screen. The investigator could let the screen drop down suddenly into the table. When the top of the screen was at the height of the shaft of the control, two timers started to run (displaying the time in hundredth seconds). Now the subject could see the orientation of the control and the magnitude and direction of the required rotation task. Target orientation was indicated by a red area on the scale of the pointer attached to the control. The subject was asked to react as quickly as possible. When the subject raised his hand, the first timer stopped. The recorded time, t_r, is called the reaction time, the reaction time being defined as 'the time from the arrival of a suddenly presented and unanticipated signal to the beginning of the response to it' (Schmidt, 1982 p.74). As soon as the control was moved through more than two degrees, the second timer stopped. This timer displayed the total time, t_t. The movement time, t_m, is easily determined by subtracting the reaction time from the total time.

In this experiment 10 students performed as subjects (6 males, 4 females, age 19 to 23 years old). All were right-handed and were not aware of the purpose of the experiment. In this experiment the investigator set the initial orientation of the control. Subjects were not able to see this until the screen dropped down. The magnitude of the rotation task was either -45° or 45°. The initial orientation ranged from 20° to 360° in increments of 20°. Each rotation task was offered five times. The rotation tasks were presented at random.

Results

Not only the reaction time but also the grip used was recorded. For each of the subjects the weighted kappa was estimated. All were significantly different from 0 ($p<.01$). The range of the kappas was .63 to .85, the mean estimated weighted kappa .71. For each subject and for both rotation tasks, i.e. -45° and 45°, two reversal points and the two mid-section points were determined (see figure 6-9).

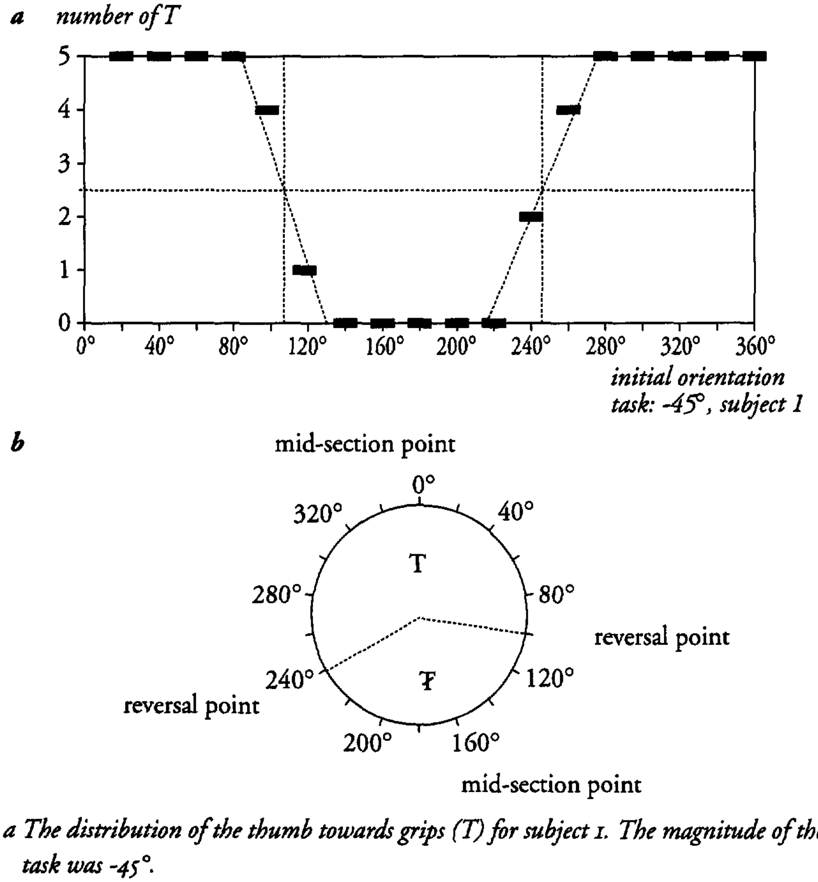


figure 6-9: a The distribution of the thumb towards grips (T) for subject 1. The magnitude of the rotation task was -45°.
b The position of the mid-section and reversal points. See text for explanation.

To identify the reversal points, we determined the linear regression line for the two areas in which the subject alters his grip (in figure 6-9 initial start positions 80° to 140° and 220° to 280°). The initial positions closest to the point where the regression line crosses the 2.5 value (in this case $p(T)=.5$) were defined as the reversal points. The two reversal points divide the whole circle into two parts, one in which the thumb-towards grip was used and one in which the thumb-away grip was used. The mid-section points were defined as the middle of these two sections.

Do subjects require a longer time to react at the reversal points?
In the next analysis we compared the mean reaction time, movement time, and total time for the reversal and mid-section points, by using a t-test for paired samples. The means were determined for each subject by taking the average time needed for 20 movements, i.e. five repetitions, two reversal or mid-section points, and two directions of rotations (-45° and 45°). Figure 6-10 displays the boxplots of the reaction, movement, and total time for the mid-section points and the reversal points. The measurements of the reaction time showed no significant differences ($t(9)=-1.51$, $p=.08$). However, the movement time and the total time at the reversal points were significantly longer than at the mid-section points ($t(9)=-3.04$, $p<.01$; $t(9)=-3.88$, $p<.01$, respectively), although the differences were very small (about .03 sec),.

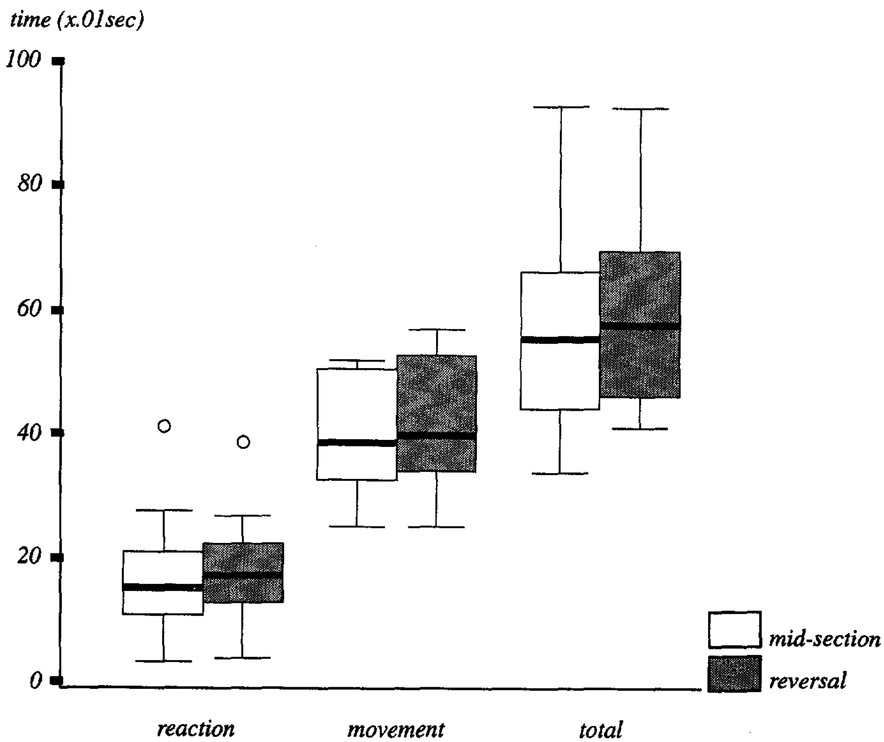


figure 6-10: A boxplot of the influence of the initial orientation of the control (i.e. at the mid-section point or at the reversal point) on the reaction, movement, and total times.

The results agreed well with our expectations. Although the reaction times exhibited no significant differences, there was a significant difference in the movement times and total times. In the experiment it appeared that subjects started to move their hand as soon as the screen began to drop into the table; they did not wait until they had decided which grip to use. This decision, however, had to be made. Since the movement time for initial positions at the reversal points is significantly longer, we assume that the subject decided which grip to use while moving the hand towards the control.

6.2.3 Short handle

Until now, we had only used handles that could be grasped easily in the hand. Either the control was round (O-control) and could be hold in the palm of the hand or the control was cylindrical (T- and L-control) and long enough to hold in the hand. The choice of the used grip (thumb-towards vs. thumb-away) has no influence on the contact area of the hand with the control. One can assume that the most important part of the grip, however, is near the thumb. At this point the fingers fully surround the control in two directions (the thumb and the index finger). On the other side only the weaker little finger can be used.

Method
In this next experiment we investigated this assumption by using the same L-control but now only half as long (i.e. 5 cm). The idea was that the subjects would use the thumb-away grip more often, since it would be easier to handle the control with the thumb away from the pointer, i.e. towards the shaft.

For this experiment we used the ten subjects from the preceding experiment. The experimental conditions were also the same. Subjects had to rotate the control -45° or 45°. Eighteen evenly distributed initial positions were used. Every task was repeated five times. In this experiment too the rotation tasks were presented at random.

Results

Does the short handle attract the thumb-away grip?
Again the weighted kappa was estimated. The range was .65 to .78, the mean .70. All weighted kappas differed significantly from 0 ($p<.01$). Data analysis consisted of determining the mid-section and reversal points, as described in paragraph 6.2.2. It was expected that because the L-control was only half as long, the magnitude of the section for the thumb-away grip, i.e. the -area, would be larger than in the former experiment (with the thumb-away grip the thumb is close to the shaft of the control, i.e. the thumb is away from the pointer). Figure 6-11 on the left shows the boxplots of the magnitude of the Ŧ-area, i.e. the area in which the thumb-away grip was most frequently used. On the right the positions of the mid-section points of this Ŧ-area are shown. The data were analysed by means of analysis of variance. This test affirmed our expectations; there was a significant effect of the variation ($F(1,9)=15.01$, $p<.01$), i.e. the magnitude of the thumb-away area is significantly larger for the short handle than under standard conditions. The mid-section points remained at the same position ($F(1,9)=2.32$, $p=.16$). This difference between the short handle and the long handle did not, however, have a significant influence on the estimated weighted kappa.

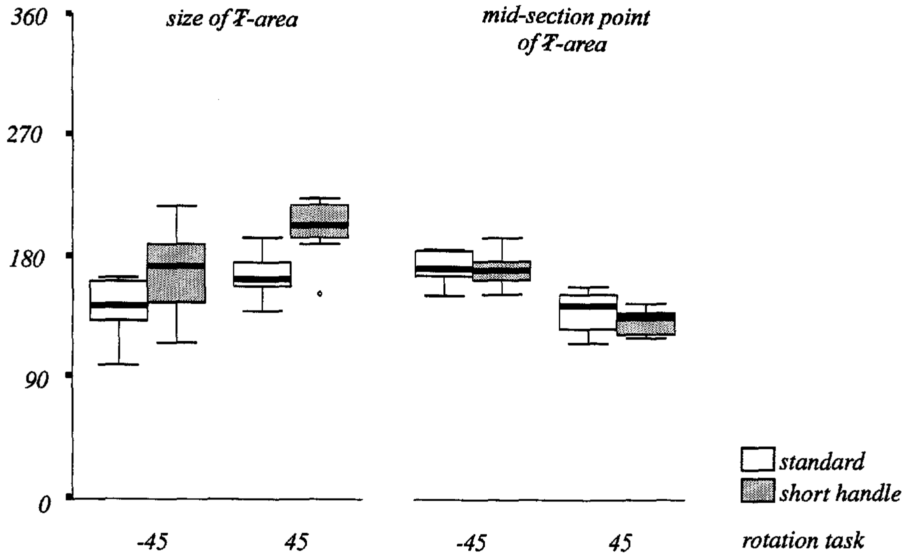


figure 6-11: A boxplot of the influence of the size of the handle on the size of the Ŧ -area (left), and the position of the mid-section point (right).

6.3 Conclusion

This chapter dealt with the directional controls. The results show that, independent of where the control is attached to the shaft, the grip used can be predicted accurately from the SUP+CAR range. Subjects did not differ significantly in the distribution of the grips used over all rotation tasks. The interindividual differences in the range of movement of SUP+CAR were too small to be significant. Therefore if the initial orientation and magnitude of the required rotation task are known, one can predict the grip people will use accurately. For some combinations two ways of grasping the control may be possible, i.e. thumb-towards or thumb-away. In such a case the movement time is significantly longer. This indicates that in case of a choice, the mental processes need more time to control the arm movements.

The arm movements made by the subjects differed. There was, however, a general tendency for all subjects to do the same thing. The same limited use of SUP and CAR combinations as found for the O-control was indicated by the motion analysis of rotation of the T- and L-controls. A combination of a near-maximum SUP and a near-minimum CAR value never occurred. As described in the previous chapter, we assume that use of SUP and CAR is controlled not only by hard constraints, such as the range of movement of SUP and CAR, but also by a soft constraint, i.e. a subconscious process resulting in the preference for SUP instead of CAR. This can possibly be explained by the fact that the arm is not highly differentiated. We can do many different things with the arm. An essential aspect is the manipulative activity of the hand: the hand has developed into a 'handsome' mechanism. An essential characteristic is that the hand can be brought to various places relative to the trunk and in many different orientations. The first aspect is accomplished mainly by the shoulder and elbow joints. The adjustment of orientation is accomplished partly by supination. The rotations performed in our experiments required changing orientations of the hand. Therefore it might be logical that this was accomplished mainly by SUP.

Analysis of the directional controls showed that only when the orientation of the control was -30° did all subjects grasp the control in the same way, independent of the magnitude and direction of the rotation task. In this case the control was grasped with a wrist orientation of -30°; a wrist orientation of 150° never occurred. For all other initial orientations the grip used depended on the magnitude and direction of the rotation task as well as placement of the pointer. As Rosenbaum and colleagues mentioned, for the rotation of a directional control one can find a thumb-towards bias. In case of two possibilities subjects will use the thumb-towards grip relatively more often than the thumb-away grip. This effect remains only a bias; it cannot be said that in the case of a choice subjects will always use the thumb-towards grip. However the subjects tended to use the thumb-towards grip more often than the thumb-away grip. The choice of grip can be influenced, for instance, by altering the dimensions of the control. We showed that when the length of the control was shortened by half, the number of thumb-away grips increased significantly.

Due to the directional aspect of the controls, the variation between subjects, albeit always significant, did not result in different tactics for the set of rotation tasks. All subjects used a limited number of combinations of SUP and CAR. The consequence is a relationship between the mid-wrist orientation and delta for the rotation. In case of a small, i.e. negative, SUP+CAR value CAR will exceed SUP. The opposite will be the case when the mid-wrist orientation is positive.

7 Conclusions and discussion

7.1 General conclusions

In chapter 1 our study was described as being an investigation of the differences, interindividual as well as intraindividual, in the various movements used to operate rotary controls, taking into account the relevant aspects of the controls as well as the changing tasks. In chapter 2 the question of degrees of freedom was considered in detail. When analysing human movements at the joint level, one can see that in many situations the number of degrees of freedom of the subject, determined by the degrees of freedom of the joints involved, exceeds the number of degrees of freedom required for the task. The subjects in our experiments had to perform a rotation task and were allowed only two degrees of freedom. The rotation task, however, required only one degree of freedom. The consequence is an indeterminate problem (Jordan and Rosenbaum, 1989): there is more than one way to perform the rotation task. It has been shown that in spite of the extra degrees of freedom people tend to move in a constant way. Why? What are the control mechanisms? Whatever the reason, it does not mean that humans have too many degrees of freedom. Motor equivalence is an important characteristic of the human being. It enables us, for instance, to go around obstacles while reaching straight ahead. Many other types of motor tasks reveal that the human body has more degrees of freedom than strictly required for the task. In literature many studies on this problem can be found. The benefit of these studies is, among others, increased insight into human motor control. It has been shown that the problem of the degrees of freedom can be solved by constraints. A constraint is a restriction of the use of a particular degree of freedom. Rosenbaum et al. (1992a) divided constraints into hard and soft constraints. Hard constraints are rules, soft constraints are preferences. When, for instance, pointing tasks are analysed, it can be seen that the length of the bones and the range of movement of the joints involved determine the area which one can reach. Soft constraints, on the other hand, are a kind of preference. When the subject points with his arm, a constant relationship between anteflexion of the upper arm and flexion of the elbow can be found (see e.g. Lacquaniti et al., 1982; Soechting and Lacquaniti, 1981 and 1983). This relationship is not rule-based, since it is possible to perform a pointing task without this constraint. People, however, tend to move in a limited way. In most cases efficiency can be seen as the basic reason for such a constraint.

Besides these constraints, which are characteristics of the human being, Jeannerod showed that the grasping movements made by a subject depend on the intrinsic and extrinsic properties of the object. In chapter 2 the literature on this concept was reviewed. At the end of the chapter it was stated that the ideas of Jeannerod are not always applicable. For grasping movements the transport phase is influenced by the extrinsic as well as intrinsic properties. Similarly the grasping phase is also influenced by these two properties. Due to the experiments of, for instance, Weir et al. (1991a and 1991b) it has become clear that the concept of intrinsic properties must be extended. Properties include more than the visual aspects, as indicated by Jeannerod. In addition to the properties of objects the task, i.e. what has to be done after prehension, also influences prehension (Marteniuk et al., 1987). From this it can be propounded that the movements made while using an object depend on three aspects, namely: -1- the physical aspects, -2- the position and orientation relative to the user, and -3- the task that has to be performed.

In our experiments we analysed the influence of these three aspects on the performances of the subjects. In figure 7-1 an overview of all the experiments is presented. The figure also shows the participation of each of the subjects in the ten experiments. In all experiments the task was to rotate a control. Three different controls were used: a non-directional O-control and the directional T- and L-controls. In addition to these physical aspects we also investigated the rotational resistance and introduced a short version of the L-control. In most cases the position of the control was constant. In one experiment with the O-control we altered the position of the control relative to the subject. The orientation of the non-directional control could not be altered. We could however systematically vary the orientation of the T- and L-controls. Finally the magnitude and direction of the task were varied. In most cases subjects had to perform nine rotations of the control.

experiment	grip		characteristics
1	O	central	standard
2	O	lateral	standard
3	O	cent./lat.	lefthanded
4	O	central	no vis. info
5	O	central	elbow flexion
6	O	lateral	resistance
7	T	-	standard
8	L	-	standard
9	L	-	time
10	L	-	short handle

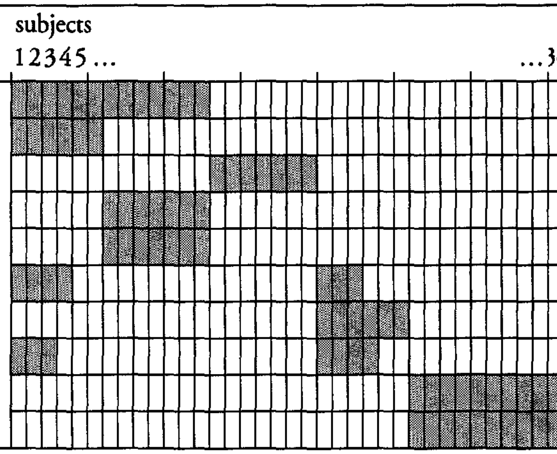


figure 7-1: An schematical overview of the ten experiments. On the right the participation of the subjects in the experiments is displayed.

When rotating the control, which requires only one degree of freedom, the subjects were allowed to use two degrees of freedom: combined arm rotations (CAR) and supination (SUP). Subjects were not allowed to rotate the control by means of trunk or shoulder movements, nor were they allowed to use finger movements. Therefore for this task there was an excess of one degree of freedom, and, consequently, the use of SUP and CAR cannot be determined. However, the subjects were expected to be constant in their performance of the rotation tasks. Consequently, hard and/or soft constraints must exist. Our aim was to find those constraints.

Rotation of the O-control, i.e. the non-directional control, was hardly constrained by the control. The difference between the final and the initial orientation, which is the sum of the SUP and CAR angles, must be equal to the magnitude of the knob rotation. The subject is free to choose the initial wrist orientation. Moreover, the subject is free to choose any combination of SUP and CAR. During rotation, the subject can change the joint angles. This can be accomplished by changing only SUP, only CAR, or a combination of SUP and CAR. Furthermore, although we did not expect this to occur, the subject can change SUP or CAR in the direction opposite to the direction of the required task. In this case the remaining degree of freedom must be used to rotate the control and to compensate for the other joint rotation. The results of the experiments showed that none of the subjects used this combination of SUP and CAR.

Although the control does not impose an initial wrist orientation, we found constant wrist orientations for each rotation task, for each subject and between subjects. The performance of a set of rotation tasks in a constant manner is called a tactic. Our data, however, revealed that more than one tactic can be applied to a set of rotation tasks. The outcome of cluster analysis of the differences between the final and initial joint angles showed that at least two distinct groups exist, A and B. Each group is presumed to use a specific tactic to perform the set of rotation tasks.

Tactic A can be described as an overall constant initial wrist orientation (of about -40°). Depending on the magnitude and direction of the rotation tasks, these subjects altered the SUP and CAR angles. In general the ratio of SUP to CAR was 2:1, so the subjects used twice as much SUP as CAR. For larger negative rotation tasks, however, the subjects used relatively more CAR. The reason is that during these rotation tasks, the forearm reached the limit of the range of movement of SUP. Consequently, they had to use relatively more CAR. A characteristic of this tactic is the fact that these subjects used a constant initial wrist orientation. Therefore they did not anticipate the task, neither the direction nor the magnitude.

The other group of subjects, who followed the B tactic, performed the rotation tasks in another way. All of these subjects anticipated either the magnitude and/or the direction of the rotation task. We divided this group into two subgroups, B1 and B2. The subjects using tactic B1 started from a constant initial joint angle which depended only on the direction of the rotation task. For negative rotation tasks this constant angle was close to the maximum SUP angle; for positive rotation tasks the minimum SUP angle served as the constant initial angle. When this tactic is compared with the A tactic, one can see that the major differences between the two tactics involve the negative rotation tasks. Subjects who used the B2 tactic performed the positive tasks in the same way as the subjects who used tactic A or tactic B1. Only the performance of the negative rotation tasks was clearly different. The subjects of group B adapted the initial angle to each of the negative rotation tasks. On the other hand, these subjects ended the negative rotation tasks at an almost constant joint angle. Another difference between tactic B1 and B2 was the use of CAR. Subjects who used tactic B1 used almost only SUP. They were able to anticipate the SUP angle so that they could perform the task with only SUP. Subjects who used tactic B2 used a significant proportion of CAR for all the rotation tasks. In all cases, however, the contribution of SUP exceeded that of CAR.

An overall characteristic of the performances of all subjects was the limited use of combinations of SUP and CAR. CAR was evidently only used when the SUP angle approached the minimum angle. Apparently, subjects preferred SUP over CAR. Another remarkable outcome was the fact that a wrist orientation of about -40° was preferred for both the initial and final orientation.

Thus, almost all of the twenty-three subjects (right-handed as well as left-handed) used one of three specific tactics to perform the set of rotation tasks. The rotation tasks clearly were not performed in an arbitrary fashion. In other words, the indeterminate problem was solved in one way or another. Underlying constraints should explain the preference for these tactics.

At first we expected end-state comfort (Rosenbaum and colleagues) to be a soft constraint. Rosenbaum and colleagues stated that rotation tasks are performed such that the final position of the arm will be comfortable. The results of our experiments, however, indicated that the final joint angles are evenly distributed over nearly the whole range of movements. Since only a small portion of that range of movement is considered to be comfortable, we could not confirm the concept of end-state comfort. On the contrary, the data showed that subjects who used tactic A started from a constant initial orientation. For the B1 and B2 tactics too a constant initial position was more common than a constant final position. A possible reason for this difference might be the fact that Rosenbaum's subjects always had to choose between two grips, i.e. an overhand grip and an underhand grip. This was not the case in our experiments with the non-directional control. Subjects were free to choose any initial orientation. Probably therefore the end-state comfort effect is only applicable when the subject has to make a choice between two possible grips.

Another concept which could restrict the use of SUP and CAR was presented by Bullinger and Solf (1979). They contended that rotation tasks will be performed by distal rotation; only when necessary will more proximal movements be used. Our data show that such extremes do not apply. Subjects always used a certain amount of proximal CAR, although in most cases they used significantly more SUP than CAR. Analysis of the anatomical structure of the arm reveals that a movement involving only SUP or only CAR requires complex motor control. When one wants to rotate a control by means of SUP only, one must also activate the muscles acting on CAR. Otherwise, the upper arm will rotate instead of the control. When only SUP is used, the muscles acting on CAR must become isometrically active, i.e. they have to deliver some momentum to prevent rotation of the upper arm. This is, of course, also the case when one wants to rotate the control only by CAR. These considerations suggest that a rotation performed only by SUP or CAR will be rare, since extensive control of the muscles is then required. It is therefore expected that SUP as well as CAR will almost always be used. Moreover, it is expected that these two movements will cooperate to each other, i.e. change the wrist orientation in the same direction. If not, eccentric contractions will be necessary, but they are wasted energy and should therefore be avoided. However this still does not explain why subjects prefer to use SUP instead of CAR.

We investigated whether the use of only limited combinations of SUP and CAR could be attributed to gravity or passively imposed wrist angles. It was found that neither could explain the preference. Therefore, we conclude that the limitation must be caused by, according to the definition of Rosenbaum et al. 1992a, a soft constraint, i.e. a mental preference. We demonstrated that this limitation cannot be caused by a hard constraint, since subject 13 performed the negative rotation tasks with increased resistance without following this constraint at all. The subject started with a nearly maximum SUP angle, which remained maximum during the performance. The rotation tasks were only performed by using CAR, and the forearm remained passively in the maximum SUP angle. By means of this strategy, the subject used combinations of SUP and CAR which were never used by any of the other subjects.

A possible explanation for the preference for distal SUP over CAR is the fact that the SUP movement is closer to the object. In addition SUP movement requires little space because the rotation occurs around the longitudinal axis of the forearm. Another explanation could be the fact that shoulder movements, i.e. CAR, are normally used for positioning of the hand, while SUP is used to change the orientation of the hand.

The main difference between the A and the B tactics is anticipation. Those in the A group did not anticipate the task, while those in the B group can be characterized by anticipation. From this it can be concluded that the A tactic will be the simplest tactic. Bernstein (1967) showed that when people learn a new skill, they tend to freeze several degrees of freedom so that motor control will be easier. Later on, all restrictions are lifted. Subjects who apply tactic A, in fact, decrease their amount of freedom by choosing an overall constant initial orientation. This was affirmed by experiments with the lateral grip. This grip is more common than the cumbersome central grip, which influenced the perceived complexity of the rotation tasks. When the subjects changed their grip, they altered their tactics. In most cases a subject who used the A tactic in the standard situation - i.e. the central grip - changed to either B1 or B2 when the lateral grip was used. Therefore first they did not anticipate, later they did. Moreover when visual information was excluded, which one would expect to make rotation more difficult, some of the subjects changed back to the A tactic. When the B1 tactic is compared to the B2 tactic, it appears that the B1 tactic involves significantly less CAR: almost the entire rotation task was performed by SUP. As the use of the distal SUP is more economical than the use of the proximal CAR, it is concluded that the most economic way to perform the set of rotation tasks is the B1 tactic.

In a second group of experiments we used 'directional controls', the T- and the L-control. This type of control imposes initial and final wrist orientations. The hand has to grasp the control in a full grip; consequently the wrist orientation has to be equal to the orientation of the control. These controls, therefore, constrain the act of rotation more than the O-control (whereby the subject was free to choose the initial wrist orientation). Evaluation of the rotation of the O-control revealed that subjects prefer the use of SUP over CAR. This was also the case for the directional controls. When analysing the use of combinations of SUP and CAR, it appeared that also for directional controls the contribution of CAR was only significant when the SUP angle was close to the minimum value. Therefore, for rotation of the directional control, the preference of SUP works as a soft constraint on performances. Since wrist orientation depended on the orientation of the control, the ratio between the two degrees of freedom depended on the initial position of the control and the way the control was grasped.

We have shown that the way subjects grasped the directional control could be predicted from the sum of the range of movement of SUP and CAR. The differences between the T- and the L-controls were not relevant to the prediction. In experiments with the L-control it appeared that a general range of -180° to 150° could be used to predict the grasp accurately. For most combinations of the initial position and the magnitude and direction of the rotation task the subjects could only use one of two possible grips, i.e. the thumb-towards (the tip of the pointer) and thumb-away grip. A remarkable outcome of the experiments was that for all rotation tasks with an initial orientation at 5 o'clock or 11o'clock all subjects grasped the control with a wrist orientation of -30°. For the rotation tasks which could be performed with either grip, we showed that the concept of end-state comfort or the thumb-towards bias (Rosenbaum et al., 1992a) did not improve the prediction. For this purpose we estimated the probability by linear approximation with respect to the surrounding grips, i.e. with changing adjacent initial positions (see Stelmach et al., 1994) and adjacent magnitudes obviously the choice will change from the thumb-towards to the thumb-away grip. Subjects have to make a choice, which significantly increased the movement time.

The results of the experiments with the directional controls showed, however, that subjects tend to use the thumb-towards grip relatively more often than the thumb-away grip. Rosenbaum et al. (1992a) defined the thumb-towards bias as a preference for the thumb-towards grips, i.e. the thumb is pointed towards the pointer. In our prediction model, however, we tested the idea of a thumb-towards bias by predicting a thumb-towards grip whenever there was a choice. It was found that this did not improve our prediction of the grip used. The data, however, did suggest that subjects tend to use the thumb-towards grip relatively more often than the thumb-away grip. Therefore, we can confirm the idea of a thumb-towards bias. The choice of grip is not only dependent on the initial position of the control and the magnitude and direction of the rotation task. We have demonstrated that the choice of grip can be influenced by changing physical aspects. For instance, the experiment with the short L-control illustrated that under certain circumstances the subjects will use thumb-away grips significantly more often.

Depending on the magnitude and direction of the rotation and the initial orientation of the control, a subject will grasp the control in a thumb-away or thumb-towards grip. This will result in an initial wrist orientation. We have found that the ratio of SUP to CAR is related to the mid-wrist orientation, i.e. the wrist orientation at the middle of the rotation task. When this mid-wrist orientation approaches the lower limit of the range of movement of the sum of SUP and CAR, the contribution of CAR exceeds the contribution of SUP. This ratio will change in favour of SUP as this mid-wrist orientation increases up to the upper limit of the range of movement.

Our experiments show that the way subjects perform rotation tasks can be predicted with reasonable accuracy. If the hard constraints imposed by the anatomical structure of the arm and resulting in a given range of SUP and CAR and the soft constraint causing the preference of SUP over CAR are known, rotation of the directional controls can be predicted. For the non-directional O-control however, at least three different tactics remain possible. One can anticipate the magnitude and direction of the rotation task (tactic B1 and B2) or not (tactic A). The choice of the tactic probably depends on the skillfulness of the subject. In the event of a more difficult situation, e.g. central grip or no visual information, the subjects tended to use the A tactic. When it was possible to use the more common lateral grip, most of the subjects used the B1 tactic.

In short, the main conclusions are:

Non-directional controls

- The performance cannot be explained by end-state comfort nor by the idea that proximal movements are only used when distal movements reach the limit of the range of movement.
- There are at least three different tactics for performing the rotation tasks with the non-directional control; these tactics are assumed to represent a hierarchical order.
- Not all combinations of SUP and CAR are normally used by a subject. The full range of movement of CAR is evidently only used when the SUP approached the minimum value. This restriction cannot be explained by the passively imposed wrist angles nor by the effect of the gravity on the arm.
- Subjects prefer to use SUP rather than CAR, but CAR is nearly always also used.
- The neutral wrist orientation is -40°.

Directional-controls:

- The choice between a thumb-towards and a thumb-away grip is in most cases imposed by the range of movement of SUP and CAR.
- In case both grips are possible, the linear approximation model predicted the grip used as well as the theoretically based models (thumb-towards, avoid extreme, and final comfort).
- Subjects tend to use relatively more thumb-towards grips than thumb-away grips.
- The ratio between the use of SUP and CAR depended on the mid-wrist orientation.
- The difference between the T- and L-control did not result in a difference in performance.
- The movement time at the reversal points is significantly longer than the movement time at the mid-section points.
- The choice between the thumb-towards and thumb-away grip can be influenced by shortening the cylinder of the L-control.

7.2 Some practical implications

Whether the results of our experiment can be used in practice depends, among others, on whether the results of our experiments can be generalised. In all of our experiments the joint angles were assessed within an accuracy of several degrees. Saltzman (1979) stated that an action plan, which is said to incorporate abstract information about task demands, the environment, and the motor apparatus (Turvey, 1977), can be defined at seven levels. The highest level is the conceptual level. At this level the act is defined in terms of 'reach', 'rotate', etc. One can decide to assess human movement at this level (see e.g. the therbligs used in motion studies; Barnes, 1968). Analysis of the rotation tasks at this level will result in an overall constant outcome because all subjects grasped the control and rotated it. When, however, the level of interest is muscles or even activation of motor units, all movements will be different. We chose to record the movements at the level of body-space motion and joint motion (levels 4 and 5 of Saltzman). At this level there are variability and invariability within and between subjects, which is attractive to study. Furthermore, the level of joint motion provides knowledge which can be applied to the design of controls or control panels. When, for instance, the optimum orientation angle of a control is known as well as the movements of the arm involved in rotating a control, the designer can construct and place his control in such a way that it is possible to grasp the control easily with enough space left to make the required arm movements.

In our experiments the subjects were restricted in the degrees of freedom. They had to grasp the control with a full grip, so none of the degrees of freedom of the hand could be used. Also they were not allowed to use shoulder and trunk movements to rotate the controls. The results of the experiments showed that about 85% of the rotation was performed by SUP and CAR. The remaining part is attributed to other movements. It also appeared that in most cases most of the rotation was performed by distal SUP. The contribution of CAR was significantly less. It is assumed that even when subjects are free to rotate the control as they wish, most of the action will still be SUP. A smaller percentage will be performed by CAR, and consequently an even smaller proportion will be attributable to shoulder and trunk movements. Of course, the requirement of a full grasp will have a significant influence. If subjects are allowed to use the entire range of movements of the hand, the performance of rotation will be very different and the problem of indeterminacy will become much more complex (see e.g. Kanis, 1993).

The position of the control relative to the subject was also restricted. In chapter 3 the range of movement of CAR was said to depend on the position of the wrist relative to the trunk. The scope of this range could be decreased considerably, e.g. by placing the wrist at shoulder height in the frontal plane. The consequence will be that the sum of the ranges of movement of SUP and CAR will decrease. Therefore, the prediction of the grasp for all rotation tasks will be different. Some rotation tasks will for instance no longer be possible.

Therefore, the range of movement influences the probabilities of grasping the control in one way or another. Consequently, some musculo-skeletal disorders will influence the results of these experiment. We, intentionally, used only healthy subjects. Subjects who suffer from arthritis or a muscular disease are expected to use the degrees of freedom in an entirely different way. This was studied by Kanis (1993). In his experiment he showed that physically impaired subjects rotate a control in a completely different manner. He, therefore, recommends that there should be a high degree of freedom for the manipulation of controls. For our experiments we used only subjects who were perfectly able to perform the set of rotation tasks. If, however, the maximum magnitude of the rotation tasks were increased, some of the rotations of the T- and L-control simply could not be performed; for instance, if the initial orientation is 5 o'clock or 11 o'clock and the rotation task is 150° (see figure 6-3). In this case, the subject either has to use shoulder or trunk movements or has to transfer his grip during rotation.

In our study we have shown that the kinematic-kinesiological analysis provides fundamental insight into the act of rotating a control. This method can be used for other kinds of motor task. We intentionally chose a simple rotation task with only one extra degree of freedom. The more degrees of freedom, the more complex the analysis will be (see e.g. Kanis and Wendel, 1990).

A remarkable outcome of the study was the neutral wrist orientation for rotation of the non-directional O-control. The most frequently used initial or final wrist orientation was about -40° and consisted of about -20° SUP and -20° CAR. For the directional controls (T- and L-control) too it appeared that all subjects grasped the control with a wrist orientation of -30° when the control pointed towards 11 o'clock or 5 o'clock. A subject never grasped the control with an initial wrist orientation of 150°. In all other cases the subjects changed the grip depending on the initial orientation. This applied especially when the initial orientation was 2 or 3 o'clock. We have shown that in that case the movement time was significantly longer than at the mid-section points. This indicates that when a control has to be grasped and quickly rotated in either the positive or the negative direction through less than 120°, the best initial position is the neutral orientation of -40°. Unfortunately this is a paradox. Usually the neutral position of a control, which has to be rotated in both the negative and the positive direction, is 12 o'clock (see, for instance, the balance control for an amplifier). Moreover, the neutral position of -40° is only neutral if the user is right-handed. Therefore, we suggest that only in the case of frequent right-handed usage, without visual information, may the neutral position of a rotary control be -40°. Rotary controls which are seldom used or have to be used by right-handed as well as left-handed operators should have a neutral orientation of 0°.

table 7-1: The applicability of the three controls under various conditions (numbers 7 to 15 - written in italics - are not directly based on the results of our experiments)

		O	T	L
1	number of possible grip orientations in full grasp	∞	2	2
2	number of tactics	3	1	1
3	predictability of grip orientation	-	+	+
4	freedom to grasp	+	-	-
5	neutral orientation of control (right wrist)	-40°	-40°	-40°
6	ratio between proximal and distal arm rotations	1:2	1:0 to 0:1	
7	*possible obstruction at full grasp*	-	++	+
8	*maximal rotation speed*	+	+	-
9	*visual overview during prehension*	+	-	-
10	*visual overview while rotating*	-	+	++
11	*visual orientation*	-	+	++
12	*somaesthetic orientation*	-	+	++
13	*possibility to deliver high momentum*	-	+	++
14	*accurate positioning*	-	+	+
15	*possible range of rotation*	+	-	-

In addition to these practical implications we would like to offer some suggestions on application of the three controls. In table 7-1 the applicabilty of the three controls is presented. Only the first six points are based directly on the results of our experiments. The underlying assumptions are that the controls will be used under the same conditions, i.e. in front of the user, rotated by using only upper arm and forearm rotation, grasped by one hand, etc. Moreover we assume that the dimensions will resemble those of the controls we used in our experiments. A change in, for instance, the size of the control will result in a change in usage.

The three controls differed in shape. The construction of the T-control yields the highest probability of obstruction of the grip. The cylinder of the control obstructs the fingers while grasping, moreover, the shaft must ultimately lie between two fingers. The shaft is not an obstruction when the L-control is grasped. The qualifications change when the subject is free to choose the grip. Then, for instance, the T- and L-control can be grasped at the end of the cylinder. Now the shaft will not obstruct the grasp. When a control has to be rotated quickly, we advise the O- or T-control. Both controls enable the user to grasp the control in line with the arm. The maximum speed of rotation depends, among others, on the inertia of the arm. Since, when grasping the L-control, the arm is not in line with the control, more force is required to rotate the control quickly. Visually, the O-control will cause the least visual obstruction; one can, for instance, easily see the scale behind the control. Both the T- and L-control obscure a part of this scale. When rotating the control, orientation of the directional controls is easier to determine. The L-control, however, is preferable, because the T-control can be pointed in two directions, since this control is symmetric at the shaft. When the control is grasped, somaesthetic orientation of the control can best be determined for the L-control, not the O-control, because in the latter case the orientation of the wrist with respect to the control will differ in most cases. Due to the orientation of the cylinder relative to the shaft, one can deliver greater momentum to the directional control. When greater momentum is required, the L-control is advised. When the task is a question of accuracy, the directional controls will probably be better than the non-directional control since wrist orientation equals orientation of the control for the directional control. Of course, an increase in the control/response ratio for the O-control means that this control can also be used for accurate positioning. When the non-directional control is grasped the difference between the orientation of the control and the orientation of the wrist will depend on the actual grip. As a consequence the non-directional control allows more freedom of the grip. In addition, the subject is free to choose any of the possible grasps (e.g. central or lateral). In some cases this might be advisable, but when one has to react quickly and accurately, the extra freedom may delay the performance. Finally, an imposed initial wrist orientation for directional controls influences the maximum range of rotation: the maximum range of rotation is almost always less than the total range of SUP and CAR. For the O-control the subject can choose the initial wrist orientation; consequently the full range of SUP and CAR can be used in one single rotation.

7.3 Suggestions for further study

In our experiments we studied the use of rotary controls. Although the experiments provided some fundamental insight and had some practical implications, we must conclude that many questions remain unanswered. For instance, why do subjects limit themselves to certain combinations of SUP and CAR? By constructing a mathematical model which includes the active and passive characteristics of the anatomical structures, it might be possible to explain the combinations of SUP and CAR. We admit that this will not be easy, but we expect that such a model will help to clarify the complex interactions between the diverse degrees of freedom. In addition, it will help to determine the function of all muscles. At this time the function of most of the muscles is only defined in terms of the anatomical posture (see for instance table 3-2). When using the arm, the direction of the force of the muscles will change relative to the axis of rotation of the joints. The consequence is an altered function. Therefore, we again would like to emphasize that the function of the muscles, as given in table 3-2, only applies when the activity is started from the - uncommon - anatomical posture. In the end, kinematic as well as kinetic studies may furnish knowledge which can be used in product design, for instance for the construction of orthosis, control placement, etc.

To obtain such a mathematical model, one will first have to understand the kinematic characteristics of the hand and the shoulder. From our point of view, we are interested in the movements occurring in those specific parts of the body involved in the use of a product, i.e. reaching for it or manipulating it. What kind of movements occur when, for instance, one has to manipulate the controls with the fingers? What is the contribution of shoulder movements when one has to reach? This kind of information could help to determine the position of controls on complicated control panels.

In our study we have examined the movements involved in the rotation of a control. We explicitly did not study the 'reach' before the grasp. This part of the movement has been the topic of recent scientific studies in human movement science (see for instance, Bennett and Castiello, 1994). In this discipline, firstly, the simple tasks of aiming was studied. Then, the grasp movement was studied. Little is known about manipulating experiments. What is the effect of the task on prehension? This kind of information is not only useful for movement scientists. Product designers can also use this kind of information to design optimum work situations.

We found that subjects who rotate an O-control, exhibited at least three different tactics. We assumed some hierarchy but did not investigate this field completely. Which characteristics of the subject or interaction between the subject and the object explain the choice of tactic? We assumed that the A tactic was the simplest one. Is it true that, as in learning difficult motor skills, the subjects change tactics once they get used to the task? In our experiments we noted that when a more common grip was allowed, the subjects changed to a B tactic. And when visual information was excluded, some of the subjects changed back to the A tactic. But when standard rotation tasks with the O-control are rehearsed for a longer period of time, will subjects who initially used the A tactic change to a B tactic? And if so, will there be a transition phase, or are tactics in fact discrete entities?

In our study we only studied a few rotary controls. It would be interesting to use the same kinematic-kinesiological method to study other kinds of controls. For instance, how do people use translation controls? Or one could study the performances involved in controlling a joystick, which offers still more degrees of freedom. Also the size of the controls could play a role. One could, for instance, study the way the steering wheel of a car is controlled. When do we need to change grips? Is a better control available to perform the same steering tasks? It would also be interesting to investigate controls which have to be held in two hands. There are therefore many controls and tasks which would be worth studying.

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Samenvatting

Armbewegingen bij het bedienen van draaiknoppen

Introductie

In dit proefschrift wordt een onderzoek beschreven naar de relatie tussen enerzijds armbewegingen bij de bediening van draaiknoppen en anderzijds kenmerken van de knop en of de taak. In hoofdstuk 1 worden de kaders aangegeven van het te bestuderen gebied. In het tweede hoofdstuk wordt een overzicht gegeven over de relevante literatuur, waarop het onderzoek voortbouwt. In de twee daar op volgende hoofdstukken (3 en 4) wordt de methode beschreven die gehanteerd is bij het uitvoeren van de experimenten. Deze experimenten worden verder in hoofdstuk 5 en 6 beschreven. In het laatste hoofdstuk (7) wordt de studie afgesloten met algemene conclusies, pogingen tot praktische implicaties van de uitkomsten voor het ontwerpen van draaiknoppen en suggesties voor verder onderzoek.

Kader

Bij het gebruik van veel goederen zijn menselijke bewegingen noodzakelijk voor de bediening van het produkt. Deze bedieningsbewegingen zijn op een bepaalde manier gerelateerd aan het produkt. De relatie tussen een produkt en de bedieningsbewegingen vormen het object van deze studie. Het onderzoek bevindt zich dan ook tussen bewegingswetenschappen en het produktontwerp. Dit gebied wordt bestreken door de produkt ergonomie.

De ergonomie houdt zich bezig met de aanpassing van het produkt aan de mens. Daarvoor is kennis nodig van enerzijds de mens en anderzijds het produkt. In de ergonomie bij uitstek worden deze twee kennisgebieden geïntegreerd. Op het gebied van de beweging met produkten ligt nog een grotendeels onontgonnen terrein. Waarom worden produkten op een bepaalde manier gehanteerd? Is het mogelijk de bediening van een produkt te sturen door het produkt een bepaalde karakteristiek mee te geven? Op dit soort vragen is in het algemeen geen eenduidig antwoord te geven. Het doel van dit onderzoek is fundamenteel inzicht te leveren in een dergelijke problematiek.

Nu is het binnen een project als dit niet mogelijk het gehele gebied te bestrijken. Er moeten daarom keuzes voor wat betreft de produkten worden gemaakt. De voorkeur gaat er naar uit om in eerste instantie niet met complexe, samengestelde produkten te beginnen. We kiezen in dit onderzoek voor de bedieningselementen (controls). De bediening hiervan is vaak niet dermate gecompliceerd dat de bestudering van de menselijke beweging een onmogelijke opgave wordt. Wederom moet het gebied verder beperkt worden, er zijn immers tal van bedieningselementen. We kiezen uiteindelijk voor draaiknoppen. In de experimenten worden drie soorten knoppen gebruikt: de O-, de T- en de L-knop, waarover later meer. In de reeks van experimenten zal worden onderzocht of er een relatie ligt tussen enerzijds kenmerken van de knop, zoals vorm, afstand en oriëntatie ten opzichte van de gebruiker en de rotatie taak en anderzijds de manier waarop deze bediend worden.

In hoofdstuk 1 wordt een overzicht gegeven van diverse registratiemethoden van de beweging en/of houding van de bovenste extremiteit van de mens. Deze methoden worden in veel verschillende gebieden gebruikt. Zo worden er voorbeelden gegeven van systemen die gebruikt worden in de arbeidsanalyse, voor balletregistratie en voor het noteren van gebarentaal. Het blijkt dat deze methoden onderling veel verschillen. Een opvallend verschil is de fijnheid of resolutie waarmee een beweging kan worden geregistreerd. Een algemeen kenmerk van al deze systemen is het feit dat de beweging in eerste instantie met het blote oog moet worden geobserveerd, pas daarna wordt de beweging omgezet in een bepaalde code. Uit onderzoek blijkt dat veel van deze methoden niet valide zijn. Daarom is er voor deze studie gekozen om gebruik te maken van een, in de bewegingswetenschappen gebruikelijk, bewegingsregistratiesysteem. Deze systemen kenmerken zich door een objectieve nauwkeurige registratie van beweging. Feitelijk worden de 3D posities van bepaalde gemarkeerde lichaamspunten in de tijd geregistreerd. Binnen ons onderzoek maken we gebruik van het OPTOTRAK systeem. Dit systeem is in staat om met een hoge temporele en spatiële resolutie de positie van markers vast te leggen; de meetfout is minder dan 0,5 mm.

Derhalve kan het doel van ons onderzoek worden omschreven als het uitvoeren van een kinematische studie, naar (in)variante bewegingen, zowel binnen een proefpersoon als tussen proefpersonen, bij het bedienen van roterende bedieningselementen, mede als functie van bedieningselement- en taak aspecten. Om het aantal vrijheidsgraden binnen de perken te houden, heeft er een verenging van het meetveld plaats gevonden. De metingen vonden plaats in een experimentele laboratorium situatie, en de nadruk lag op kinematisch - ergonomische variabelen.

Literatuur

Op het gebied van de menselijke beweging is al veel onderzoek gedaan. Het gebied, waar een duidelijke bewegingsinteractie ligt tussen een produkt en de mens, is echter nog voor een groot deel onontgonnen. In hoofdstuk 2 wordt een verslag gedaan van onderzoeken waarbij een relatie werd gelegd tussen menselijk bewegen en kenmerken van een object. Veelal betreft het hier uitermate eenvoudige objecten; vaak worden blokjes gepakt, maar ook het wijzen naar een doel kan worden gezien als een soort van interactie met een simpel object. Een algemeen probleem hierbij is het zogenaamde vrijheidsgradenprobleem. Het probleem omvat het feit dat in veel situaties het aantal vrijheidsgraden van de beweger groter is dan het aantal vrijheidsgraden dat minimaal nodig is om de taak uit te voeren. Het gevolg hiervan is dat de beweging niet op voorhand gedetermineerd kan zijn: er zijn in principe vele verschillende mogelijkheden om de taak uit te voeren. Oplossingen voor het vrijheidsgradenprobleem worden gevonden in de 'constraints'. Deze constraints zijn wetmatigheden of voorkeuren die leiden tot een koppeling of vermindering van een aantal vrijheidsgraden, waardoor invariant gedrag verklaard kan worden.

Binnen de literatuur zijn er vele voorbeelden te vinden van simpele taken waarin men constraints heeft gezocht om constantheid van gedrag te beschrijven. Deze taken variëren van uiterst simpele wijstaken tot complexe hanteringen van produkten. Het literatuuroverzicht in hoofdstuk 2 is gegroepeerd naar taak. In eerste instantie worden wijstaken behandeld. Daarna volgen de grijptaken. Ten slotte worden manipulatietaken beschreven. Deze volgorde kan worden gezien als steeds meer omvattend. De grijptaken sluiten immers ook een reik (of wijs) fase in. De manipulatieve taken omvatten naast het manipuleren ook het reiken en het grijpen. In deze laatste categorie kan ons werk worden geplaatst. De proefpersonen moeten in onze experimenten tal van verschillende rotatietaken met verschillende bedieningselementen uitvoeren. Binnen het project wordt slechts de fase wanneer er contact is tussen de hand en de knop nader bestudeerd. De reik- en grijpbewegingen vormen derhalve geen deel van het onderzoek.

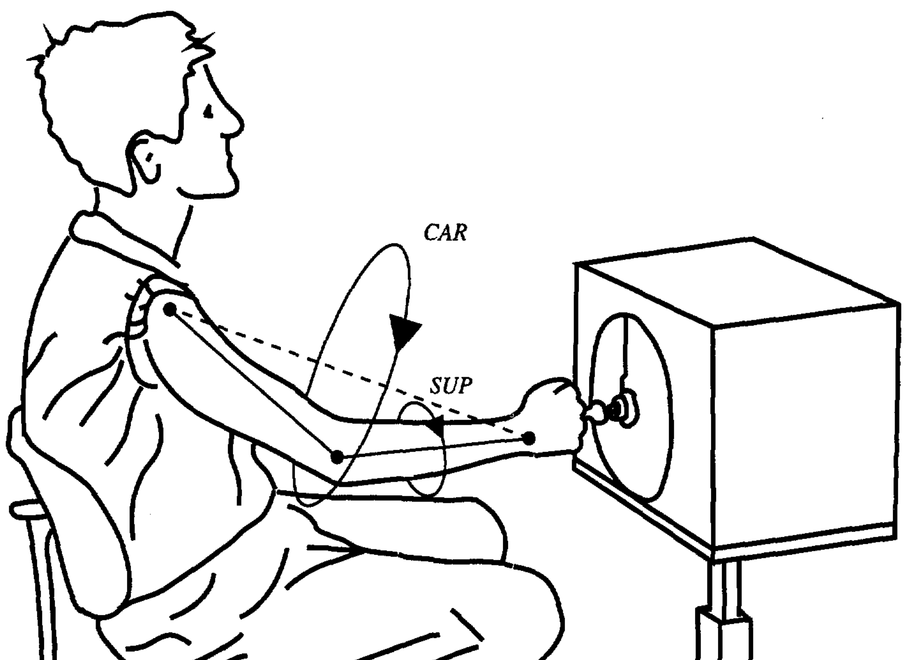
Bij het onderzoeken van wijstaken blijkt dat het gedrag binnen en tussen de verschillende proefpersonen vaak invariant is. Het afgelegde traject van de pols bij een wijstaak is bijvoorbeeld vaak rechtlijnig. Tevens blijkt dat de grootte van het doelgebied en de afstand die moet worden afgelegd bepalend is voor de bewegingstijd. d.w.z. er is een omgekeerd evenredige relatie tussen de moeilijkheidsgraad en de bewegingstijd (Fitt's law). Een andere uitkomst uit de literatuur omtrent de wijstaken is een relatie die is gevonden tussen proximale schouder- en distale elleboogbewegingen. Veelal is verhouding tussen de verandering van de schouderhoek en de verandering van de elleboogshoek lineair gekoppeld. Tevens blijkt dat de polsbewegingen niet aan een dergelijke koppeling worden onderworpen.

In de experimenten met grijptaken wordt er naast het reiken ook nog grijpen gevraagd. Jeannerod beschrijft hier de invloeden die een object heeft op de uitvoering van een grijpbeweging. Hij geeft een onderverdeling aan tussen intrinsieke en extrinsieke eigenschappen. De eerste zouden de grijpfase moeten beïnvloeden, terwijl de tweede de reikfase stuurt. Uit later onderzoek blijkt dat deze tweedeling niet zo strikt kan worden gemaakt. Tevens blijken de definities, zoals gehanteerd door Jeannerod, te strak te zijn; zo beïnvloeden onder andere ook haptische aspecten de manier van grijpen.

In het laatste deel worden de manipulatieve taken beschreven. Uit dit werk blijkt dat ook de taak van het manipuleren van een object reeds invloed heeft op de reikbeweging. Belangrijk onderzoek is uitgevoerd door Rosenbaum en collega's. Zij lieten proefpersonen diverse rotatietaken uitvoeren met cilindervormige objecten. In veel gevallen konden de proefpersonen kiezen tussen twee verschillende manieren om het object vast te grijpen: met de duim naar een markant punt van het object of juist er vanaf. Zij concluderen dat de keuze door het 'end-state comfort' kan worden verklaard: proefpersonen anticiperen dusdanig op een taak dat de eindhouding comfortabel is. Ook beschrijven zij de 'thumb-towards bias'. Deze omhelst de aantrekkingskracht van de duim in de richting van een markant punt op het te bewegen object, bijvoorbeeld een wijzer of een marker. Een totaal andere wetmatigheid wordt beschreven door Bullinger en Solf. Zij beschrijven de volgorde waarin rotatietaken worden uitgevoerd: in eerste instantie wordt de rotatie distaal uitgevoerd, en pas indien noodzakelijk worden de meer proximale bewegingsmogelijkheden aangewend.

Methode

Na eerst een beknopt anatomisch overzicht betreffende de bovenste extremiteit te hebben gegeven, worden in hoofdstuk 3 de mogelijke gewrichtsrotaties beschreven, zoals die gelden binnen onze experimentele opzet. Bij het hanteren van een draaiknop, die zich voor de proefpersoon bevindt, kan de proefpersoon gebruik maken van slechts twee gewrichtsrotaties: Combined Arm Rotation (CAR) en Supinatie (SUP). In figuur 1 staan deze twee bewegingsmogelijkheden weergegeven. CAR is de rotatiemogelijkheid in het schoudergewicht (proximaal). De rotatie-as loopt hier vanaf de schouder tot aan de pols, die hierbij als een cardan-verbinding dient. De bewegingsbereik is ongeveer van -120° tot +60° (een positieve CAR-rotatie resulteert in een rechtsom rotatie van de knop). De distale bewegingsmogelijkheid is SUP. Deze beweging manifesteert zich in de onderarm. Het bereik is van ongeveer -90° tot aan +90°. Ook SUP is zodanig gedefinieerd dat een positieve SUP-rotatie tot een rechtsom rotatie van de knop leidt. Beide bewegingen zijn commutatief ten opzichte van elkaar, d.w.z. de volgorde waarin de rotaties worden beschreven heeft geen invloed op de uiteindelijke positie. SUP en CAR kunnen beide volledig worden aangewend om de knop te roteren. De maximale rotatieuitslag is derhalve van ongeveer -210° tot 150°. In dit hoofdstuk wordt beschreven hoe een armbeweging wordt gekwantificeerd tot een CAR en SUP beweging. Aan het eind van dit hoofdstuk wordt ingegaan op de reproduceerbaarheid en validiteit van de gebruikte methode.



figuur 1: De positie van de proefpersoon ten opzichte van de draaiknop. Tevens zijn de twee toegestane armbewegingen weergegeven: proximaal de CAR *en distaal de* SUP.

Hoofdstuk 4 bevat de verdere beschrijving van de experimentele opzet. In de meetopstelling zit de proefpersoon achter de knop, zoals is weergegeven in figuur 1. In hoofdstuk 4 worden de drie gebruikte draaiknoppen nader omschreven. In de eerste experimenten wordt de O-knop gebruikt. Deze ronde knop is richting indifferent: het frontale aanzicht is onafhankelijk van de ingenomen rotatiehoek. Binnen de experimenten mag de O-knop op twee manieren worden gegrepen: de centrale en de laterale greep. Afhankelijk van het experiment wordt er één van de twee grepen opgelegd aan de proefpersoon. Bij beide grepen bevindt de knop zich in de palm van de hand. Bij de centrale greep loopt de as tussen de middelvinger en de ringvinger door. De onderarm, hand en as van de knop liggen hierbij, in de neutrale houding, in een rechte lijn. De centrale greep is een ongebruikelijke greep, de laterale greep daarentegen is meer gebruikelijk. In deze greep ligt de as tussen de wijsvinger en de duim in, op de manier waarop veelal een schroevedraaier wordt gehanteerd.

Naast de O-knop zijn ook nog de T- en de L-knop gebruikt. Deze zijn richtingsgevoelig: een verandering rond de rotatieas van de knop leidt tot een ander frontaal aanzicht. Haaks op de rotatieas van de knop is een cilinder gemonteerd, die in de hand moet worden genomen. Het verschil tussen de T- en de L-knop is de plaatsing van de cilinder ten opzichte van de as. Bij de T-knop ligt deze centraal; de as loopt tussen de middelvinger en de ringvinger door. Bij de L-knop ligt de rotatieas aan het uiteinde. Deze knoppen mogen in de experimenten op twee verschillende manieren worden gepakt: de duimgreep en de pinkgreep. De keuze van de greep wordt overgelaten aan de proefpersoon. Bij de duimgreep ligt de duim in de richting van de wijzer die op de rotatieas geplaatst is. Bij een verandering van de oriëntatie van de hand ten opzichte van de knop van 180° ligt de pink in de richting van de wijzer. Deze greep wordt dan ook de pinkgreep genoemd.

In de experimentele zitting krijgen de proefpersonen de opdracht om de knop in een bepaalde richting en over een bepaalde hoek te draaien. Zij mogen hiervoor alleen SUP en CAR aanwenden, en moeten dus rompbewegingen vermijden. Ook is het niet toegestaan tijdens het uitvoeren van de taak de knop te verpakken.

Vrijheidsgradenprobleem

We hebben nu gezien dat in de door ons gebruikte experimentele situatie de proefpersoon over twee vrijheidsgraden beschikt: CAR en SUP. De rotatietaak vraagt echter slechts één vrijheidsgraad. Het aantal vrijheidsgraden van de proefpersoon overtreft dus het aantal vrijheidsgraden van de taak. Het gevolg is dat de rotatiebewegingen aan de knop niet gedetermineerd zijn.

Experimenten met de O-knop

Kenmerkend voor de ronde O-knop is dus dat deze knop geen oriëntatie, in het frontale vlak, aan de pols oplegt. Bij een bepaalde grootte van een rotatietaak moet alleen het verschil tussen de eind- en de begin-polsoriëntatie gelijk zijn aan de grootte van de rotatietaak, waarbij de polsoriëntatie gelijk is aan de som van de SUP en de CAR hoek. Tevens is er niets vast gelegd over de verhouding tussen het gebruik van SUP en CAR. Het kan in beginsel zo zijn dat de SUP tegengesteld gericht is aan de CAR en de richting van de taak. In dat geval moet de CAR net zo groot zijn als de grootte van de taak plus de grootte van de SUP verandering. De experimenten zijn deels exploratief (wat doen proefpersonen) maar ook hypothese toetsend. Op grond van de literatuur in hoofdstuk 2 wordt verwacht dat de proefpersonen de rotatietaken dusdanig uitvoeren dat, hetzij de eindhouding comfortabel is (op grond van 'end state comfort'-concept van Rosenbaum en collega's), hetzij dat men eerst de distale bewegingsmogelijkheid volledig zal gebruiken. Pas wanneer deze niet toereikend zal zijn, wordt de proximale mogelijkheid benut (Bullinger en Solf). In een derde mogelijk model worden deze twee concepten gecombineerd.

tabel 2: Overzicht van de 10 experimenten. Voor elk van de experimenten is aangegeven welke knop en greep gebruikt is. Tevens wordt een karakteristiek element van elk experiment genoemd. In het rechter gedeelte staat de deelname van de verschillende proefpersonen weergegeven voor de 10 experimenten.

experiment	knop	greep	karakteristiek	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
1	O	centraal	standaard	■	■	■	■	■	■	■	■	■	■	■	■	■																							
2	O	lateraal	standard	■	■	■	■	■	■																														
3	O	cent./lat.	linkshandig														■	■	■	■	■	■	■																
4	O	centraal	geen vis. info							■	■	■	■	■	■	■																							
5	O	centraal	elleboog flexie							■	■	■	■	■	■	■																							
6	O	lateraal	weerstand	■	■	■	■																	■	■	■													
7	T	-	standaard																					■	■	■	■	■	■										
8	L	-	standaard	■	■	■																		■	■	■	■												
9	L	-	tijd																											■	■	■	■	■	■	■	■	■	■
10	L	-	korte knop																											■	■	■	■	■	■	■	■	■	■

In het standaard experiment (zie tabel 1 exp.nr. 1) hebben proefpersonen aan de ronde O-knop 9 verschillende rotatietaken uitgevoerd. De grootte van de geïnstrueerde hoekverdraaiing varieerde van 0° tot 120°. De rotaties moesten zowel links- als rechtsom worden uitgevoerd. Bij alle taken dienden de proefpersonen de centrale greep te gebruiken. De resultaten laten zien dat er geen sprake kan zijn van 'end-state comfort'. Een constante eindpositie is beslist niet een karakteristiek van de uitvoeringen. Tevens laten de resultaten zien dat een strikte scheiding, zoals voorgesteld door Bullinger en Solf, niet juist is. Alle drie de voorspellingsmodellen blijken dus niet op te gaan.

Uit de resultaten blijkt echter wel dat er verschillende soorten tactieken bestaan waarop de taken worden uitgevoerd. Een tactiek kan dan worden omschreven als een bepaalde constante manier waarop de verschillende rotatietaken worden uitgevoerd. We maken een onderscheid tussen A- en B-tactieken. De A-tactieken kenmerken zich door de afwezigheid van anticipatie. Ongeacht de grootte en de richting van de rotatietaak is er een bepaalde constante initiële armhouding. Het blijkt dat er, over alle taken heen, een redelijk constante verhouding is tussen het gebruik van de distale SUP en de proximale CAR. Het aandeel van SUP is twee maal zo hoog als het aandeel van CAR. Indien echter de grenzen van de bewegingsbereik van SUP worden bereikt, blijkt dat de beweging dan vooral uit CAR bestaat. Proefpersonen echter die een B-tactiek hanteerden lieten wel een vorm van anticipatie zien.

Afhankelijk van de grootte en/of richting van de taak wordt er op een bepaalde manier geanticipeerd. Het gevolg is veelal dat de bijdrage van CAR beduidend minder is dan wat we zagen bij de A-tactiek. In een enkel geval wordt CAR zelfs bijna niet aangesproken.

Kenmerkend bij alle proefpersonen is het specifieke gebruik van de combinaties SUP en CAR. Beide, dus SUP en CAR, worden over nagenoeg hun gehele bereik gebruikt. Het blijkt echter dat niet elke combinatie tussen deze twee wordt gebruikt. CAR wordt alleen dan aangewend, als de SUP waarde tegen de minimale grens aanligt, d.w.z. als de rechter onderarm zo ver mogelijk linksom is geroteerd. Een combinatie van positieve SUP met positieve CAR komt niet voor. Een mogelijke verklaring voor deze beperking van combinaties kan mogelijk worden gevonden door de invloed van de zwaartekracht (CAR rotatie behoeft een relatief grotere spieractiviteit vanwege de verplaatsing van het lichaamszwaartepunt van de arm) en/of door de passief opgelegde polsrotaties (indien de knop met behulp van CAR wordt geroteerd induceert deze beweging automatisch een deviatie van de pols vanuit de neutrale stand). Experiment nummer 5 gaat hier verder op in.

In experiment nummer 2 wordt de - ongebruikelijke - centrale greep vervangen door de laterale greep. Voor de rest is het experiment identiek aan het voorgaande. De resultaten laten zien dat de proefpersonen in deze situatie beduidend minder CAR gebruiken. Als de gebruikte tactieken worden bekeken, blijkt dat geen van de proefpersonen nog de A-tactiek hanteert. Dit leidt tot een speculatie omtrent een hiërarchie van de gevonden tactieken. De resultaten laten zien dat de proefpersonen, die in het experiment met de centrale greep de A-tactiek gebruikten, in het experiment met de laterale greep de tactiek hebben geruild voor een B-tactiek. Wellicht door de meer gebruikelijke greep waren deze proefpersonen in dit laatste experiment ook in staat op de richting en/of grootte van de taak te anticiperen. In het experiment met de centrale greep moesten zij zich door de ongebruikelijke greep in de initiële vrijheid beperken, hetgeen zich uitte in de A-tactiek.

In een volgend experiment (3) zijn linkshandige proefpersonen gemeten. De wereld om ons heen kenmerkt zich voor een belangrijk deel door zijn aanpassing aan rechtshandigen. Op grond hiervan kan verwacht worden dat linkshandige proefpersonen eenzelfde motorische output geven als rechtshandige. De anatomische bouw van de linker arm is echter gespiegeld ten opzichte van de rechter arm. Daarom kunnen we vanuit de anatomie verwachten dat de taken op dezelfde manier worden uitgevoerd, dus met een gespiegelde motorische output. Dit laatste blijkt inderdaad het geval te zijn. De linkshandige proefpersonen laten dezelfde, zij het gespiegelde, tactieken zien. Ook als de greep wordt gewijzigd van een centrale naar een laterale greep, blijkt er een zelfde verandering van tactiek te ontstaan. Geen van deze proefpersonen gebruikte bij de laterale greep nog de A-tactiek.

Vervolgens is er een klein aantal variaties op het standaard experiment met de O-knop uitgevoerd. Als eerste (exp.nr. 4) is er gekeken of er een duidelijke invloed is op de keuze van tactieken wanneer de visuele informatie wordt weggenomen. Drie van de zeven geblinddoekte proefpersonen lieten een A-tactiek zien. De overigen hadden voor een B-tactiek gekozen. We concluderen dat er geen overduidelijk effect van visuele informatie op de keuze van de tactiek is.

Vervolgens is de afstand van de proefpersoon tot de knop gevarieerd (exp.nr. 5). In alle overige experimenten was de ellegoog 45° gebogen. In experiment nummer 5 werd de positie van de knop ten opzichte van de proefpersoon dusdanig gewijzigd, waarmee de ellebooghoek werd gevarieerd. In de ene situatie was de arm 90° gebogen, en in de andere slechts 10°. Verwacht werd dat een eventuele beperking in het gebruik van combinaties SUP en CAR zou kunnen worden verklaard door hetzij passief opgelegde polsbewegingen, hetzij door de ligging van het zwaartepunt van de arm ten opzichte van de CAR-as. Het vermoeden bestond dat in de variant met de bijna gestrekte arm de bijdrage van SUP gelijk zou zijn aan die van CAR. Als de elleboog 90° gebogen zou zijn was de verwachting dat de taak bijna volledig door SUP zou worden uitgevoerd. Dit bleek beide niet het geval. De resultaten lieten zien dat proefpersonen in de 90° variant significant meer CAR gebruikten dan in de 10° variant. Een mogelijke verklaring is hiervoor niet gevonden. Wel kan worden geconcludeerd dat de ligging van de lichaamszwaartepunten ten opzichte van de rotatie-assen en de passieve polsbewegingen de beperkte keuze van combinaties van de twee vrijheidsgraden niet kan verklaren.

Al laatste variatie (exp.nr. 6) is de rotatieweerstand verhoogd tot 50% van de maximale isometrische kracht. In deze situatie hebben de proefpersonen de laterale greep gebruikt. De verwachting was dat de proefpersonen relatief meer CAR zou gebruiken. Bijna alle proefpersonen gebruikten een B-tactiek. Kenmerkend voor deze tactiek is het minimale gebruik van CAR. De rotaties werden derhalve hoofdzakelijk door SUP volbracht.

Eén proefpersoon laat hier een opvallende tactiek zien. Deze tactiek verschilt van de hiervoor beschreven A- en B-tactiek. In deze tactiek worden bewegingen gebruikt die nog niet eerder waren gezien. Bij de rotatietaken linksom plaatste deze proefpersoon de onderarm in de maximale SUP-positie, en voerde de beweging met bijna alleen CAR uit. Door op deze manier de taken uit te voeren voorkwam de proefpersoon de noodzaak tot actieve handhaving van de distale SUP-hoek. De schouderkrachten konden zo via de passieve anatomische elementen (botten en banden) worden doorgevoerd naar de knop. Bovenal kenmerkend is dat deze proefpersoon combinaties liet zien die nog niet eerder waren getoond. Hieruit concluderen wij dat de restrictie in de keuze tussen de SUP en CAR derhalve niet door een wetmatigheid is opgelegd, maar dat deze beperking een voorkeur van een proefpersoon is.

Experiment met de T-knop

Vervolgens wordt in hoofdstuk 6 verslag gedaan van de experimenten met de T- en de L-knop. Als eerste wordt de T-knop behandeld (exp. nr. 7). Omdat deze knop richtingsgevoelig is, is het aantal taken aanzienlijk verhoogd. Er worden twaalf initiële oriëntaties gebruikt (om de 30°) en negen verschillende taken (variërend van -120° tot +120°). Bij deze richtingsgevoelige knoppen is het vrijheidsgradenprobleem minder complex dan bij de O-knop. Bij de T- en de L-knop wordt de initiële oriëntatie van de pols opgelegd; deze moet immers overeenkomen met de oriëntatie van de knop. Wat resteert is de vrijheid van de samenstelling van de polsoriëntatie.

De knop kan vaak op twee manieren worden vastgepakt: met de duim naar de marker - de duimgreep - of met de pink naar de marker. In de introductie wordt duidelijk gemaakt dat de keuze tussen deze twee in veel gevallen bepaald is door de grootte en richting van de taak, de initiële oriëntatie en het bewegingsbereik van SUP en CAR. Op grond van dit idee wordt er een voorspelling gemaakt voor het gebruik van deze twee grepen over de verschillende taken.

Het blijkt echter dat er voor bepaalde taken twee keuzen over blijven. Met behulp van vier theoretische ideeën, waaronder 'end-state comfort' en 'thumb-towards bias', wordt ook hier de kans op een duimgreep bepaald, elk resulterend in een specifiek voorspellingsmodel.

De resultaten laten zien dat er een significante interactie is tussen de initiële oriëntatie en de taak op de keuze van de greep. De verdeling van de greepkeuze blijkt over de verschillende proefpersonen niet significant te variëren. Uit de resultaten blijkt dat in meer dan 50% van de gevallen een duimgreep wordt gebruikt. Deze tendentie tot het gebruik van een duimgreep is echter niet zo groot dat de modellen de greep niet goed voorspellen. Alle vier de modellen geven een significante voorspelling. Het model, dat gebaseerd is op de 'thumb-towards bias', blijkt geen betere voorspelling op te leveren dan de andere.

De initiële- en eindhouding blijkt tevens significant te worden beïnvloed door de interactie tussen taak en initiële oriëntatie van de knop. Op grond van de uitkomsten van de experimenten met de O-knop verwachten we dat ook bij het gebruik van de T-knop er eenzelfde restrictie zal zijn ten aanzien van het gebruik van combinaties SUP en CAR. Aangezien nagenoeg het gehele bereik van SUP en CAR gebruikt dient te worden, hadden we de verwachting dat de verhouding tussen het gebruik van CAR en SUP afhankelijk is van de initiële oriëntatie en grootte en richting van de taak. De ratio tussen het gebruik van SUP en CAR blijkt inderdaad afhankelijk te zijn van het midden van het traject van de polsoriëntatie tijdens het roteren van de knop (waarin de initiële oriëntatie, grootte en richting van de taak zijn verdisconteerd). Indien deze waarde sterk negatief is, d.w.z. als de rechter pols bijna volledig linksom gedraaid is, dan is de bijdrage van CAR het grootst en wordt er nagenoeg geen SUP gebruikt. Hoe groter deze waarde wordt, hoe groter de bijdrage van SUP wordt. Indien het midden van het traject van de polsoriëntatie groot is, blijkt de beweging inderdaad uit nagenoeg alleen SUP te bestaan.

Experimenten met de L-knop

De laatste drie experimenten worden uitgevoerd met de L-knop. Ook deze knop kan worden geroteerd met behulp van SUP en CAR. In de kinematische studie (exp. nr. 8) blijkt dat, zoals verwacht, er geen verschil bestaat tussen het gebruik van de T- en de L-knop, noch voor de keuze van de greep, noch voor het gebruik van SUP en CAR.

In experiment 9 is de reactie- en bewegingstijd gemeten. De verwachting was dat op die initiële posities waar een keuze mogelijk is tussen de duim- en de pinkgreep een langere reactietijd zal worden gevonden. De reactietijd toont echter geen significant verschil. Indien de bewegingstijd wordt bestudeerd, dan tonen de resultaten dat bij de omslagpunten, dat is waar een keuze tussen de twee grepen mogelijk is, een significant langere bewegingstijd gemeten is. Hieruit concluderen we dat de beslissing genomen is tijdens de reikfase naar de knop.

Als laatste experiment is er een fysiek aspect van de L-knop veranderd. De lengte van de knop wordt gehalveerd tot 5 cm. Dit blijkt, naar verwachting, een significant effect te hebben op de grootte van het gebied waarin de pinkgreep wordt gekozen. De verklaring hiervoor is dat bij een pinkgreep de duim in de richting van de rotatie as ligt. Omdat de gebruikte knop niet in de gehele hand kon worden genomen, lag het voor de hand dat deze greep, waar mogelijk, meer zou worden gebruikt, immers in deze greep kan men de knop beter omvatten.

Conclusies

In het kort kunnen de volgende conclusies worden vermeld:

Richtings-indifferente knop (O):

- De bedieningsbewegingen kunnen niet worden verklaard door de theorie die voorspelt dat rotatiebewegingen dusdanig worden uitgevoerd dat de eindpositie comfortabel is. Ook geldt niet dat eerst de distale bewegingen worden gebruikt, en slechts indien dit niet meer mogelijk is pas de meer proximale bewegingen.
- Er zijn op zijn minst drie verschillende tactieken waarop de rotatietaken kunnen worden uitgevoerd. Vermoed wordt dat deze in een hiërarchische ordening ten opzichte van elkaar staan.
- Niet alle mogelijke combinaties tussen de distale SUP en de proximale CAR worden gebruikt. Er is alleen een duidelijke bijdrage van CAR als de SUP de grenzen van zijn bereik benadert. Deze beperking kan niet worden verklaard door het effect van de zwaartekracht op de arm of door de passief opgelegde polsbewegingen.
- Er is een voorkeur voor distale SUP boven het gebruik van de proximale CAR. CAR wordt daarentegen bijna altijd tevens aangewend.
- De neutrale polsoriëntatie is -40°.

Richtings-gevoelige knoppen (T en L):

- De keuze tussen een duim-greep en een pink-greep wordt in de meeste gevallen opgelegd door het bewegingsbereik van SUP en CAR.
- Indien beide grepen mogelijk zijn levert het lineaire benaderingsmodel eenzelfde voorspelling als de modellen die gebaseerd zijn op theoretische concepten.
- Proefpersonen neigen meer duimgrepen dan pinkgrepen te gebruiken.
- De verhouding tussen het gebruik van SUP en CAR is afhankelijk van het midden van de polsoriëntatie tijdens de rotatietaak.
- Het verschil tussen de T- en de L-knop leidt niet tot een andere bediening.
- De bewegingstijd neemt toe als er een keuze mogelijk is tussen de duim-greep en de pink-greep.
- Door de lengte van de L-knop te halveren is de keuze tussen de twee grepen te beïnvloeden.

Praktische toepasbaarheid

Of de uitkomsten van de experimenten praktisch toepasbaar zijn, hangt onder andere af van de generaliseerbaarheid van de resultaten. In de experimenten is er bewust gekozen voor een strikt experimentele opzet in een laboratorium. Indien er werd gekozen voor een grof niveau (bijvoorbeeld reiken - grijpen - draaien) dan zou dat tot algemeen invariant gedrag leiden. Een veel fijnschaliger niveau zou daarentegen leiden tot veel variabeler gedrag. De bewegingen werden echter gekwantificeerd op een tussenliggend niveau: gewrichtsrotatiehoeken. Dit niveau kenmerkt zich door variant en invariant gedrag, wat een aantrekkelijk niveau is om te bestuderen. Bovendien levert dit gegevens op die van toepassing kunnen zijn binnen het ontwerpproces. De optimale oriëntatie van een knop kan immers direct toegepast worden. Ook de gemaakte bewegingen geven aan welke ruimte noodzakelijk is om een rotatie-knop vrij te kunnen bedienen.

Er zijn in onze experimenten echter wat restricties ingevoerd. Zo mochten de proefpersonen de knoppen alleen met behulp van SUP en CAR roteren. Romp-, hand- en vingerbewegingen werden niet toegestaan. De verwachting is dat, indien de rompbewegingen worden toegestaan, dit niet leidt tot een drastische verandering van het bedieningsgedrag. Daarentegen zal het toestaan van gebruik van hand- en vingerbewegingsmogelijkheden wel invloed hebben op het bedieningsgedrag.

Ook de positie van de knop ten opzichte van de proefpersoon was bepaald. Dit heeft invloed op het gedrag. Indien deze positie wordt gewijzigd, zal dat ondermeer invloed hebben op het totale bereik van CAR, en derhalve op de manier van bedienen. Een andere invloed op het bewegingsbereik van de gewrichten is de gezondheidstoestand. In de experimenten is bewust voor gezonde proefpersonen gekozen. Verwacht wordt dat bijvoorbeeld reumapatiënten een totaal andere bedieningstactiek zullen laten zien.

Deze studie laat zien dat een kinematisch-kinesiologische analyse inzicht geeft in de manier waarop draaiknoppen worden bediend. Vooralsnog zal elk nieuw produkt een eigen analyse vergen. Wellicht zal in de toekomst het inzicht in de menselijke beweging dermate toenemen dat het bedieningsgedrag voorspelbaar wordt. Men moet echter niet vergeten dat in veel situaties een vrijheid in het spel is, zodat men zich niet hoeft te onderwerpen aan wetmatigheden. In veel produktbedieningen is de mate van vrijheid zo groot dat een studie hiervan uitermate complex wordt.

A.J.M. van der Vaart

Curriculum vitae

Guus van der Vaart was born in Schiedam on December 21, 1961. He attended the Titus Brandsma-college (Dordrecht) from 1974 to 1980 to obtain the VWO-B certificate. In 1980 he started to study Human Movement Sciences at the Free University of Amsterdam. After obtaining his teaching certificate he graduated in 1988 in Functional Anatomy. In 1986 he taught anatomy, biomechanics, and anatomy in vivo at the 'Leidse Hogeschool voor Beroepsonderwijs'. In 1988 he started to teach anatomy and anatomy in vivo at the 'Opleiding Oefentherapie Mensendieck' in Amsterdam. May 1989 marked the start of his PhD project at the Faculty of Industrial Design Engineering of the Delft University of Technology; this thesis is the result.