Comfort in Using Hand Tools
Theory, Design and Evaluation

Proefschrift

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus Prof. dr. ir. J.T. Fokkema,
voorzitter van het College van Promoties,
in het openbaar te verdedigen op 19 januari 2007 om 12.30 uur

door Lottie Francisca Maria KUIJT-EVERS
doctorandus in de bewegingswetenschappen

geboren te Weert

Dit proefschrift is goedgekeurd door de promotoren:
Prof. dr. P. Vink
Prof. dr. M.P. de Looze

Samenstelling promotie commissie:

Rector Magnificus, voorzitter
Prof. dr. P. Vink, Technische Universiteit Delft, promotor
Prof. dr. M.P. de Looze, Vrije Universiteit Amsterdam, promotor
Prof. dr. C.J.P.M. de Bont, Technische Universiteit Delft
Prof. dr. J. van Dieën, Vrije Universiteit Amsterdam
Prof. ir. D.J. van Eijk, Technische Universiteit Delft
Prof. dr. C.J. Overbeeke, Technische Universiteit Eindhoven
Dr. L. Sperling, Lund University, Sweden

TNO Kwaliteit van Leven
Arbeid

Cover drawings by Tom Kuijt
Printing PlantijnCasparie, Amsterdam

ISBN-10: 90-5986-218-X
ISBN-13: 978-90-5986-218-X

Contents

Introduction

Chapter 1

1 Introduction

Hand tools like scissors, forks and knives are used daily by almost all European citizens. A large proportion of these European citizens also use hand tools (like hammers, pliers, chisels, and trowels) during their work, as non-powered hand tools constitute an important element of work and production systems (European Agency for Safety and Health at Work, 2000). Some jobs cannot be done without hand tools, like the work of carpenters, surgeons, cooks and maintenance workers. Consequently many tools are sold yearly. For instance Bahco Tools, an important manufacturer of non-powered hand tools, has a turnover of 300 MEur per year, selling in 1998 its 100.000.000th wrench.
(http://www.selligent.com/open.asp?file=1118).

Despite the frequent use of hand tools by many people over many, many years, the design of hand tools did hardly change during the last century (Haapalainen et al., 1999/2000). For instance, the trowel still looks the same as years ago (Figure 1.1). New materials (like plastics) have become available for hand tool manufacturing and provide the possibility to change the design, but these materials are hardly applied.

Figure 1.1 Collection of old trowels in a hand tool museum (Maison de l'Outil et de la Pensée Ouvriere, Troyes, France).

For several reasons, it is important to reconsider the traditional design of hand tools, that is to avoid feelings of discomfort during the job, to reduce musculoskeletal disorders on a longer term, to increase the workers' productivity and to provide comfort to the workers. Although, the relationship between hand tool design and musculoskeletal disorders was only directly obtained from the study of Tichauer (1978, in Chaffin et al., 1999), other studies have indicated poor hand tool design as a risk factor of musculoskeletal disorders (Mital and Kilbom, 1992; Chaffin et al., 1999).

Moreover, other studies show that less discomfort was experienced by using appropriately designed hand tools (e.g., Kilbom et al., 1993; Chang et al., 1999; Dempsey et al., 2002). This is important as discomfort can lead to musculoskeletal problems on a longer term (Proper et al., 1999). In a longitudinal study, in which 1789 white collar workers were followed for 4 years, a high score on postural muscular discomfort was associated wih a significantly higher percentage of sick leave due to MSD (Proper et al., 1999). Therefore, it is important to prevent workers from discomfort by appropriate hand tool design.

There are even more reasons to prevent workers from feelings of discomfort when using hand tools. Discomfort in hand tool use seems to be inversely related to productivity (Kilbom et al., 1993; Kong and Freivalds, 2003; Chang et al., 1999; Dempsey et al., 2002; Wu and Hsieh, 2002). For instance, higher ratings of discomfort were accompanied by lower productivity in using pliers (Dempsey et al., 2002), plate-shears (Kilbom et al., 1993) and meat-hooks (Kong and Freivalds, 2003). Discomfort may also reduce job satisfaction (Fellow and Freivalds, 1991). For those reasons, the avoidance of discomfort has been a crucial issue in hand tool design for many years (e.g., Dempsey et al., 2004; Kong and Freivalds, 2003; Das et al., 2005; You et al., 2005).

In recent years, approaches have changed and new notions of increased comfort and reduced biomechanical loads with regard to users' functional capacities have been introduced into tool design (Aptel et al., 2002). In the past, the tool was designed to respond to the needs of the greatest possible number of users, and had to be as cheap as possible (Aptel et al., 2002). Nowadays, new product manufacturing techniques are developed, which make it possible to customize products (Gerrits et al., 2004). In the near future it may be quite normal to order a fully custom-made hand grip for a hand tool. Hence, even customization is no science-fiction anymore and can be implemented to hand tool design in the near future. Because of these developments on customization, it is possible to more easily adapt the design to personal preferences. In the near future, this will give the opportunity to provide higher individual comfort levels in tool design. Therefore, comfort may become an even more important issue in hand tool design with respect to these developments. Manufacturers and hand tool distributors already recognise comfort as a major selling point (Singer, 1999), which is illustrated by Figures 1.2 and 1.3.

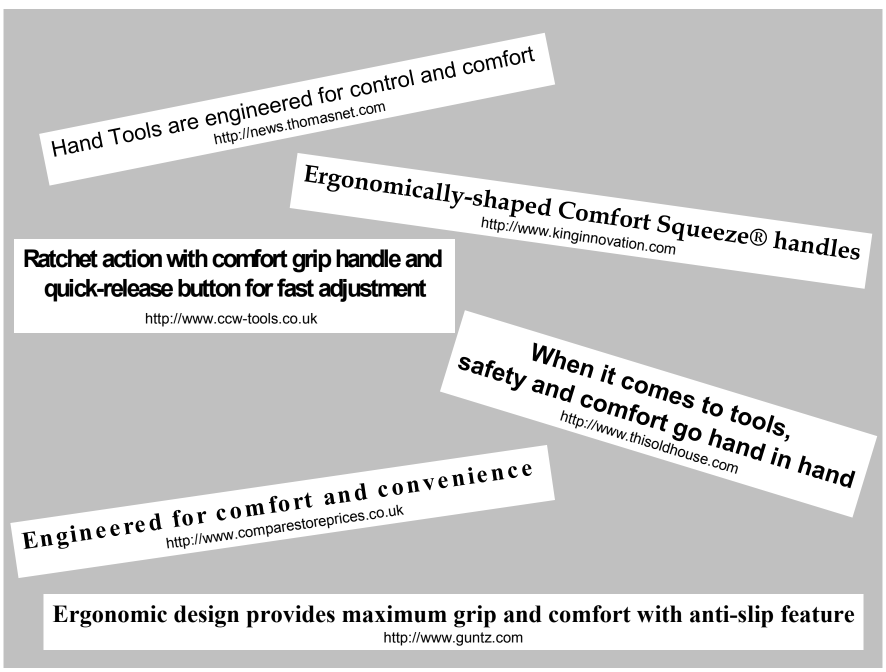


Figure 1.2 Advertisement slogans of comfort in hand tools from the internet

Figure 1.3 Advertisement of comfort in a commercial paper.

The frequent use of the concept comfort in (scientific) literature would suggest that it is a consensually held construct. However, there is no widely accepted definition of comfort (Lueder, 1983; Helander and Zhang, 1997). Although, there are issues that are commonly accepted: 1) comfort is a construct of a subjectively defined personal nature, 2) comfort is affected by factors of a various nature (physical, physiological, psychological), and 3) comfort is a reaction to the environment (Looze, et al., 2003).

The differences between comfort and discomfort are an on-going debate in literature. Much research has been conducted on sitting comfort and three major theories have been proposed: Comfort and discomfort have been considered as two discrete states (Hertzberg, 1958; Branton, 1969), as two opposites on a continuous scale (e.g., Vergare and Page, 2000; Jianghong and Long, 1994; Wilder et al., 1994; Jensen and Bendix, 1992), and as two separate entities underlied by different factors (Zhang et al., 1996).

The comfort/discomfort theories described above are mostly based on studies on comfort and discomfort in sitting and knowledge about comfort and discomfort in using hand tools is lacking. However, it is important to know the difference between comfort and discomfort in using hand tools, for instance, to choose the appropriate evaluation method in hand tool evaluation studies. Additionally, the end-users' opinion about the aspects which determine comfort in using hand tools is important, as these are the user requirements for hand tools that provide comfort during their use. Moreover, these requirements have to be translated into product characteristics and product design, in order to provide comfort in using hand tools.

1.1 Relevance to the design industry

Three market segments can be distinguished in hand tool design, namely a low-price, mid-price, and high-price categroy. Hand tools belonging to the low-price category are made by mass production for low prices. The aim of manufacturers of these kinds of hand tools is to produce their products as cheap as possible. Hand tools from this low-price category are mostly used by people who seldom use hand tools in and around their homes. For two reasons it is not necessary to focus on comfort during the design process of hand tools from this category. Firstly, the people who use hand tools from this category seldom use hand tools and if they use hand tools it is for a short period of time. Hence, they will not be interested in a hand tool which provides comfort. The price of the hand tool is more important to them, which takes us to the second reason. By addressing comfort in the design process, the design process of the low-price category hand tools will become more expensive and the prices of the low-price category hand tools will increase. People using hand tools from the low-price category do not want to spend much money for hand tools.

The other categories are the mid-price category and the high-price category. Hand tools from both categories are used by professional end-users and experienced Do-It-Yourself users. The focus on comfort during the design process is especially important for those categories, because these hand tools are used by people who use hand tools very frequently and for longer periods of time. Therefore, they are willing to buy more expensive hand tools as they are more satisfactory to them and increase their work efficiency.

Last decades the focus in mid-price and high-price hand tool design has always been on the work-side of the hand tool as the hand tool is used for performing a specific task (cutting wood for instance). The hand-side of the tool (the hand-handgrip interface) was considered as less important. This may be partly due to the background of the designers of hand tools, which are most of the times technical engineers. In the recent years, more attention has been paid to the avoidance of discomfort in hand tool design. Different hand grips (e.g., two-component grips and soft grips) were applied in which new materials were used. Nowadays, it is time to shift attention to providing comfort.

These steps from functionality to physical discomfort and comfort are also seen in the development of office chairs. The design of the first office chairs were focussed on functionality: provide a place to sit and to work. However, they caused physical discomfort to people of different body sizes, because the chairs were not adjustable. In order to reduce these feelings of discomfort, new fully adjustable office chairs were designed. Some years ago, the focus has been shifted towards aesthetics and comfort in office chairs. Lots of studies are conducted on this topic (e.g., Bishu et al., 1988; Demontis and Giacoletto, 2002; Helander et al., 1987, Helander and Zhang, 1997; Lee et al., 1993, Motavalli and Ahmed, 1993; Inagaki et al., 2000). Manufacturers of office chairs strive for comfortable products in order to stay ahead of competition (Vink, 2005). For instance, Helander and Zhang (2001) stated that nowadays comfort and aesthetics in office chair design are even more important than all ergonomic features, unless there are no obvious violations of biomechanics design rules. Their opinions are based on a study which indicates that the human body is not very sensitive to variations in chair design (Helander et al., 2000). Chair users could only discriminate between office chairs based on aesthetics. Therefore, Helander and Zhang (2001) argue that aesthetics and comfort, which is related to a sense of well-being, relaxation, relief and happiness, are more important in chair design than physical ergonomics.

It is my vision that the same development is desirable for hand tools in the mid and high price sector. Hand tools should not only avoid discomfort, but also provide comfort to the end-user. In the future, it will be necessary for hand tool manufacturers to address comfort hand tool design in order to stay ahead of competition. This can be established by a design process in which the work-side and the hand-side will be addressed simultanously during the whole design process, with special attention for comfort, which will result in an integrated hand tool design.

1.2 Objective of this thesis

The main objective of this thesis is to provide knowledge to designers and researchers on comfort and discomfort in hand tool design and evaluation. This knowledge should contribute to an improvement in hand tools, which leads to more comfort and less discomfort for hand tool users during their job. To achieve this objective, some sub-goals are described:

- To contribute to the theory of comfort and discomfort in using hand tools;
- To propose how comfort can be integrated in the design process;
- To investigate how hand tools can be evaluated regarding comfort and discomfort.

In order to provide comfort in using hand tools, it is necessary to know how hand tool design affects the comfort experience (user's perception of comfort) of end-users. It is not easy to get insight in this relationship. A study of Oudendijk et al. (2001) can illustrate this. They investigated the strategy, which people use to select the best scissors from a set. End-users were asked to evaluate 4 and 8 scissors, respectively. The four scissors systematically differed in sharpness, and shape of the tip, and the eight scissors differed in sharpness, shape of the tip, and required force. The task of the end-users consisted of cutting out a capital D. After that, they were asked to rank the four or eight scissors from unpleasurable to work with to pleasurable to work with. Then, they had to argue why they chose this ranking.

It was remarkable that a large majority of the subjects did not mention the differences in sharpness or the differences in required force when ranking the four scissors. They explained their choices using statements of performance of the scissors, like 'this pair of scissors doesn't cut', or 'this pair of scissors can easily cut a curvy line'. When the subjects had to rank eight pairs of scissors, more subjects started to look at differences in the product properties, like sharpness, shape of the tip and required force to make their decision. However, half of the sample still used the experienced performance only to rank the scissors and did not notice or use the differences in product properties to discriminate between the scissors. This example illustrates that most end-users do not think in terms of product properties, even when they have to make a complex decision of ranking 8 pairs of scissors. These findings are in line with Dempsey et al. (2004). The preference for one of the evaluated screwdrivers in their study, was explained by the end-users in their own words. The responses were all formulated in terms of performance (e.g., does not slip as much, easier to manipulate) and not in terms op product properties.

The former examples showed, that it will not be useful to ask people directly to what extent product properties contribute to their comfort experience, as they do not 'use' the product properties to percept or describe their comfort feelings. Their answers will not be reliable. Therefore, a 'step' between product properties and comfort experience is needed to get information about the underlying reasons of people to rank hand tools on comfort experience. This step should consist of descriptions of underlying comfort experiences as people used in the study of Oudendijk et al. (2001) to rank the scissors. Therefore, it is necessary to identify the descriptions that are related to comfort in using hand tools. These descriptions will be referred to as comfort descriptors. Hence, comfort descriptors are descriptions (in the end-users' own words) of benefits to be fulfilled by a hand tool, that provides comfort to the end-user.

The relationship between product properties and the comfort experience (with the comfort descriptors in between) is illustrated in a conceptual model in which the chapters of this thesis are positioned (Figure 1.4).

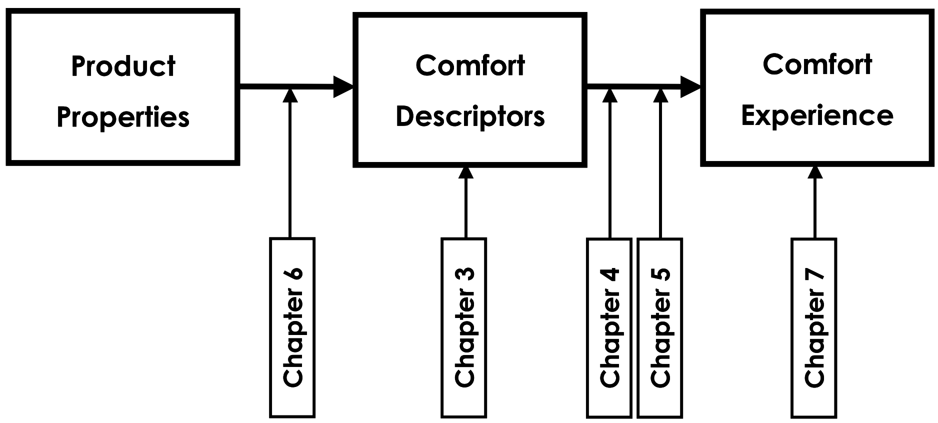


Figure 1.4 Conceptual model of the relationship between product properties of hand tools and the comfort experience of the end-users.

1.3 Outline of this thesis

Chapter 2 (which is not shown in the model of Figure 1.2) concerns the state of science on comfort theory, hand tool evaluation studies and hand tool design and will lead to a specification of the sub-goals as mentioned in section 1.1. Then, the comfort descriptors will be identified in Chapter 3. In Chapter 4 the most important comfort descriptors in using hand tools will be defined based on empirical data of a screwdriver evaluation study. This chapter focuses on the relationship between these comfort descriptors and the comfort experience for screwdrivers. Chapter 5 investigates the differences and similarities between different kinds of hand tools regarding the relationship between comfort descriptors and comfort experience. The relationship between comfort descriptors and comfort experience is determined for screwdrivers, paintbrushes and hand saws. Chapter 6 studies the application of the Quality Function Deployment (QFD) to ensure attention for comfort in the design process. The QFD method is a design tool which can help to translate customer needs (comfort descriptors) into engineering characteristics (product properties). Chapter 7 focuses on the evaluation and measurement of comfort and discomfort in using hand tools. The association between subjective comfort and discomfort measures and objective measures, like contact pressure and muscle activity is investigated.

1.3 References

Aptel, M., Claudon, L., Marsot, J., 2002. Integration of ergonomics into hand tool design: principle and presentation of an example. International Journal of Occupational Safety and Ergonomics, 8 (1): 107-115.

Branton, P. 1969, Behavior, body mechanics and discomfort. Ergonomics, 12 (2): 316-327.

Bishu, R.R., Cochran, D.J., Riley, M.W., 1988. Evaluation of office seats – a validation study. In: Trends in Ergonomics/Human factors, Aghazadeh, V.F. (ed). Elsevier Science Publishers B.V. North-Holland. 417-424.

Chaffin, D.B., Andersson, G.B., Martin, J.M., 1999. 3th edition. Occupational biomechanics. Wiley, New York.

Chang, S.R., Park, S., Freivalds, A., 1999. Ergonomic evaluation of the effects of handle types on garden tools. International Journal of Industrial Ergonomics, 24 (1): 99-105.

Das, B., Jongkol, P., Ngui, S., 2005. Snap-on-handles for a non-powered hacksaw : An ergonomics evaluation, redesign and testing. *Ergonomics,* 48 (1): 78-97.

Demontis, S., Giacoletto, M., 2002. Prediction of car seat comfort from human-seat interface pressure distribution. SAE-paper 2002-01-0781: 105-111.

Dempsey, P.G., McGorry, R.W., Leamon, T.B., O'Brien, N.V., 2002. Bending the tool and the effect on human performance: Further investigation of a simulated wire-twisting task. AIHA Journal, 63 (7): 586-593.

Dempsey, P.G., McGorry, R.W., O'Brien, N.V. 2004. The effects of work height, workpiece orientation, gender, and screwdrivers type on productivity and wrist deviation. International Journal of Industrial Ergonomics, 33 (4): 339-346.

European Agency for Safety and Health at Work, 2000. OSH in marketing at company level - marketing of ergonomic hand tools- fiskars. In: Occupational safety and health in marketing and procurement. Available from: http://europe.osha.eu.int.

Fellows, G.L., Freivalds, A., 1991. Ergonomics evaluation of a foam rubber grip for tool handles. Applied Ergonomics, 22 (4): 225-230.

Gauthy, R., 2005. Musculoskeletal disorders: where we are, and where we could be. Hesa Newsletter, 27: 22-27.

Gerrits A., Jones C.L., Valero R., 2004. Custom-Fit: A knowledge-based manufacuring system enabling the creation of custom-fit products to improve the quality of life. Rapid Product Development 2004. Paper 4004, 12th October 2004, Centimfe, Portugal.

Haapalainen, M., Kivistö-Rahnasto, J., Mattila, M., 1999/2000. Ergonomic design of non-powered hand tools : An application of quality function deployment (QFD). Occupational Ergonomics, 2 (3): 179-189.

Helander, M.G., Czaja, S.J., Drury, C.G., Cary, J.M., Burri, G., 1987. An ergonomic evaluation of office chairs. Office: Technology and People, 3: 247-262.

Helander, M.G., Zhang, L., 1997. Field studies of comfort and discomfort in sitting. Ergonomics, 40 (9): 895-915.

Helander, M.G., Little, S.E., Drury, C.G., 2000. Sensitivity and adaptivity to postural change in sitting. Human Factors, 42 (4): 617-629.

Helander, M.G., Zhang, L., 2001. Forget about ergonomics in chair design? Focus on esthetics and comfort! In: Proceedings of the International Conference on Affective Human Factors Design. Helander, M.G., Khalid, H.M., Tham, M.P. (Eds). Asean Academic Press, London. 256-261.

Hertzberg, H.T.E., 1958. Seat comfort. In: Annotated Bibliography of Applied Physical Anthropology in Human Engineering, Hansen, R., Cnrnog, D.R. and Hertzberg, H.T.E. (eds). WADC Technical report 56-30. Wright-Patterson Airforce Based, Dayton. 297-300.

Inagaki, H., Taguchi, T., Yasuda, E., Lizuka, Y., 2000. Evaluation of riding comfort: From the viewpoint of interaction of human body and seat for static, dynamic, long time driving. SAE-paper 2000-01-0643: 197-201.

Jensen, C.V. and Bendix, T. 1992. Spontaneous movements with various seated-workplace adjustments. Clinical Biomechanics, 7 (2): 87-90.

Jianghong, Z., Long, T., 1994. An evaluation of comfort of a bus seat. Applied Ergonomics, 25 (6): 386-392.

Kilbom, Å., Mäkäräinen, M., Sperling, L., Kadefors, R., Liedberg, L. 1993. Tool design, user characteristics and performance: a case study on plate-shears. Applied Ergonomics, 24 (3): 221-230.

Kong, Y-K, Freivalds, A., 2003. Evaluation of meat-hook handle shapes. International Journal of Industrial Ergonomics, 32 (1): 13-23.

Lee, J. Ferraiuolo, P., Temming, J., 1993. Measuring seat comfort. SAE-paper 930105. 1-5.

Li, K.W., 2003. Ergonomic evaluation of a fixture used for power driven wire-tyring hand tools. International Journal of Industrial Ergonomics, 32: 71-79.

Looze, M.P. de, Kuijt-Evers, L.F.M., Dieën, J. van, 2003. Sitting comfort and discomfort and the relationships with objective measures. Ergonomics, 46 (10): 985-997.

Lueder, R.K., 1983. Seat comfort: a review of the construct in the office environment. Human Factors, 25: 701-711.

Mital, A., Kilbom, Å., 1992. Design, selection and use of hand tools to elleviate trauma of the upper extremities: Part II – The scientific basis (knowledge base) for the guide. International Journal of Industrial Ergonomics, 10 (1-2): 7-21.

Motavalli, S., Ahmad, F., 1993. Measurement of seating comfort. Computers and Industrial Engineering, 25 (1-4): 419-422.

Oudendijk, M.L.W., Lotens, W.A., 2002. Productevaluatie en keuzestrategie bij toenemende complexiteit. TNO rapport TM-02-D012. TNO Human Factors, Soesterberg.

Proper, K.I., Bongers, P.M., Grinten, M.P. van der, 1999. Longitudinaal onderzoek naar rug-, nek- en schouderklachten. Deelrapport 5. Lokaal ervaren ongemak. De relatie met en de voorspelling van klachten aan het bewegingsapparaat. TNO Arbeid, Hoofddorp.

Singer, S., 1999. A better grip on ergonomic design. Machine design, 71 (15): 50-52.

Vergara, M., Page, A., 2000. System to measure the use of the back rest in sitting-posture office tasks. Applied Ergonomics, 31 (3): 247-254.

Vink, P., Overbeeke, C.J., Desmet, P.M.A. 2005, Comfort experience. In: Comfort and design; principles and good practice, Vink, P. (ed.) CRC Press, Boca Raton. 1-12.

Wilder, D., Magnusson, M.L., Pope, M., 1994. The effect of posture and seat suspension design on discomfort and back muscle fatigue during simulated truck driving. Applied Ergonomics, 25 (2): 66-76.

Wu, S-P, Hsieh, C-S., 2002. Ergonomics study on the handle length and lift angle for the culinary spatula. Applied Ergonomics, 33 (5): 493-501.

You, H., Kumar, A., Young, R., Veluswamy, P., Mahlzahn, D.E., 2005. An ergonomic evaluation of manual cleco plier designs: Effects of rubber grip, spring recoil, and worksurface angle. Applied Ergonomics, 36 (5): 575-583.

Zhang, L., Helander, M.G., Drury, C.G., 1996. Identifying factors of comfort and discomfort in sitting. Human factors, 38 (3): 377-389.

State of science

Chapter 2

2 State of Science

This chapter describes the state of science on the three main topics of this thesis: comfort theory, hand tool design, and hand tool evaluation. For each topic, the gaps and points of interest in the scientific literature are indicated resulting in the research questions of the current thesis. At the end of this chapter, the sub-goals of this thesis as described in the introduction and the additional research questions are summarized.

The studies used to write this chapter were retrieved through a search in Ergonomic Abstracts using the following words: 'hand tools and musculoskeletal disorders', 'hand tools and injury', 'hand tools and disorders', 'hand tools and design' (1990-2006), 'hand tools and EMG', 'hand tools and pressure', 'comfort and pressure', 'comfort and EMG' (1990-2004). A selection was made for non-powered hand tools. Additional studies were retrieved through the snow-ball method.

2.1 Comfort theory

2.1.1 Comfort in scientific literature

End-user comfort is well-addressed in the scientific literature. The MEDLINE database lists 261 papers with the term comfort in its title between April 1993 and April 2003 (Vink, 2005a). Most of these papers (140) are about climate comfort or thermal comfort. Other main topics concerning comfort are comfort in treatment of patients, and physical comfort. The 'Ergonomic Abstract' database contains 325 papers with the term comfort in its title from 1996-2006. Most papers (73) concern comfort applied to automotive and transport, like car seat comfort, passengers comfort in public transport and operators comfort in earth moving machinery. The second and third largest categories contain papers of thermal comfort (63), and seat or bed comfort (45, car seats excluded). The other topics concern wearables (e.g., helmets, shoes, gloves, backpacks), work station (layout, input devices) and (work) environment (visual, acoustic; climate excluded). This overview shows the wide range of topics that are covered by comfort research. This section will mainly focus on comfort in using products (like seats and wearables) as this is mostly connected with hand tools. Visual, acoustic and thermal comfort will not be addressed.

2.1.2 Definitions of comfort

Because of the wide range of topics that are associated with comfort, there is no common definition of the term. Comfort has been defined as a state or feeling of having relief, encouragement and enjoyment by Webster's Dictionary. Slater (1985) defines comfort as a pleasant state of physiological, psychological and physical harmony between a human being and its environment, and Richards (1980) stresses that comfort is a state of a person involving a sense of subjective well-being in reaction to an environment or situation. Vink et al. (2005b) focus their definition on comfort in product design. They define comfort as a convenience experience by the end-user during or just after working with the product. Dumur et al. (2004) show various definitions of comfort. They say that comfort is 1) a pleasant and satisfying feeling of being physically or mentally free from pain and suffering, 2) a feeling of freedom from worry or disappointment, 3) freedom from financial difficulty promoting a comfortable state, 4) a state of quiet enjoyment, freedom from pain, want or anxiety, and 5) material well-being, conveniences that make life easier and more pleasant. It is remarkable that these definitions take both a negative approach (like absence of pain) and a positive one (such as quiet enjoyment) (Dumur et al., 2004). These various definitions show that comfort is not clearly defined and many opinions exist. However, some issues are not under debate: 1) comfort is a construct of a subjectively defined personal nature, 2) comfort is affected by factors of a various nature (physical, physiological, psychological), and 3) comfort is a reaction to the environment (Looze et al., 2003).

2.1.3 Comfort versus Discomfort

The differences between comfort and discomfort are still debated in the scientific literature. In general, there are three common opinions: comfort and discomfort have been considered 1) as two discrete states (Hertzberg, 1958; Branton, 1969), 2) as two opposites on a continuous scale (e.g., Vergare and Page, 2000; Jianghong and Long, 1994; Wilder et al., 1994; Jensen and Bendix, 1992), and 3) as two separate entities underlied by different factors (Zhang et al., 1996).

If comfort and discomfort are considered as two discrete states (comfort presence and comfort absence), then comfort is defined as the absence of discomfort and vice versa (Hertzberg, 1958; Floyd and Roberts, 1958). In that case, the ultimate goal of designers is to reach the state of absence of discomfort. This implies that comfort does not necessarily entail a positive effect (Branton, 1969).

The second approach considers comfort and discomfort as two opposites on a continuous scale, ranging from extreme discomfort through a neutral state to extreme comfort (e.g., Demontis and Giacoletto, 2002; Kolich and Taboun, 2002). This stems from the fact, that people frequently and naturally distinguish ordered levels of their subjective responses across the entire continuum from strongly positive to strongly negative (Richards, 1980). Graded scales, which are also used to evaluate comfort in sitting (Chester et al., 2002; Kolich and Taboun, 2002) are based on the same principle.

The last assumption is that comfort and discomfort are both single dimensions on their own continuous scale. This assumption is based on studies that indicate that comfort and discomfort are affected by different variables in both seats and gloves (Kleeman, 1981; Kamijo et al., 1982; Zhang et al., 1996; Cherry et al., 2000). In that case, comfort and discomfort are measured separately (e.g., Bishu et al., 1988; Helander et al., 1987). For instance, Helander et al., (1987) used both the Shackel's scale for General Comfort Rating and the Body Part Discomfort scale developed by Corlett and Bishop (1976) to evaluate office chairs.

Zhang et al. (1996) identified the variables which underlie comfort and discomfort in sitting. They concluded that comfort and discomfort are based on independent factors. Feelings of discomfort are mainly associated with pain, tiredness and soreness. These feelings are mediated by physical factors, like body posture, tissue pressure and circulation blockage. On the other hand, comfort is associated with feelings of well-being and relaxation. A later study of Helander and Zhang (1997), confirmed these findings. Moreover, they found that aesthetics was associated with comfort but not with discomfort and low values of discomfort were associated with a full range of comfort values, while only low values of comfort occur when discomfort ratings are high. This implies that discomfort has a dominant effect (Helander and Zhang, 1997). When feelings of discomfort are present, comfort factors (like aesthetics) are of minor influence in the comfort/discomfort perception. Additionally, when discomfort is lacking this will not automatically lead to (high) comfort perception.

Cherry et al. (2000) also investigated whether comfort and discomfort are part of the same continuum or separate continua. They examined the factors that mediate comfort and discomfort for gloves. It was concluded that comfort and discomfort are likely part of the same overall construct and that there is overlap between the two. However, they also found that not all components were associated with both comfort and discomfort (Cherry et al., 2000).

The studies of Zhang et al. (1996) and Cherry et al. (2000) contribute to the comfort/discomfort discussion. The difference between their conclusions suggests that it is possible that the treatment of comfort/discomfort (on a continuous scale or as two separate entities) may depend on the type of product. Therefore, it is interesting to find out what kinds of aspects underlie comfort and discomfort in using hand tools. Moreover the question is whether in hand tools either these aspects are different for comfort and discomfort and thus comfort and discomfort are different entities, or the same aspects underlie comfort and discomfort and thus comfort/discomfort can be treated as one entity on one and the same continuum. Additionally, it may be possible that the aspects which determine comfort are also different across different kinds of hand tools.

2.1.4 Factors affecting comfort experience of a product

Comfort is a complex concept, consisting of a mix of feelings, perception, mood and situation (Dumur et al., 2004). Moreover, it is a subjective, personal experience, affected by various factors and a reaction to the environment (Looze et al., 2003). This makes it even more complicated. As comfort is a personal experience and a reaction to the environment, a product can never be comfortable in itself. It becomes comfortable (or not) in its use (Vink et al., 2005b). Hence, comfort may be affected by the interaction between the user, the hand tool and the task in an environment. Moreover, user characteristics, product properties and task characteristics may play a role. Figure 2.1 illustrates these interactions.

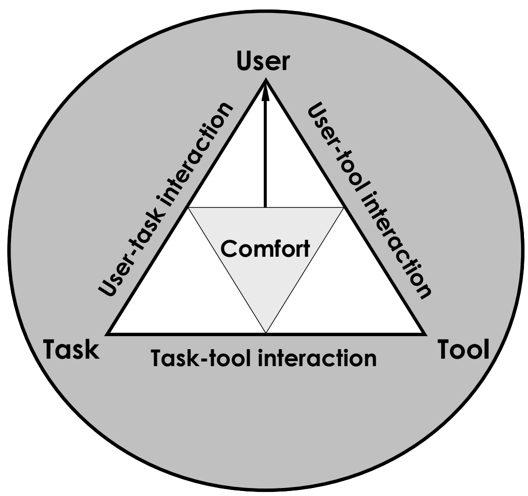


Figure 2.1 Illustration of the interactions between user-hand tool-task illustrated by the triangle within the environment (illustrated by the large circle).

User

The user is placed at the top of the triangle. He is the one who experiences comfort. His perception will be influenced by the task he performs, the tool he uses and the environment in which he works. However, there are more aspects which affect his experience. One of those aspects is the user’s history (Vink et al., 2005b). The level of comfort he is used to, determines his comfort experience of new hand tools (Vink et al., 2005b). For instance, a man from the Stone Age period, who always uses a stone that fits in his hand to break up firewood (Figure 2.2a), would experience a bronze axe with wooden handle (Figure 2.2b) more comfortable than people, who live nowadays and are used to an axe made of a steel blade at the end of a shaped wooden handle (Figure 2.2c).

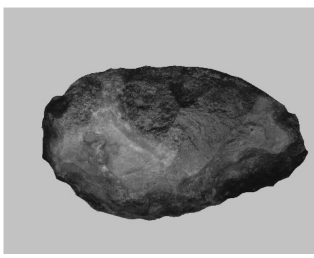


Figure 2.2a Paleolithic stone hand axe

Figure 2.2b replica of bronze axe (Ancient Arts)

Figure 2.2c Axe as used nowadays

Additionally, sociological factors play a role (Dumur et al., 2004). For instance, the notion of comfort varies largely between different countries and between social classes (Dumur et al., 2004). Hence, the origin of the user and the level of comfort he is used to contribute to the user's history which may affect his comfort experience. In hand tool use, the user's history may also be influenced by for instance education or experience of family members. Therefore, it is interesting to study if the aspects which underlie comfort are different for professional hand tool users compared to Do-It-Yourself hand tool users.

The personal state is another aspect which affects the user's comfort experience. As an example, the ancient axes are used again. A modern wood cutter who wants to finish his work as soon as possible, would feel more comfortable when using the modern axe. However, if the same wood cutter is working for an archaeology museum in his spare time, demonstrating how people used to work in ancient times, he would enjoy working with the bronze axe or even the stone hand axe and feel very comfortable.

User-tool interaction

The interaction between user and tool is twofold. The user receives tactile input (by holding the tool in the hand) and visual input (by looking at the tool) (Vink et al., 2005b). Tactile input deals with physical comfort as described by Dumur et al. (2004). It concerns freedom from pain and suffering, being relaxed, feeling pleasant and satisfied, and feelings of physical well-being (Dumur et al., 2004). Pressure is considered to be very important in contact interfaces as it can cause discomfort and may also improve comfort (Goonetilleke, 1998; Vink et al., 2005b). Additionally, a mismatch between the handle size and the hand anthropometry can decrease the comfort experience (Das et al., 2005).

Visual input also influences the user's experience. Dumur et al. (2004) refer to this as aesthetic comfort, which depends on taste and personal perceptions of sensations of, for instance, forms and materials. Positive visual qualities of hand tools are of great importance in working life, as they contribute to the image of the workplace and the pride of users (Sperling and Olander, 2004).

However, visual impressions of a handle may not always meet the experience when using it. For instance, grooves and knurls in handles presented on a colour photo, gave strong visual signals of hand –friendliness to novices as well as professional users, while widely accepted ergonomic principles emphasized the risks and disadvantages of such handles (Sperling and Olander, 2004). Hence, the user – hand tool interaction is based on tactile and visual input, which can sometimes be conflicting.

User-task interaction

The task which the user has to perform may affect his comfort experience. This may be explained by the postures and movements induced by the task and the physical capacity of the user to perform the task. Several postures and movements dictated by the task, can affect the comfort experience (Kee and Karwowski, 2001). The postures are not only induced by the task, but the design of the hand tool can also determine the working posture (e.g., Bobjer and Jordt, 1997; Kadefors et al., 1993). The comfort experience can also be indirectly influenced by the physical capacity of the user, as the physical capacity of a user determines the physical response to external exposure (Looze et al., 2003). For instance, a professional carpenter who is used to cross-cut a wooden beam using a hand saw will not get sore muscles by sawing one piece of wood, as his arm and shoulder muscles are used to perform this task and are trained for this job. However, a novice who does never cross-cut a wooden beam, will get sore muscles very quickly. Therefore, he may not experience the used hand saw as comfortable to work with. In summary, the user-task interaction, which may affect the comfort experience, consists of the postures and movements and the physical capacity of the user to perform the task.

Hand tool-task interaction

The interaction between hand tool and task may influence the comfort experience in two ways. First the comfort experience may be influenced by -what Dumur et al. (2004) called- material comfort, which means satisfying basic needs. Applied to hand tool design, this means that the hand tool should be suitable to perform the required task. For instance, using a flat-head screwdriver to turn a Phillips screw into a beam would not be easy, as the tip of the screwdriver does not fit very well in the head of the screw. In that case, the flat-head screwdriver will not be suitable to fulfill the basic need of turning the Phillips screw into the wood. Therefore, the flat-head screwdriver may not be experienced as comfortable to perform this task. Secondly, the comfort experience may be influenced by awkward postures in for instance wrist and shoulder by a mismatch between the shape of the tool and the work station (Chaffin and Anderson, 1999).

Work environment

The work environment of the hand tool user consists of the physical work environment and the social work environment. Both of them may affect the comfort experience of the end-user. The physical work environment contains aspects as noise, smell, and temperature and humidity, which are supposed to be aspects that affect the comfort experience (Vink et al., 2005b). The work station layout also belongs to the work environment. As described before, a mismatch between workstation, tool and user can cause feelings of discomfort. The social work environment deals with conformity comfort, which means that people want to feel they belong to a group and do not want to be outsiders (Dumur et al., 2004). In using hand tools at the construction place this can lead to the users' preference for specific brand marks or hand tools that do not deviate in quality or appearance from the hand tools from colleagues.

This thesis focuses on the hand tool – user interaction. Although the environment and task seem to affect the comfort experience, they are kept constant during the experiments.

2.2 Hand tool design

The first hand tools were 'designed' in ancient times. By using hand tools, humans were able to shape and mould the physical world around them (Signo and Jackson, 1999). They discovered that specific tasks could be done faster and with higher efficiency when using tools. The use of tools has led humans to overcome their natural limitations, and started the development of culture and technology (Signo and Jackson, 1999).

Several processes can be recognized in the evolution of hand tool making (Signo and Jackson, 1999) or, later on: hand tool design. Making hand tools started with reduction, which means that a tool is made by reducing the size of a larger object, for instance removing flakes from a stone to make it sharper. Next step was the conjunction process in which two or more parts are combined (e.g., a tone-tipped spear). Closely related to the conjunction is linkage, where discrete and separate parts are used together, like arrow and bow. After that the replication process started, which helps to improve the effectiveness of a tool, while decreasing the chance that the tool will break or fail (e.g., spears with multiple barbs). Humans were helped to move to the modern age by the transformation process, which involves changing the molecular structure of raw materials (e.g., extracting ore). The next time period, which is still going on, is the period of mass production; hand tools are made by automate machines and robots. New materials are developed like plastics (Haapalainen et al., 1999/2000). Hand tools are available for many people and the hand tool is required to respond to the needs of the greatest possible number of users and be as cheap as possible (Aptel et al., 2002).

The first step to the future will be customization, which is the newest development. A new production technique (rapid manufacturing) makes it possible to provide products to the end-user, optimised to their individual geometrics and requirements (Gerrits et al., 2004). These steps in the history of hand tool design show that approaches of tool making have changed from a tool only being an extension of the human body to perform a task to a tool performing a task and decreasing human discomfort. And nowadays the approach changed to increase comfort with regard to the user's (individual) capacities.

In order to design hand tools that decrease discomfort, several design approaches have been used in the near past. The next section describes only the design approaches found in the literature with regard to hand tool design. Later on, design criteria and guidelines for hand tool design are addressed.

2.2.1 Design approaches

Many different approaches have been used in designing hand tools. Some of them are general approaches concerning the whole design process, like participatory design (Vink, 2005c; Wilson and Haines, 2001) and the design approach based on the theory of Rozenburg and Eekels (1995). For instance, a participatory design approach was used to design new bricklayers' trowels (Kuijt-Evers and Eikhout, 2006) and a hand-held steel fixing tool was developed using the approach of Rozenburg and Eekels (Visser et al., 2005). In addition, Quality Function Deployment (QFD) was used in hand tool design. QFD is also a general design approach, but mostly one part is used in hand tool design: the House of Quality

(Marsot, 2005; Marsot and Claudon, 2004, Leppänen et al., 2000). Additionally, some approaches are especially developed with a focus on hand tool design, like the 11-point programme(Bobjer and Jansson, 1997), the Swedish cube model (Sperling et al., 1993) and a methodology to integrate ergonomics in hand tool design (Marsot and Claudon, 2004). For instance, a new paint scraper and screwdrivers were developed using the 11-point programme(Eikhout et al., 2005a, Eikhout et al., 2005b) and Kilbom et al. (1993) redesigned a plate shear in order to reduce one of the critical factors of the cube model, and Marsot and Claudon (2004) developed a new boning knife using their method. The mentioned approaches will be described.

Participatory design

There has been a considerable growth in participatory design since the 1980s, partly due to regulatory requirements and partly because it matches newer management philosophy with workforce and trade (Wilson and Morris, 2004). Several definitions are found in literature. Vink et al. (2005c) state that participatory ergonomics is the adaptation of the environment to the human (i.e., ergonomics) with involvement of the proper persons in question (participants). Wilson and Haines (2001) look at it in a broader perspective. They define participatory design as the involvement of people in planning and controlling a significant amount of their own work activities, with sufficient knowledge and power to influence both processes and outcomes in order to achieve desirable goals (Wilson and Haines, 1998 cited from Wilson and Haines, 2001). Although the definitions of participatory design differ slightly, some common characteristics can be recognized. Firstly, participatory design is recognized as an umbrella term under which various approaches can be found, and secondly, attention is explicitly paid to the role of designers, employees, end-user, and others involved during the design process.

Vink et al. (2005c) recognize 6 steps in the participatory design process: 1) preparation 2) analysis of tasks, work and health, 3) selection of improvements and design 4) pilot study with the improvements, 5) implementation, and 6) evaluation. The participatory design process starts with the preparation step, in which participants (end-users, management and other stakeholders) are informed about the project during a central meeting. The aim of the project, strategy (step-by-step approach), members of the steering committee and possible outcomes are discussed. After that, the tasks, work and health of end-users are studied using interviews, observations, questionnaires or simulation techniques. Based on the analysis in step 2, user requirements are set, focused on the goals set in step 1. Essential in this third step is that participants report ideas for improvement. Based on these first ideas, first versions of design can be made. In the fourth step, the new design is tested in a mixed reality environment or in reality and prototypes could be made. In the next step, the new design is implemented in the actual workplaces. In a central meeting the participants are informed about the new situation. In the last step, the new design will be evaluated. After the end-users are adapted to the new product and eventually a new working technique, the new situation can be compared with the situation in the second step. If necessary, adaptations can be made to the new design.

Essential in the participatory design process is that all participants (end-users, designers and stake-holders) progress step-by-step towards the end result. Participants should be kept informed after each step (Vink et al., 2005c).

Basic design cycle by Roozenburg and Eekels

Roozenburg and Eekels (1995) consider the design process as a problem solving process that takes place from a goal (function) to means (design). They state that design is a trial-and-error process as many means can realize the same goal and it is initially uncertain what means are most effective. Based on their theory, Roozenburg and Eekels propose the basic design cycle (Figure 2.3).

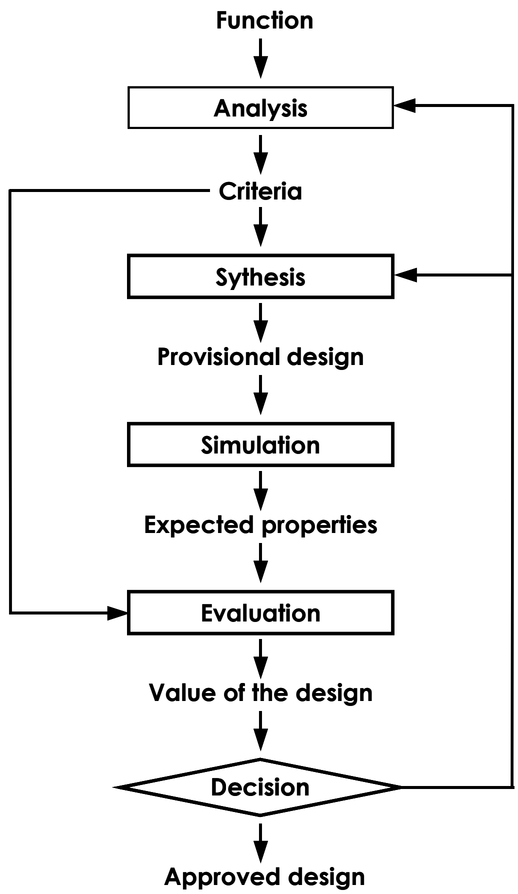


Figure 2.3 Basic design cycle (Roozenburg and Eekels, 1995)

The basic design cycles starts with the function. This is the intended behaviour of the product in the widest sense of the word. It concerns for instance the technical, physiological, social, and economic function of the product. During the analysis phase, designers form an idea of problems around the new product idea that fulfils the function as described in the beginning. The problem statement is described (who has the problem, what is thought to be the problem and what causes it). Additionally, criteria are described, which the solution should meet. These criteria are needed to evaluate the provisional design proposal later on in the process. Finally, the goal is formulated. This is the image of a future situation which is preferred to the present situation. The goal is formulated as concretely as possible in a list of requirements, that is the design specifications.

In the next phase, which is called synthesis, provisional design proposals are generated to solve the problems. In the simulation phase, the designer forms an image of the behaviour and properties of the provisional design proposals. This leads to expectations about the actual properties of the new product. The value and quality of the provisional design are established in the evaluation phase. The expected properties are compared with the design properties in the design specification from the analysis. Based on the evaluation, a decision has to be made: elaborate the design proposal or manufacture it. Two feedback loops are possible. The designer returns to the synthesis phase to generate better design proposals or the designer goes back to the design specifications of the analysis phase to reformulate the list of requirements, because exploring the solutions can give insight in the problem.

Quality Function Deployment (QFD)

Quality Function Deployment has been described a few times in hand tool design papers (Haapalainen et al., 1999/2000; Leppänen et al., 2000; Marsot and Claudon, 2004). Especially one part of the QFD, The House of Quality (Figure 2.4), is used in hand tool design. This part helps designers to translate the customer needs into the engineering characteristics (Akao, 1990; Pullman et al., 2002; Hauser and Clausing, 1988, Marsot, 2005; Sullivan, 1986).

It starts with the customers: What do customers want? Their needs are called customer requirements or customer needs. Examples of customer requirements (for the redesign of a boning knife) are ‘allow for work on meat’, ‘comply with food hygiene regulations’, and ‘be gripped in different positions’ (Marsot, 2005).

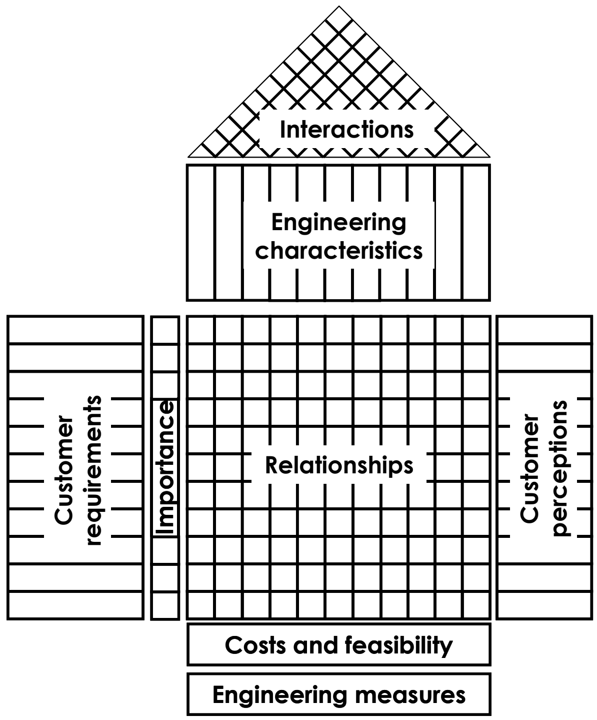


Figure 2.4 House of Quality

The importance of the customer requirements is indicated, as some customer needs have higher priorities to the end-users than others. Next question is: How can the product be changed to fulfil the customer needs? The product is described in the language of the engineer, like 'handle shape', 'blade shape', 'pressure level', 'weight', and 'balance' (Marsot, 2005). The next step is to indicate how much each engineering characteristic affects each customer need. The benefit of this overview of relationships between engineering characteristics and customer needs is that it quickly indicates whether the engineering characteristics adequately cover the customer requirements of expectations (Sullivan, 1986). After that, the interactions between the engineering characteristics are indicated in the roof of the House of Quality, which is useful to identify conflicting engineering characteristics. For instance, the hardness of the handle should not be high in the boning knife example, to prevent from pain. However, a rigid connection between blade and handle is necessary and can only be established if the blade is attached to a hard (non-flexible) handle (Marsot, 2005). Resolving these conflicts during the design process, will avoid implementing compromise-based solutions at the end of the design process (Marsot, 2005).

The QFD method offers a systematic approach involving quantified information about interactions between customer needs and design criteria. However, the most troublesome part of the QFD is to establish these 'Whats'/'Hows' correlations as it is often based on experience, intuition, and determination of members of the design team (Mitsufuji and Uchida, 1990). Haapalainen et al. (1999/2000) argued that there is no reliably established information concerning all 'Whats'/'Hows' correlations in the House of Quality. Moreover, information is lacking about the accuracy of the estimations of a design team when finalizing the House of Quality in hand tool design.

The House of Quality is completed by the customer perceptions of performance (which is a formal market research measurement of how customers perceive products that now compete in the market), feasibility and costs of changing engineering characteristics, and data of objective engineering measures of existing products on the engineering characteristics (Griffin and Hauser, 1993).

The 11-point programme

The 11-point programme was proposed by Bobjer and Jansson (1997). This is a research based approach to hand tool design. The design team consists of ergonomists, industrial designers and engineers. Professional hand tool users are also involved in research and prototype design stages. The approach consists of eleven stages (Figure 2.5).

In the first step (preliminary specifications) a task analysis is performed, followed by a market analysis (step 2) and background research (step 3).

1	**Preliminary specification**
2	**Market analysis**
3	**Background research**
4	**Prototype design**
5	**User test #1**
6	**Prototype evaluation and modification**
7	**User test #2**
8	**Final design recommendations**
9	**Product specifications**
10	**User test #3; preparation for launch**
11	**Follow-up**

Figure 2.5 Steps in the 11-point program.

In the background research information is gathered from literature and databases about for instance, risk factors of work-related injuries and technical performance tests. After that, in the next step (step 4) experimental prototypes are developed and information is achieved from users' tacit knowledge. During the first user test, professional end-users test the experimental prototypes under realistic conditions (step 5). Next to that, the prototype evaluation and modification takes place in which improvements are made based on in-depth analysis of user test #1 (step 6). In the next user test (step 7) the new prototypes are tested by a wider selection of users and in different countries. The final design recommendations, like the size, shape and engineering of the tool are decided in step 8. In step 9 the production of manufacturing specifications is prepared. After that, the last user test is conducted in step 10, in which the user gives feedback on the tool's performance over an extended period of time. Based on these results, the tool is approved for mass production. The last step concerns the follow-up (step 11). In co-operation with independent researchers the new tool and their users are checked over a longer period of time.

Cube model

The cube model for the classifications of work with hand tools and the formulation of functional requirements (Sperling et al., 19930) is not only focussed on hand tool design, but takes into account the whole work environment, including user, workplace, work organization, and hand tools. Sperling et al. (1993) recognize three basic variables at working with hand tools: 1) time factor, 2) demands on force, and 3) demands on precision. These variables can be influenced by the design of the tool, the workplace and the work organization. The relationship between the dimensions time, force and precision are visualized in the cube model (Figure 2.6).

Each face of the cube was divided into three levels: low, moderate, and high, resulting in 27 sections. The definition of acceptable or non-acceptable work depends on the combination of time, force and precision demands. Ten sections were decided upon as acceptable (light grey) and seven as non-acceptable (black). The dark grey sections indicate situations that must be further investigated. Preliminary studies have shown that the cube model is a useful tool for the classification of manual work and for discussing different ways of improvement (Sperling et al., 1993).

A plate shear is an example of a hand tool with high demands in terms of force, precision and duration (Kilbom et al., 1993). Therefore, this hand tool was chosen by Kilbom et al. (1993) to investigate the influence of one of the critical factors, namely force requirements, on productivity and fatigue (as substitute of risk of injury). In order to do so, a new plate shear was designed in which the grip diameter was optimized and a spring grip was added. The results showed that this leads to improved biomechanical qualities. Thereby, the male subjects could increase their productivity, while the female subjects could reduce their relative load level (percentage of maximum grip force that is needed to cut), with unchanged productivity. However, objectively (by EMG) and subjectively measured fatigue did not show any differences between the plate shears (Kilbom et al., 1993).

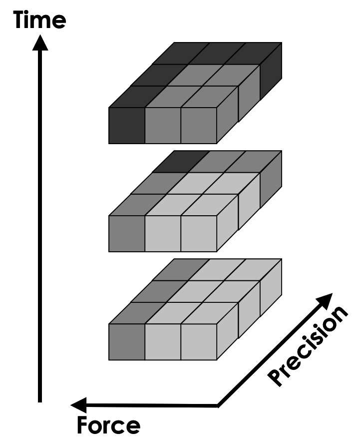


Figure 2.6 The cube model (Sperling et al., 1993).

Method to integrate ergonomics in hand tool design

Marsot and Claudon (2004) recognized three problems in current ergonomic hand tool design processes: 1) iteration in the process is seen as waste of time and as a result of making mistakes 2) insufficient or absence of communication between design players and 3) lack of guides to assist designers in selecting design tools that are suited to integrate ergonomics. Therefore, they propose a spiral model which makes use of both functional analysis and prototyping techniques (Aptel et al., 2002). It allows for the integration of all project participants before completion of each design phase. In addition, they combined several design approaches (i.e., Functional Analysis, Quality Function Deployment and TRIZ) to integrate ergonomics in the design stage in a boning knife redesign study (Marsot and Claudon, 2004). These three approaches were chosen as they were thought to satisfy the requirements on iteration, multi-disciplinary and communication. Functional Analysis was used to list all functions from technical and financial data provided by manufacturers, results of a field survey among operators and information obtained at interdisciplinary working meetings. The functions were divided into nine functional groups. The QFD was used to link the customer needs (based on the functions of the Functional Analysis) to engineering characteristics. Moreover, the potential conflicts between ergonomic criteria and other design parameters could be identified in the roof of the House of Quality (Marsot, 2005). These conflicts were solved using TRIZ, which is a method to solve technological problems in a methodical manner (Marsot and Claudon, 2004).

2.2.2 Design approaches and comfort

As stated before, comfort is a subjective phenomenon: it is the experience of the end-user, when using a product to perform a task in an environment. Therefore, it is necessary to involve the end-user in the design process when one wants to develop hand tools that provide comfort to the user. From this point of view, a design approach used to ensure comfort in the end product should in any event be a participatory design process.

However, a participatory design process only may not ensure attention for comfort in the hand tool design process. After step 2 of the design process, the user requirements based on the task, work and health analysis (also regarding comfort), have to be translated into ideas for a new product in step 3. A design method which is aimed at translating customer's demands into product characteristics in order to satisfy the end-user is the Quality Function Deployment (Akao, 1990). The House of Quality (as part of the QFD) was used in hand tool design before (Haapalainen et al., 1999/2000, Marsot, 2005). In the current thesis, It will be studied, if the House of Quality can also be used to address comfort in the design process of hand tools.

2.2.3 Design guidelines

Many handbooks contain guidelines for hand tool design (e.g., Cacha, 1999; Karwowski, 2001; Radwin, 1996) and many scientific papers concern design criteria (Lewis and Narayan, 1993; O'Meara and Smith, 2002; Mital and Kilbom, 1992; Päivinen et al., 1999/2000). Some authors present an overview of guidelines based on a literature review, like Mital and Kilbom (1992). Their paper shows optimal values on for instance grip length, grip thickness, grip shape, grip force, and orientation of handle. These criteria are based on more fundamental studies on, for instance, hand anthropometrics and maximum force exertion. Other papers are confined to user requirements in general descriptions, like durable and robust handles, no part causes pressures, grip span is suitable (Haapalainen et al., 1999/2000). Additional studies focus on specific aspects of handle design and can indirectly contribute to guideline development (e.g., Shih and Wang, 1996; O'Meara and Smith, 2002; Kong and Lowe, 2004; Johansson et al., 1999; Fransson-Hall and Kilbom, 1993). For instance, the effect of cross sectional shape (triangle, square, hexagon and circular) (Shih and Wang, 1996), handle diameter and handle orientation (Kong and Lowe, 2004) was studied on maximum torque capacity. O'Meara and Smith (2002) investigated the coefficient of static friction for different materials (stainless steel, powder coated, chrome, textured and knurled) and the sensitivity of the hand and the perception of surface pressure was studied by Fransson-Hall and Kilbom (1993) and Johansson et al. (1999). Another category of studies, which sometimes presents guidelines for hand tool design, are papers about (re)designing hand tools, like the design of a snap-on-handle for hacksaws of Das et al. (2005).

Design guidelines and comfort

The design guidelines as presented in handbooks and overview articles, like the review of Mital and Kilbom (1992), are mostly based on fundamental studies on, for instance, anthropometric data of the hand, data on maximum force exertion, and maximum acceptable pressure. Hence, the guidelines are based on the maximum capacity of end-users. However, information is lacking about how a hand tool should be designed to provide comfort.

Only a few (fundamental) studies address to comfort or discomfort (Kong and Lowe, 2004; Johansson et al., 1999; Kee and Karwowski, 2001). Kong and Lowe (2004) did not only measure the maximum torque exertion for different handle diameters, but they also assessed the participants' comfort perception (on a 7-point scale). Unfortunately, the comfort assessment was performed wearing the force glove system, which may have affected the comfort experience. Johansson et al. (1999) investigated the pain pressure thresholds on three parts of the hand surface and determined for each part the discomfort pressure level at which 50% of the participants experiences discomfort. In addition, Kee and Karwowski (2001) indicated boundaries for joint angle comfort under static circumstances.

Despite these studies, there is still a gap between how end-users experience a hand tool during its use and the actual design of the hand tool. In the current thesis, it was tried to fill this gap by investigating which engineering characteristics are related to the user requirements that are mostly related to comfort in using hand tools.

2.3 Hand tool evaluation

In the past, hand tool evaluation studies have been conducted with several main objectives. One of these objectives was to recognize ergonomically well-designed hand tools (e.g., Kluth et al., 2004; Groenesteijn et al., 2004; Chang et al., 1999), which should reduce the risk on the occurrence of musculo skeletal disorders and increase productivity. Another goal was to develop general predictive models of human performance with hand tools, as well as associated workplace design (Dempsey et al., 2004; Dempsey et al., 2002). A third aim found in literature was to find out why a specific hand tool has not achieved general acceptance in the trade (Strasser et al., 1996) and last but not least, hand tool evaluation studies have been performed to optimise product characteristics and contribute to design guidelines development (e.g., Das et al., 2005; Eksioglu, 2004, Wu and Hsieh, 2002, Kong and Lowe, 2004). Hence, a wide range of main objectives of hand tool evaluation studies was recognized in literature.

Despite the differences in main objectives of the evaluation studies, the research methods do not differ so much. The independent variables consist of different hand tools of the same kind, and sometimes different workplace layouts (e.g., Dempsey e.g., 2004; You et al., 2005; Kluth et al., 2004). As the focus of this thesis is on the hand tool – user interaction, the different workplace layouts will not be addressed here.

Hand tools can differ in either the work side, the hand side or both. For instance, the work side of a hand tool can vary in blade angle, sharpness and post sharpening finishing in knives (McGorry et al., 2005; McGorry et al., 2003), different coating materials in axes (Päivinen and Heinimaa, 2004) and different edge angles of the jaws of side cutting pliers (Groenesteijn et al., 2004). The hand side of the tool (i.e., the handle) was evaluated more often than the work side. Effects of a new handle or shaft configuration were studied very often (Kong and Freivalds, 2003; McGorry et al., 2003; McGorry et al., 2005; Boyles et al., 2003; Dempsey et al., 2002). Other studies focused on the handle material (Fellows and Freivalds, 1991; Chang et al., 1999) and various kinds of grips, for instance palm grip versus finger grip in surgical tools (Berguer et al., 1999). The dependent variables that are measured using either subjective or objective measures concern physical workload (muscle activity, posture, grip force and force distribution)(e.g., Kong and Freivalds, 2003; Dempsey et al., 2002; You et al., 2005) and perceived exertion (Wu and Hsieh, 2002), functionality (Kong and Freivalds, 2003; Groenesteijn et al., 2004), productivity (Wu and Hsieh, 2002; Kong and Freivalds, 2003; Dempsey et al., 2002), and discomfort (Kong and Freivalds, 2003; You et al., 2005; Groenesteijn et al., 2004). The measures to obtain these variables are described in more detail below.

2.3.1 Subjective measurements

Subjective measurements are mostly used when hand tools are evaluated with respect to discomfort (Boyles et al., 2003; Chao et al., 2000; Chang et al., 1999; Dempsey et al., 2002; Groenesteijn et al., 2004; Kilbom et al., 1993; Kong and Freivalds, 2003; You et al., 2005) and perceived exertion (Fellows and Freivalds, 1991; Freund et al., 2000; McGorry et al., 2003; Wu and Hshie, 2002). Additionally, the end-users preference or ranking of the evaluated tools is asked (Dempsey et al., 2002; Dempsey et al., 2004; Freund et al., 2000; Groenesteijn et al., 2004). Further, the user satisfaction with the design characteristics is studied (You et al., 2005; Kluth et al., 2004; Strasser et al., 1996; Jung and Hallbeck, 2000). Less frequently, the functionality of the tool (Jung and Hallbeck, 2000) is evaluated. In some papers comfort is mentioned as one of the dependent variables, but it turned out to be discomfort what was measured (e.g., Chao et al., 2000; Chang et al., 1999). Only four papers were found in which end-users' comfort experience was measured (Freund et al., 2000; Groenesteijn et al., 2004; Das et al., 2005; Jung and Hallbeck, 2000). The subjective measurements used in literature to obtain comfort and discomfort will be described below.

Assessment of discomfort

Different methods are found in literature to assess perceived discomfort. The most common subjective method to assess discomfort is using a body map and/or a detailed hand map (Figure 2.7) based on Corlett and Bishop (1976) (Boyles et al., 2003; Chao et al., 2000; Dempsey et al., 2002, Groenesteijn et al., 2004; Kilbom et al., 1993; You et al., 2005). For each region, the feelings of discomfort are rated. The rating scales that are used, differ between the studies. For instance, the Borg CR-10 scale is used ranging from 0 (nothing at all) to 10 (extremely strong, almost maximum) (Chao et al., 2000; Kilbom, 1993; You et al., 2005). Dempsey et al. (2002) used a rating scale ranging from 1 (extremely comfortable) to 7 (extremely uncomfortable), Groenesteijn et al. (2004) used a rating scale ranging from 0 (no discomfort) to 5 (extreme discomfort, almost maximum) and Boyles et al. (2003) used a rating scale from 0 (no pain in body parts to 7 severe pain in body parts). Another method used to obtain discomfort is to rate handle discomfort (Chang et al., 1999; Kong and Freivalds, 1993). Kong and Freivalds (1993) used a Borg scale ranging from 6 to 20 and Chang et al. (1999) used the Borg CR-10 scale.

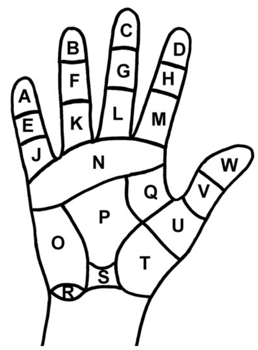


Figure 2.7 Example of a hand map

As discomfort has been measured using the body map and/or hand map, it seems reasonable to use this method to assess discomfort. Moreover, this method gives more information than assessing handle discomfort, because the location of the experienced discomfort is known. For instance, designers can derive the part of the tool handle that causes discomfort from the hand region in which discomfort is experienced.

Assessment of comfort

Comfort experience is considered in four hand tool evaluation studies (Freund et al., 2000; Jung and Hallbeck, 2000, Groenesteijn et al., 2004; Das et al., 2005). In the study of Freund et al. (2000) 'comfort of the grip' was one of the items of the subjective evaluation. This item could be rated from 1 (very bad) to 7 (very good). Groenesteijn et al. (2004) used a 5-point scale to assess comfort in working with pliers, ranging from 1 (very uncomfortable) to 5 (very comfortable). Jung and Hallbeck (2000) evaluated tool handles of a clamp. They used a questionnaire addressing five topic areas. One of the areas was postural comfort. This topic contained items like 'overall hand comfort', 'hand comfort when squeezing the handle' and 'hand comfort when clamping the material'. These items were rated on a 7-point scale, where 1 was worst and 7 was best. Das et al. (2005) also measured, what they called, acceptance/comfort. They did not ask the subjects directly after their comfort experience, but distracted it from ratings of handle design characteristics, required effort, and extent of tiredness in performing the sawing task (on a five point scale).

The mentioned methods to asses comfort have some disadvantages. The methods used by Groenesteijn et al. (2004) and Freund et al. (2000) are lacking information. The results only show the comfort experience, but do not give any more information about why subjects experience more or less comfort using one of the hand tools compared the other, or how to improve the hand tool design. The methods of Jung and Hallbeck (2000) and Das et al. (2005) focus on the handle comfort. Jung and Hallbeck (2000) evaluated the overall comfort and the comfort experience during specific actions (at least, they are the only ones mentioned in their paper) like comfort when clamping the material. However, the same problem occurs as in using the methods of Groenesteijn et al. (2004) and Freund et al. (2000). Based on this questionnaire, the clamp that is more comfortable when clamping material can be found, but the reason for this is unknown. For instance, an explanation may be that the grip span fits the hand better or less grip force is needed. For designers it is important to get more specific information in order to improve hand tool design.

Das et al. (2005) collected more information as they ask the participants' opinion about design properties, but some questions arise about this method. Firstly, it is unknown if all the handle design characteristics contribute to the comfort experience. In other words, it is unknown if comfort experience is measured using this questionnaire or something else (like acceptance or fit in the hand). Hence, information is lacking about the construct validity of the questionnaire. Furthermore, Das et al. (2005) asked the participants to rate design characteristics. In the introduction of this thesis, it was argued that hand tool users may not be able to assess design characteristics directly in terms of comfort as they used descriptions of performance to rank scissors on pleasantness. Finally, Das et al. (2005) focused only on the handle design, while comfort may also be influenced by the design of the work side of the tool (e.g., the saw blade). This is reasonable in their study, as they only evaluated the handles (remaining the work side constant), but in future studies to support comfort in design, it is needed to asses comfort of hand tools as a whole.

To summarize, a suitable subjective method to assess comfort in using hand tools was not found in literature. One goal of this thesis will be to develop a questionnaire to assess comfort experience of the end-users. The questionnaire should suit the experience of the end-user and should give additional information, which can be used by designers to improve hand tool design with respect to comfort.

Disadvantages of subjective measurements

Subjective evaluations have some clear disadvantages. Lee et al. (1993) mention that they require a large number of subjects and tests are therefore time-consuming and Chen et al. (1994) say that they are influenced by personal preferences (e.g., using always the same brand). Moreover, there are some common known sources of unreliability of using subjective measures from classical psychophysics, like time error and context effects (Annet, 2002). Time error refers to one of the systematic sources of error in making comparative judgements. This type of error can be attributed to the time between the presentation of standard and the variable stimulus, when the standard is held in memory. For instance, the second of two weights typically appears heavier than the first (Annet, 2002). Context effects have been widely recognized as a common source of bias in subjective judgements. An example of a context effect is the size-weight illusion (Annet, 2002), in which the larger object appears lighter than a standard of equal mass but smaller volume.

Another problem in subjective measurements is the construct validity. Comfort is a construct based on common experience and shared meaning, like e.g., fatigue and workload (Annet, 2002) (although definitions differ). Before developing a questionnaire it is necessary to establish construct validity by providing a coherent theoretical framework that fits the relevant observations (Annet, 2002).

Despite of the disadvantages of subjective measurements, Annet (2002) states that when subjective experience of the end-user is relevant to the purpose of the study, subjective measures are clearly indicated. Hence, when measuring comfort, it is necessary to use subjective measurements as comfort is a construct of a subjectively defined personal nature (Looze et al., 2003). However, it may be useful to know if objective measures are related to subjectively measured comfort experience. In that way, the subjective findings could be supported by objective data.

2.3.2 Objective measurements

Many objective measurements are used in hand tool evaluation studies. Even special measurement equipment was developed. For instance, Niemellä et al. (2000) attached strain gauges and a potentiometer to a prune shear in order to measure the force between the blades generated by the end-user and the opening angle of the blades. McGorry (2001) instrumented a handle of a single-handled tool to measure grip forces and applied moments in non-powered hand tools and Yun et al. (1992a) developed a system that combines grip force measurements and posture measurements. The most common objective measurements are addressed in this section.

Muscle activity

Electromyography (EMG) is very often used in hand tool evaluation studies (Figure 2.8) (e.g., Freund et al., 2000; Das et al., 2005; Habes and Grant, 1997; Fellows and Freivalds, 1991). It was used to obtain muscle effort (Berguer et al., 1999; Das et al., 2005), muscle activity (Hammarskjöld and Harms-Ringdahl, 1992), or as indirect measurement to estimate force requirements (Fellows and Freivalds, 1991; Berguer et al., 1999; You et al., 2005) muscle fatigue (Fellow and Freivalds, 1991), and physical or muscular strain (Kluth et al., 2004; Strasser et al., 1996).

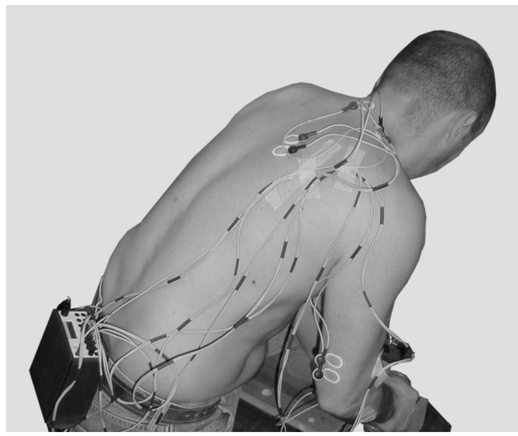


Figure 2.8 EMG measurements during sawing task

Muscle activity was not used as indirect measurement of comfort or discomfort in hand tool use. Although, the results of a study of Lee et al. (1988) on comfort and discomfort during a microscope task showed that increased muscle activation (in time) in shoulders and back were significantly related to increased discomfort. Further, there are some seat evaluation studies in which statistical evidence is lacking, but a tendency of a relationship was shown between discomfort or comfort and EMG measurements (Looze et al., 2003).

In hand tool evaluation studies, these kinds of tendencies were also seen. For instance, Chang et al. (1999) found in evaluating 3 different handle types that the handle material which required less muscle effort also was subjectively perceived as most comfortable. However, the opposite was found by Fellows and Freivalds (1991), who found that the normalized EMG was higher for the rubber grip tool handle which was preferred by the participants.

Pressure and force distribution

Force distribution was studied in only a few hand tool evaluation studies (Kong and Freivalds, 2003; Fellows and Freivalds, 1991; Yun et al., 1992b). However in sitting comfort, pressure distribution appears to be the objective measure that has the clearest association with subjective comfort or discomfort ratings (Looze et al., 2003). Several seat evaluation studies showed a significant relationship between pressure measures and comfort or discomfort (e.g., Thakurta et al., 1995; Yun et al., 1992b, Vergara and Page, 2000). Goonetilleke (1998) states that pressure in the human interface can cause discomfort as well as improve comfort.

Kong and Freivalds (2003) studied the force distribution on the fingers when using different meat-hook handles. They found that the force distribution between the fingers should not be distributed equally, but that the strongest fingers should provide the largest contribution compared to the weakest fingers. However, they argued that a uniform distribution within all phalanges should be aspired. Fellows and Freivalds (1991) found that the handle which provided a more uniform force distribution achieved the lowest values on perceived exertion. However, the relationship between pressure distribution and comfort or discomfort in using hand tools is unknown.

Grip force

Grip force was directly measured in a few studies (e.g., McGorry et al., 2003; McGorry et al., 2005; Niemellä et al., 2000; Kilbom et al., 1993). In some other studies grip force was estimate based on EMG measures (e.g., You et al., 2005). Only in the study of Kilbom et al. (1993), who evaluated plate shears, grip force measurements were combined with subjective comfort or discomfort ratings. As expected the highest ratings on perceived discomfort were found for the same conditions as the highest required grip force. But no correlations were calculated.

Working posture

The working posture of a hand tool user is dictated by the workplace layout and the design of the tool, which influences how the end-user applies the tool, including the postures that will be attained (Kadefors et al., 1993; Dempsey et al., 2004; Dempsey et al., 2002). However, whole body monitoring is not a prime interest in hand tool evaluation (Kadefors et al., 1993). Moreover, wrist load is one of the most important aspects of hand tool use, especially in combination with force exertion (Kadefors et al., 1993).

Therefore, most evaluation studies consider postures of wrist and fore arm (Figure 2.9) (e.g., Dempsey et al., 2004; Dempsey et al., 2002; Eikhout et al., 2001). Dempsey et al. (2002) evaluated the influence of bended pliers handles, work height and work orientation on wrist deviation and discomfort. They found that radial and ulnar deviation varied strongly between subjects. That is why relative wrist deviations are calculated: dividing the wrist deviation by the maximum active wrist deviation (Eikhout et al., 2001). Moreover, the interactive effects of work piece orientation and work height affect wrist deviations, which illustrates how a specific tool design will not necessarily minimize the wrist deviation in all work settings (Dempsey et al., 2004). Nevertheless, Hsu and Chen (2000) concluded that file handles should be bended in order to minimize postural deviation and fatigue, but they evaluated the file handles only at one work height and neglected the influence of work height. Hence, it seems that wrist deviations are more influenced by work station layout than by hand tool design.

The relationships between static body postures and comfort and discomfort were studied in a series of studies (Kee and Karwowski, 2001; Kee and Karwowski, 2003). They found that joint postures (percentage of range of motion) of for instance wrist, elbow, shoulder were highly correlated to score of comfort (R^2>0.90)(Kee and Karwowski, 2001) and extreme joint postures (high percentage of range of motion) were accompanied by high discomfort levels (Kee and Karwowski, 2003). These findings are subscribed by hand tool evaluation studies. For instance, Dempsey et al. (2002) found that higher levels of wrist deviation were associated with relatively high discomfort ratings.

Figure 2.9 Example of wrist posture measurement, using goniometers.

2.3.3 Relationship between objective and subjective measures of comfort and discomfort

This literature overview shows that the relationships between objective measures and comfort and discomfort experience are unknown for most objective measurements. Joint posture measurement is an exception on this, although the relationship between joint angles and comfort were obtained from static postures (Kee and Karwowski, 2001). The question is whether these results are representative for hand tool use (which is mostly a dynamic action). Additionally, the relationships of muscle activity, pressure distribution, and grip force with comfort or discomfort in using hand tools are unknown. These relationships should be studied in order to find an objective measurement which can support subjective ratings of comfort and discomfort.

2.4 Research questions

Next Table (Table 2.1) gives an overview of the sub-goals of the current thesis and the additional research questions. The last column shows in which chapter this research question is addressed.

Table 2.1 overview of subgoals of the thesis

Sub-goals	Research questions	Chapter
Contribute to theory on comfort and discomfort	What are the comfort descriptors of comfort and discomfort in using hand tools?	3
	Can the comfort descriptors be divided into meaningful groups (factors) of interrelated comfort descriptors?	3
	What comfort descriptors are the best predictors of comfort and discomfort in using screwdrivers?	4
	What factors (i.e. groups of descriptors) predict comfort and discomfort in using screwdrivers?	4
	Do the same factors underlie both comfort and discomfort or not?	4
	Do the same factors underlie comfort in different kinds of hand tools?	5
	Does the relevant importance of the comfort descriptors differ between different kinds of hand tools?	5
Propose how comfort can be integrated in the design process	Can the House of Quality of the Quality Function Method ensure comfort in design?	6
Investigate how hand tools can be evaluated with respect to comfort	Development of a questionnaire to evaluate hand tools on comfort	3,4,5
	Can subjective feelings of comfort and discomfort be predicted from objective measures?	7

2.5 References

Akao, Y. 1990. An introduction to Quality Function Deployment. In: Quality Function Deployment; Integration Customer Requirements into Product Design. Akao, Y. (ed.), Productivity Press, Cambridge.

Annet, J., 2002. Target paper: Subjective rating scales, science or art? Ergonomics, 45 (14): 966-987.

Aptel, M., Claudon, L., Marsot, J., 2002. Integration of ergonomics into hand tool design: principle and presentation of an example. International Journal of Occupational Safety and Ergonomics, 8 (1): 107-115.

Berguer, R., Gerber, S., Kilpatrick, G., Remler, M., Beckley, D., 1999. A comparison of forearm and thumb muscle electromyographic responses of the use of laparoscopic instruments with either a finger grasp or a palm grasp. Ergonomics, 42 (12): 1634-1645.

Bishu, R.R., Cochran, D.J., Riley, M.W. 1988. Evaluation of office chairs – a validation study. In: Trends in Ergonomics/Human Factors V. Aghazadeh, F. (ed). Elsevier Science Publishers B.V., North-Holland.

Bobjer, O. and Jansson, C. 1997. A Research Approach to the Design of Ergonomic Hand Tools. The 11-Point Programme. In: From Experience to Innovation. P. Seppälä, T. Luopajärvi, C.H. Nygård, and M. Mattila (eds.) Proceedings of the 13th Triennial Congress of the International Ergonomics Association, Tampere, June 29- July 4. vol. 2. Helsinki: Finnish Institute of Occupational Health: 193–195.

Bobjer, O., Jordt, G., 1997. Ergonomic design of hand tools frequently used in awkward postures. The ratchet wrench. In: From Experience to Innovation. P. Seppälä, T. Luopajärvi, C.H. Nygård, and M. Mattila (eds.) Proceedings of the 13th Triennial Congress of the International Ergonomics Association, Tampere, June 29- July 4. vol. 2. Helsinki: Finnish Institute of Occupational Health: 196-198.

Boyles, J.L., Yearout, R.D., Rys, M.J., 2003. Ergonomic scissors for hairdressing. International Journal of Industrial Ergonomics, 32 (3): 199-207.

Branton, P. 1969, Behavior, body mechanics and discomfort. Ergonomics, 12 (2): 316-327.

Cacha, C.A. (ed.) 1999. Ergonomics and safety in hand tool design. CRC Press, Boca Raton.

Chaffin, D.B., Andersson, G.B., Martin, J.M., 1999. Occupational biomechanics. Wiley, New York.

Chang, S.R., Park, S., Freivalds, A., 1999. Ergonomic evaluation of the effects of handle types on garden tools. International Journal of Industrial Ergonomics, 24 (1): 99-105.

Chao, A., Kumar, A.J., Emery, C. T.N.D., Nagarajarao, K., You, H., 2000. An ergonomic evaluation of cleco pliers. In: Ergonomics for the New Millennium. Proceedings of the IEA 2000/HFES 2000 congress. San Diego, 28 July- 4 August, 2000: 4-441-4-442.

Chen, H., Nigg, B.M., Koning, J. de, Relationship between plantar pressure distribution under the foot and insole comfort. 1994. Clinical Biomechanics, 9 (6): 335-342.

Cherry, J., Christensen, A., Bishu, R., 2000. Glove comfort vs. discomfort: are they part of a continuum or not? A multi-dimensional scaling analysis. In: Ergonomics for the New Millennium. Proceedings of the IEA 2000/HFES 2000 congress. San Diego, 28 July- 4 August, 2000: 5-95 - 5-98.

Chester, M.R., Rys, M.J., Konz, S.A. 2002. Leg swelling, comfort and fatigue when sitting, standing and sit/standing. International Journal of Industrial Ergonomics, 29 (5): 289-296.

Corlett, E.N., Bishop, R.P. 1976. A technique for assessing postural discomfort. Ergonomics, 19 (2): 175-182.

Das, B., Jongkol, P., Ngui, S., 2005. Snap-on-handles for a non-powered hacksaw : An ergonomics evaluation, redesign and testing. *Ergonomics*, 48 (1): 78-97.

Dempsey, P.G., McGorry, R.W., Leamon, T.B., O'Brien, N.V., 2002. Bending the tool and the effect on human performance: Further investigation of a simulated wire-twisting task. AIHA Journal, 63 (7): 586-593.

Dempsey, P.G., McGorry, R.W., O'Brien, N.V. 2004. The effects of work height, workpiece orientation, gender, and screwdrivers type on productivity and wrist deviation. International Journal of Industrial Ergonomics, 33 (4): 339-346

Demontis, S., Giacoletto, M., 2002. Prediction of car seat comfort from human-seat interface pressure distribution. SAE-paper 2002-01-0781: 105-111.

Dumur, E., Barnard, Y., Boy, G., 2004. Designing for comfort. In: Human factors in design. Waard, D. de, Brookhuis, K.A., Weikert, C.M. (eds.) Shaker Publishing, Maastricht.

Eikhout, S.M., Bronkhorst, R.E. and Grinten, M.P. van der, 2001. Evaluation of a new scraper. Proceedings of the 45th HFES congress 2001, Minneapolis (US): HFES: CD rom: 722-726.

Eikhout, S.M., Bronkhorst, R.E., Vink, P., Grinten, M.P., van der, 2005a. Towards a comfortable paint scraper. In: Comfort and design; principles and good practice. Vink, P. (ed.) CRC Press, Boca Raton. 181-191.

Eikhout, S.M., Vink, P., Grinten, M.P. van der, 2005b. Comfort effects of participatory design of screwdrivers. In: Comfort and design; principles and good practice. Vink, P. (ed.) CRC Press, Boca Raton. 207-217.

Eksioglu, M., 2004. Relative optimum grip span as a function of hand anthropometry. International Journal of Industrial Ergonomics, 34 (1): 1-12.

Fellows, G.L., Freivalds, A., 1991. Ergonomics evaluation of a foam rubber grip for tool handles. Applied Ergonomics, 22 (4): 225-230.

Floyd, W.F. and Roberts, D.F., 1958. Anatomical and physiological principles in chair and table design. Ergonomics, 2: 1-16.

Fransson-Hall, C. and Kilbom, Å., 1993. Sensitivity of the hand to surface pressure. Applied Ergonomics, 24 (3): 181-189.

Freund, J., Takala, E-P., Toivonen, R., 2000. Effects of two ergonomics aids on the usability of an in-line screwdriver. Applied Ergonomics, 31 (4): 371-376.

Gerrits A., Jones C.L., Valero R., 2004. Custom-Fit: A knowledge-based manufacuring system enabling the creation of custom-fit products to improve the quality of life. Rapid Product Development 2004, Paper 4004, 12th October 2004, Centimfe, Portugal.

Goonetilleke, R.S., 1998. Designing to minimize discomfort. Ergonomics in Design, 6: 12-19.

Griffin, A. and Hauser, J.R., The voice of the customer. Marketing Science, 12: 1-27.

Groenesteijn, L., Eikhout, S.M., Vink, P., 2004. One set of pliers for more tasks in installation work: the effects on (dis)comfort and productivity. Applied Ergonomics, 35 (5): 485-492.

Haapalainen, M., Kivistö-Rahnasto, J., Mattila, M., 1999/2000. Ergonomic design of non-powered hand tools : An application of quality function deployment (QFD). Occupational Ergonomics, 2 (3): 179-189.

Habes, D.J. and Grant, K.A., 1997. An electromyographic study of maximum torques and upper extremity muscle activity in simulated screwdriving tasks. International Journal of Industrial Ergonomics, 20 (4): 339-346.

Hammarskjöld, E. and Harms-Ringdahl, K., 1992. Effect of arm-shoulder fatigue on carpenters at work. European Journal of Applied Physiology, 64: 402-409.

Hauser, J., Clausing, D., 1988. The House of Quality; Design is a team effort, but how do marketing and engineering talk to each other? Harvard Business Review, 66 (3) May-June: 63-73.

Helander, M.G., Czaja, S.J., Drury, C.G., Cary, J.M., Burri, G., 1987. An ergonomic evaluation of office chairs. Office: Technology and People, 3: 247-262.

Helander, M.G. and Zhang, L., 1997. Field studies of comfort and discomfort in sitting. Ergonomics, 40 (9): 895-915.

Hertzberg, H.T.E., 1958. Seat comfort in: R. Hansen, D.R. Cnrnog and H.T.E. Hertzberg (eds.) Annotated Bibliography of Applied Physical Anthropology in Human Engineering, WADC Technical report 56-30. Wright-Patterson Airforce Based, Dayton. 297-300.

Hsu, S-H. and Chen, Y-H., 2000. Evaluation of bent-handled file handles. International Journal of Industrial Ergonomics, 25 (1): 1-10.

Jensen, C.V. and Bendix, T. 1992. Spontaneous movements with various seated-workplace adjustments. Clinical Biomechanics, 7 (2): 87-90.

Jianghong, Z. and Long, T., 1994. An evaluation of comfort of a bus seat. Applied Ergonomics, 25 (6): 386-392.

Johansson, L., Kjellberg, A., Kilbom, A., Hagg, G., 1999. Perception of surface pressure applied to the hand. Ergonomics, 42 (10): 1274-1282.

Jung, M-C. and Hallbeck, S., 2000. Ergonomic redesign of a commercial tool handle. In: Ergonomics for the New Millennium. Proceedings of the IEA 2000/HFES 2000 congress. San Diego, 28 July- 4 August, 2000: 4-570-4-573.

Kadefors, R., Areskoug, A., Dahlman, S., Kilbom, Å., Sperling, L., Wikström, L., Öster, J. 1993. An approach to ergonomics evaluation of hand tools. *Applied Ergonomics.* 24 (3): 203-211.

Kamijo, K., Tsujimara, H., Obara, H., Katsumatu, M., 1982. Evaluation of seating comfort. SAE Technical Paper Series 820761. 1-6.

Karwowski, W., 2001. International encyclopedia of ergonomics and human factors. Vol II. Taylor and Francis, New York.

Kee, D. and Karwowski, W., 2001. The boundaries for joint angle of isocomfort for sitting and standing males based on perceived comfort af static joint postures. Ergonomics, 44 (6): 614-648.

Kee, D. and Karwowski, W., 2003. Ranking systems for evaluation of joint and joint motion stressfulness based on perceived discomfort. Applied Ergonomics, 34 (2): 167-176.

Kilbom, Å., Mäkäräinen, M., Sperling, L., Kadefors, R., Liedberg, L. 1993. Tool design, user characteristics and performance: a case study on plate-shears. Applied Ergonomics, 24 (3): 221-230.

Kleeman, W., 1981. The challenge of interior design. CBI, Boston.

Kluth, K., Kelermann, H.G., Strasser, H., 2004. Assessment of the ergonomic quality of file handles using electromyographic and subjective methods. Occupational Ergonomics, 4 (2): 133-142.

Kolich, M. and Taboun, S.M., 2002. Combining psychophyscial measures of discomfort and electromyography for the evaluation of a new automotive seating concept. International Journal of Occupational Safety and Ergonomics, 8: 483-496.

Kong, Y-K and Freivalds, A., 2003. Evaluation of meat-hook handle shapes. International Journal of Industrial Ergonomics, 32 (1): 13-23.

Kong, Y.K. and Lowe, B.D., 2004. Evaluation of handle diameter in maximum horizontal and vertical torque tasks. Proceedings of the Human Factors and Ergonomics Society 48th annual meeting. New Orleans, 20-24 September, 2004. 1295-1299.

Kuijt-Evers, L.F.M. and Eikhout, S.M., 2006. Development process of a new masoner's trowel. In: Meeting Diversity in Ergonomics, Pikaar R.N., Koningsveld, E.A.P., Settels, P.J.M. (Eds). Proceedings IEA2006 Congress. Oxford: Elsevier, 2006. CD-rom: art0571.

Lee, K.S., Waiker, A.M., Wu, L., 1988. Physical stress evaluation of microscope work using objective and subjective methods. International Journal of Industrial Ergonomics, 2 (3): 203-309.

Lee, K.S., Ferraiuolo, P., Temming, J., 1993. Measuring seat comfort.Automotive Engineering, 101: 25-30.

Lappänen, M., Mattila, M., Kivistö-Rahnasto, J., 2000. Designing the ergonomic properties of pruning shears using quality function deployment (QFD). In: Ergonomics for the New Millennium. Proceedings of the IEA 2000/HFES 2000 congress. San Diego, 28 July- 4 August, 2000: 3-647-3-650.

Lewis, W.G. and Narayan, C.V., 1993. Design and sizing of ergonomic handles for hand tools. Applied Ergonomics, 24 (5): 351-356.

Looze, M.P. de, Kuijt-Evers, L.F.M., Dieën, J. van, 2003. Sitting comfort and discomfort and the relationships with objective measures. Ergonomics, 46 (10): 985-997.

Marsot, J. and Claudon, L., 2004. Design and ergonomics. Methods for integrating ergonomics at hand tool design stage. International Journal of Occupational Safetey and Ergonomics, 10 (1): 13-23.

Marsot, J., 2005. QFD: a methodological tool for integration of ergonomics at the design stage. Applied Ergonomics, 36 (2): 185-192.

McGorry, 2001. A system for the measurement of grip forces and applied moments during hand tool use. Applied Ergonomics, 32 (3): 271-279.

McGorry, R.W., Dowd, P.C., Dempsey, P.G., 2003. Cutting moments and grip forces in meat cutting operations and the effect of knife sharpness. Applied Ergonomics, 34 (4): 375-382.

McGorry, R.W., Dowd, P.C., Dempsey, P.G., 2005. The effect of blade finish and blade edge angle on forces used in meat cutting operations. Applied Ergonomics, 36 (1): 71-77.

Mital., A. and Kilbom, A., 1992a. Design, selection and use of hand tools to alleviate trauma of the upper extremities: Part I – Guidelines for the practioner. International Journal of Industrial Ergonomics, 10 (1-2): 1-7.

Mital., A. and Kilbom, A., 1992b. Design, selection and use of hand tools to alleviate trauma of the upper extremities: Part II – The scientific basis (knowledge base) for the guide. International Journal of Industrial Ergonomics, 10 (1-2): 7-21.

Mitsufuji, Y. and Uchida, T. 1990. Using and promoting House of Qualitys. In: Quality Function Deployment; Integrating customer requirements into product design. Akao, Y. (ed.) Productivity Press, Cambridge. 53-81.

Niemellä, T., Leppänen, M., Päivinen, M., Mattila, M., 2000. Evaluation of an experimental testing system for non-powered hand tools. In: Ergonomics for the New Millennium. Proceedings of the IEA 2000/HFES 2000 congress. San Diego, 28 July- 4 August, 2000: 3-643-3-646.

O'Meara, D.M. and Smith, R.M., 2002. Functional hand grip test to determine the coefficient of static friction at the hand/handle interface. Ergonomics, 45 (10): 717-731.

Päivinen, M. and Heinimaa, T., 2004. The effects of different hand tool blade coatings on force demands when cutting wood. International Journal of Industrial Ergonomics. 32 (3): 139-146.

Päivinen, M., Haapalainen, M., Mattila, M., 1999/2000. Ergonomic design criteria of pruning shears. Occupational Ergonomics, 2 (3): 163-177.

Pullman, M., More, W., Wardell, D., 2002. A comparison of quality function deployment and conjoint analysis in new product design. The Journal of Product Innovation Management, 19 (5): 354-364.

Radwin, R.G. and Haney, J.T., 1996. An ergonomics guide to hand tools. American Industrial Hygiene Association, Fairfax.

Richards, L.G., 1980. On the psychology of passenger comfort. In: Human factors in Transport Research; Proceedings, volume 2 , user factors, comfort, the environment and behaviour; Oborne, D.J. Levis, J.A. (eds.), Swansea, September 1980. Academic Press, New York. 15-23.

Roozenburg, N.F.M. and Eekels, J., 1995. Product design: Fundamentals and methods. John Wiley & Sons, Chichester.

Signo, J.L. and Jackson, S.C., 1999. History of hand tools. In: Ergonomics and safety in hand tool design. Cach, C.A. (ed.). CRC Press, Boca Raton.

Shackel, B., Chidsey, K.D., Hipley, P., 1969. The assessment of chair comfort. Ergonomics. 12: 269-306.

Shih, Y-C and Wang, M-J., 1996. Hand/tool interface effects on human torque capacity. International Journal of Industrial Ergonomics, 18 (2-3): 205-213.

Slater, K., 1985. Human comfort. Thomas C.G., Springfield.

Sperling, L., Dahlman, S., Wikström, L., Kilbom, Å., Kadefors, R. 1993. A cube model for the classification of work with hand tools and the formulation of functional requirements. Applied Ergonomics. 24 (3), 212-220.

Sperling, L. and Olander, E., 2004. Visual experience of qualities in photo-representations of tool handles; studies with non-professional and professional subjects. In: Human factors in design. Waard, D. de, Brookhuis, K.A., Weikert, C.M. (eds.) Shaker Publishing, Maastricht.

Strasser, H., Wang, B., Hoffmann, A., 1996. Electromyography and subjective evaluation of hand tools: The example of masons' trowels. International Journal of Industrial Ergonomics, 18 (1): 91-106.

Sullivan, L.P. 1986. A system to assure that customer needs drive the product design and production process. Quality Progress, 39-50.

Thakurta, K., Koester, D., Bush, N., Bachle, S., 1995. Evaluating short and long term seating comfort. SAE-paper 950144: 33-37.

Vergara, M. and Page, A. 2000. System to measure the use of the back rest in sitting-posture office tasks. Applied Ergonomics, 31 (3): 247-254.

Vink, P., Overbeeke, C.J., Desmet, P.M.A., 2005a, Comfort experience. In: Comfort and design; principles and good practice. Vink, P. (ed.). CRC Press, Boca Raton. 1-12.

Vink, P. Looze, M.P. de and Kuijt-Evers, L.F.M., 2005b. Theory of comfort. In: Comfort in Design; principles and good practice. Vink, P. (ed.). CRC Press, Boca Raton. 13-32.

Vink, P. Nichols, S., Davies, R.C., 2005c. Participatory ergonomics and comfort. In: Comfort in Design; principles and good practice. Vink, P. (ed.). CRC Press, Boca Raton. 41-54.

Visser, J., König, T., Ruiter, I., Vink, P., 2005. Development of a handheld steelfixing tool. In: Comfort and design; principles and good practice. Vink, P. (ed.). CRC Press, Boca Raton. 193-206.

Wilder, D., Magnusson, M.L., Pope, M., 1994. The effect of posture and seat suspension design on discomfort and back muscle fatigue during simulated truck driving. Applied Ergonomics, 25 (2): 66-76.

Wilson, J.R. and Haines, H.M., 2001. Participatory Ergonomics. In: International encyclopedia of ergonomics and human factors.Vol. 2. Karwowski, W. (ed). Taylor and Francis, London. 1282-1286.

Wilson, J. and Morris, W., 2004. Participatory design of work equipment: lessons learned and suggestions for future actions. TUTB Newsletter. No 24-25: 22-25. Available from http://tutb.etuc.org.

Wu, S-P. and Hsieh, C-S., 2002. Ergonomics study on the handle length and lift angle for the culinary spatula. Applied Ergonomics, 33 (5): 493-501.

Yun, M.H., Kotani, K., Ellis, D., 1992a. Using force sensitive resistors to evaluate hand tool grip design. Proceedings of the Human Factors Society 36th annual meeting. Atlanta, 12-16 October, 1992: 806-810.

Yun, M.H., Donges, L., Freivalds, A., 1992b. Using force sensitive resistors to evaluate the driver seating comfort. In: Advances in Industrial Ergonomics and Safety IV. Kumar, S. (ed). Taylor and Francis, London. 403-410.

You, H., Kumar, A., Young, R., Veluswamy, P., Mahlzahn, D.E., 2005. An ergonomic evaluation of manual cleco plier designs: Effects of rubber grip, spring recoil, and worksurface angle. Applied Ergonomics, 36 (5): 575-583.

Zhang, L., Helander, M.G., Drury, C.G., 1996. Identifying factors of comfort and discomfort in sitting. Human factors, 38 (3): 377-389.

Identifying factors of comfort and discomfort in using hand tools

Chapter 3

Chapter 3

Abstract

To design comfortable hand tools, knowledge about comfort/discomfort in using hand tools is required. We investigated which factors determine comfort/discomfort in using hand tools according to users. Therefore, descriptors of comfort/discomfort in using hand tools were collected from literature and interviews. After that, the relatedness of a selection of the descriptors to comfort in using hand tools was investigated. Six comfort factors could be distinguished (functionality, posture and muscles, irritation and pain of hand and fingers, irritation of hand surface, handle characteristics, aesthetics). These six factors can be classified into three meaningful groups: functionality, physical interaction, and appearance. The main conclusions were that 1) the same descriptors were related to comfort and discomfort in using hand tools, 2) descriptors of functionality are most related to comfort in using hand tools followed by descriptors of physical interaction and 3) descriptors of appearance become secondary in comfort in using hand tools.

3 Identifying factors of comfort in using hand tools

3.1 Introduction

The use of hand tools (like screwdrivers, pliers, and scrapers) frequently leads to feelings of discomfort during work. These feelings of discomfort can reduce efficiency and job satisfaction of workers (Fellows and Freivalds, 1991). On a longer term, the use of hand tools can also cause musculoskeletal disorders (Aghazadeh and Mital, 1987; Chao et al., 2000). For these reasons, employers are interested in comfortable hand tools for their employees. Meanwhile, manufacturers recognize comfort as a major selling point, as it is thought to play an increasingly important role in product buying decisions. Therefore, they pay more attention to the design of comfortable hand tools, which reduce the risk of occupational injury and result in high product quality for customers, and of course, comfort for users. The major question here is, how to design hand tools that are characterized by much comfort for the user. Therefore, a clear definition of the concept of comfort is important to the designer, as well as knowledge about which factors contribute to the comfort of the end-user.

Despite the frequent use of the term, there is no widely accepted definition of comfort. Webster's dictionary defines comfort as a state or feeling of having relief, encouragement and enjoyment. Slater (1985) defines comfort as a pleasant state of physiological, psychological and physical harmony between a human being and its environment. Richards (1980) stresses that comfort is a state of a person involving a sense of subjective well-being, in reaction to an environment or situation. However, some issues are generally accepted (Looze et al., 2003): (1) comfort is a construct of a subjectively defined personal nature; (2) comfort is affected by factors of a various nature (physical, physiological, psychological); and (3) comfort is a reaction to the environment. An on-going debate in literature is about the differences between comfort and discomfort. Comfort and discomfort have been considered as two discrete states (Hertzberg, 1958; Branton, 1969), as two opposites on a continuous scale (e.g., Vergare and Page, 2000; Jianghong and Long, 1994; Wilder et al., 1994; Jensen and Bendix, 1992), and as two separate entities underlied by different factors (Zhang et al., 1996). With respect to the latter, it was found for office seats that physical factors underlie discomfort while comfort was associated with feelings of relaxation and well-being (Zhang et al. 1996).

The comfort theories described above are mostly based on studies on comfort in sitting. However, knowledge is lacking about comfort in using hand tools. The underlying factors of comfort and discomfort in using hand tools, as well as their relative importance, are unknown. Until now, several objective measures are in use to evaluate hand tools -e.g., muscle activity (EMG) (Fellows and Freivalds, 1991; Freund et al., 2000; Habes and Grant, 1997; Niemelä et al., 2000; Chang et al., 1999; Kadefors et al., 1993), grip force distribution and grip force (Fellows and Freivalds, 1991; Chao et al., 2000; Niemelä et al., 2000; Chang et al., 1999), and hand-wrist postures (Chao, 2000; Eikhout et al., 2001; Kadefors et al., 1993)- but their relationships with the user's comfort experience are generally unknown.

The aim of the current study was to find the factors that influence the comfort of end-users of hand tools. In order to achieve this goal, descriptors related to comfort/discomfort in using hand tools were collected and their relative importance was determined. Furthermore, the descriptors were classified into factors to see if these factors can be divided into meaningful groups.

3.2 Methods

To answer the research question two studies were performed. In the pre-study all possible descriptors of comfort and discomfort were collected and a first selection was made. In the main study the relationship between the descriptors and comfort was studied.

3.2.1 Pre-study

The aim of the pre-study was (1) to compose a 'complete' list of descriptors that could possibly underlie comfort and discomfort and (2) to find out whether different descriptors would underlie comfort and discomfort (as previously found for office seats (Zhang et al., 1996)) or not. The pre-study consisted of three steps.

First, we collected all possible, comfort and discomfort underlying descriptors that were mentioned in the literature. In Ergonomic Abstracts we searched for papers containing 'hand tools', 'comfort', 'discomfort', 'ergonomics AND tools', 'usability AND tools', 'user-experience AND tools', 'satisfaction AND tools'. From these papers, all possible descriptors of comfort and discomfort were selected. Synonyms and descriptors with almost the same meaning as well as descriptors of the environment or task in using hand tools, and descriptors of tool specific characteristics were left out.

In the second step, we asked 11 experienced users to describe their feelings when experiencing comfort (Group A: n=11) when using screwdrivers and pliers. Another 11 subjects (Group B) were asked to do the same for discomfort experience. All these subjects were recruited as a volunteer, while they visited a Do-It-Yourself (DIY) or ironmonger's shop. The group comprised 11 DIY and 11 professional hand tool users.

In the third step, we asked the same hand tool users to rate on a three point scale if the descriptors selected from literature were related to comfort (group A)/discomfort (group B) or not (1= related to (dis)comfort, 2 = not related to (dis)comfort, 3 = don't know). If a large majority of the subjects find a descriptor related to comfort/discomfort, we think it is a meaningful descriptor. We decided to select descriptors which were mentioned by more than 70% of the subjects as related to comfort/discomfort for the main study (like Zhang et al., 1996).

3.2.2 Main study

The aim of the main study was to 1) determine the relationship between the descriptors collected in the pre-study and comfort in using hand tools and 2) to classify the descriptors into factors to see if they can be divided into meaningful groups. We decided not to treat comfort and discomfort as two different constructs as from the pre-study was seen that the same descriptors were mentioned as being related to comfort and discomfort (see results section).

A convenience sample was obtained through approaching visitors of several Do-It-Yourself (DIY) and ironmonger's shops. Similar to the pre-study, only visitors who frequently use screwdrivers or pliers were included in this study. The respondents got informed about the study. Fifty hand tool users filled in the questionnaire (45 male and 5 female, mean age 43.4 years ± 14.0). The respondents were split up into two groups: DIY and professional users, both counting for 25 respondents.

First some standard information was given: *'This questionnaire is about comfort in using hand tools. Comfort in using hand tools occurs when using a hand tool gives a state or feeling of having relief, encouragement and enjoyment. Imagine you are working intensively for eight hours a day with a screwdriver/pliers. How are the next descriptors and statements related to comfort in using screwdrivers/pliers? 1) very closely related, 2) closely related 3) slightly related, 4) not related, 5) don't know)'.* After that, the respondents rated the descriptors in terms of comfort on the five point scale.

3.2.3 Data analysis

In the pre-study, the Mann-Whitney-U test was used to see if descriptors were rated differently between respondents who filled in the comfort questionnaire and the discomfort questionnaire.

In the main study, the Mann-Whitney-U test was used to analyse if there were differences between the ratings of DIY and professional users, and between screwdrivers and pliers. After that, the descriptors were ranked on mean ranks of their rating score (as used in Friedman-test). If the subjects rated 5 (don't know) this was regarded as a missing value. For classification of the descriptors into factors, Principal Components Analysis (PCA) with varimax rotation was used.

3.3 Results

3.3.1 Pre-study

From the literature search, several papers were found. Studies were selected on their relevance by reading the abstracts. Finally, 25 studies were used (Berguer et al., 1999; Björing et al., 2002; Chaffin et al., 1999; Chang and Wang, 2000; Chang et al., 1999; Chao et al., 2000; Ciriello et al., 2001; Fransson-Hall and Kilbom, 1993; Freund et al., 2000; McGorry, 2001; Gurram et al., 1995; Habes and Grant, 1997; Johansson et al., 1999; Kim and Kim, 2000; Kumar et al., 1999; Liao and Drury, 2000; Lin et al., 2001; Lowe and Freivalds, 1999; Matern, 2001; Niemelä et al., 2000; Rose et al., 2000; Smith et al., 2000; Spielholz et al., 2001; Wakula and Landau, 2000a; Wakula et al., 2000b). From these studies, 58 descriptors of comfort and discomfort in using hand tools were selected.

From the user interviews, we found that none of the respondents did add any new descriptors to the list of descriptors we found from literature. Furthermore, no significant differences in rating of the 58 descriptors were found between respondents who completed the comfort questionnaire and the discomfort questionnaire. Therefore, it is assumed that comfort and discomfort have the same underlying descriptors in using hand tools.

For the main study, we selected 36 descriptors based on the 70%-criterion. We added another four descriptors (professional look, styling, nice colour and solid design) although they did not fit the 70%-criterion in the pre-study. Nevertheless, we decided to add these descriptors to our list as they were found to be strongly related to comfort in a previous study (Zhang et al., 1996). The descriptors which were left out were descriptors of general feelings (e.g., satisfied, happy, proud, bored, relaxed, cheerful, tired), descriptors of the appearance (e.g., nice appearance, the tool looks like it is comfortable to work with, luxurious) and others (e.g. tool distracts worker from task, the tool is all-weather proof). Finally, 40 descriptors were selected for the main study.

3.3.2 Main study

From the main study, we found that DIY and professional users can be regarded as one sample, because no significant differences were found between DIY and professional users except for two descriptors. DIY users considered that 'no irritation of tissue' and 'no pain' are more related to comfort in using hand tools than professional users. The type of hand tool (pliers or screwdrivers) also did not result in significant differences in rating, except for two descriptors. Users who completed the pliers questionnaire thought 'good fit in hand' and 'easy to take along' are more related to comfort than respondents who filled in the screwdriver questionnaire. As only two out of forty descriptors are rated significantly different between screwdrivers and pliers, we also consider the data of screwdrivers and pliers as one set. As a result, we used one sample of n=50 for further analysis.

Table 3.1 shows the ranking of the descriptors based on mean ranks of the rating score. From this table is seen that descriptors such as reliable, functional, good fit in hand, and easy in use are most related to comfort in using hand tools according to the users (mean ranks from 14.68 to 25.99). Descriptors such as solid design, professional look, styling, and nice colour are less related to comfort (mean ranks from 32.56 to 37.69).

Table 3.1 Ranking of descriptors based on mean ranks (MR)

Descriptor	MR	Descriptor	MR
1 Reliable	14.68	21 No irritation	19.20
2 Functional	15.45	22 Handle shape	19.27
3 Good fit in hand	15.67	23 Sharpness	19.27
4 Easy in use	15.99	24 Pleasurable	19.63
5 Force exerted from tool	16.10	25 No inflamed skin	19.69
6 No blisters	16.33	26 No slippery handle	19.81
7 Safe	16.39	27 Relaxed working posture	20.48
8 No pain	16.51	28 No sore muscles	20.50
9 Handle feels comfortable	16.59	29 Weight of tool	22.32
10 No peak pressures on hand	16.65	30 Handle size	22.50
11 High quality tool	16.82	31 No sweaty hands	22.53
12 High product quality	17.20	32 Easy to take along	22.73
13 Task performance	17.20	33 No pressure on hand	22.76
14 No body part discomfort	17.44	34 Roughness of handle surface	22.85
15 Lack of tactile feeling	17.70	35 Handle doesn’t feel clammy	23.30
16 Friction between hand and handle	18.16	36 Handle hardness	23.66
17 No muscle cramp	18.40	37 Solid design	32.56
18 Low hand grip force	18.43	38 Professional look	33.97
19 No numbness in fingers	18.73	39 Styling	36.03
20 Comfortable working posture	18.80	40 Nice colour	37.69

With the PCA with varimax rotation, the descriptors were classified in 12 major factors with eigenvalues greater than 1. Table 3.2 shows the factor loadings. The first six factors explain 53.8% of the internal variance. The other six factors are hard to interpret as the underlying descriptors do not logically match. Besides, these factors explain less variance (27.6%) than the first six factors. For these reasons, factor 7 to factor 12 are not further mentioned.

The first factor contains descriptors as reliable, functional, task performance, ease in use, safe, etc. We labelled this factor *functionality*. The second to the fifth factor correspond to the physical interaction between user and hand tool: *posture and muscles* (factor 2), *irritation and pain of hand and fingers* (factor 3), *irritation of hand surface* (factor 4), and *handle characteristics* (factor 5). The sixth factor is about the *aesthetics*, containing descriptors such as professional look, styling, nice colour, and solid looks.

Table 3.2 Factor loadings of the descriptors (PCA with varimax rotation) only the factor loadings >0.4 are shown: factor 1 (*functionality*), factor 2 (*posture and muscles*), factor 3 (*irritation and pain of fingers*), factor 4 (*irritation of hand surface*), factor 5 (*handle characteristics*), factor 6 (*aesthetics*).

Descriptors	**Factor 1**	**Factor 2**	**Factor 3**	**Factor 4**	**Factor 5**	**Factor 6**
Reliable	0.937					
Functional	0.897					
Task performance	0.768					
Easy in use	0.756					
Safe	0.668					
High product quality	0.553					
Easy to take along	0.520		-0.405			
Handle feels comfortable	0.491					
No muscle cramp		0.894				
Relaxed working posture		0.837				
No sore muscles		0.832				
Handle hardness		0.536				
Low hand grip force supply		0.522				
No blisters			0.829			
No lack of tactile feeling			0.786			
No irritation			0.785			
No numbness in fingers		0.409	0.737			
No pain			0.656	0.435		
No peak pressure on hand				0.817		
Handle doesn't feel clammy		0.498		0.586		
No inflamed skin				0.436		
Handle shape					0.884	
Roughness of handle surface					0.721	
Friction between hand and handle				0.483	0.667	
Styling						0.775
Nice colour						0.763
Professional look						0.763
Solid design						0.545

3.4 Discussion

The aim of this study was to find the underlying factors of comfort and discomfort in using hand tools and their relative importance according to the user. From the pre-study was seen that descriptors of general feelings (e.g., satisfied, happy, proud) and aesthetics (nice appearance, luxurious) are not related to comfort/discomfort according to the hand tool users. The pre-study also showed that the same descriptors were related to comfort and discomfort. Therefore, we decided not to treat comfort and discomfort as different constructs, but to look at comfort and discomfort as one general concept. The main study showed that the descriptors of the factor *functionality* are most related to comfort and the descriptors of the factor *aesthetics* are least related to comfort in using hand tools.

In the main study, hand tool users rated the relationship of 40 descriptors with comfort in using hand tools. They were asked to make their judgement imagining working with screwdrivers/pliers. We decided that they should not see or use a screwdriver or pliers at that moment, because we thought the respondents' opinion could be influenced by the very specific characteristics of one particular screwdriver or pliers. Instead, we wanted them to think about screwdrivers or pliers in general terms. Consequently, they used their own experience and imagination as reference. The effect may be that respondents consider, for example, 'nice colour' as not related to comfort in using hand tools. This does not mean that 'nice colour' can be ruled out as a relevant factor in hand tool design. In fact, if the colour is not a standard (not fitting the user's expectation) the colour possibly influences the user's comfort.

A major difference exists between the results of our study and the results of the study of Zhang et al. (1996). Zhang et al. (1996) concluded that comfort and discomfort in sitting are based on independent factors with different underlying determinants. They found that physical aspects such as ache, circulation legs cut off, cramped, fatigue, pressing, stiff, unsupported etc. underlie discomfort, while comfort was related to relaxation and well-being with underlying descriptors such as: at ease, calm, content, luxurious, pleasant, supported, warm, etc. We found descriptors of discomfort (e.g., muscle cramp, sore muscles, blisters, etc.) are also related to comfort. This could be explained by the different nature of seats and hand tools. Unlike sitting, the use of hand tools is mostly accompanied by discomfort. Helander and Zhang (1997) argue that when discomfort factors are present, comfort factors become secondary in the perception of comfort/discomfort. Because discomfort factors are present in hand tool use, comfort may be dominated by discomfort. Therefore, respondents may also think of comfort in using hand tools in terms of absence or reduction of discomfort. Our results are illustrated by several hand tool evaluation studies in which comfort is measured in terms of discomfort (Chao et al., 2000; Fellows and Freivalds, 1991). From this, comfort and discomfort in using hand tools can be seen as two opposites on a continuous scale, as subscribed by Vergare and Page (2000), Jianghong and Long (1994), Wilder et al. (1994) and Jensen and Bendix (1992). Additionally, our methods differed from Zhang et al. (1996) due to not seeing the hand tools while rating the descriptors. This may also explain the difference between our results and the results from Zhang et al. (1996).

Some similarities can be seen between comfort research and product satisfaction research. The evaluation of comfort/discomfort is mostly based on cognitive judgments. In product satisfaction theories it is assumed that cognitive judgment consists of two major dimensions: (1) utilitarian performance, whereby the product is seen as performing a useful function and (2) hedonic performance, whereby products are valued for their intrinsically pleasing properties (Mano and Oliver, 1993). Based on the PCA with varimax rotation these two groups can also be distinguished in our study, where factor 1 (*functionality*) belongs to the utilitarian performance and factor 2 to factor 6 (*posture and muscles, irritation and pain of hand and fingers, irritation of hand surface, handle characteristics, aesthetics*) to hedonic performance. Within the group of hedonic performance factors the relatedness to comfort varies: factors 2 to 5 are much more related to comfort in using hand tools than factor 6. Therefore, it seems not meaningful to consider these factors as one group. We propose another classification for comfort in using hand tools, which consists of three groups: *functionality* (consisting of the descriptors of factor 1), *physical interaction* (factor 2 to 5) and *appearance* (factor 6).

From the PCA in combination with the ranking of the descriptors is seen that *functionality* is more related to comfort in using hand tools than *physical interaction*. Descriptors of *appearance* are slightly or not at all related to comfort in using hand tools. This is in contradiction with the results of Zhang et al. (1996) who found that aesthetics is an important underlying factor of comfort in sitting. Maybe the relevance of aesthetic aspects depends on the kind of product and the task which is performed with the product. The use of hand tools is mostly accompanied by feelings of discomfort. The dominant effect of discomfort maintained by Helander and Zhang (1997) can explain that aesthetics is less related to comfort in using hand tools. When discomfort factors are present, a hand tool will not be comfortable just by a nice appearance. First discomfort in using hand tools must be avoided or reduced by optimization of the functionality and physical interaction. After that, appearance may contribute to comfort in using hand tools. Besides, aesthetics of hand tools may play an important role in buying decisions or in choosing between hand tools of the same kind with common functionality and physical interaction.

3.5 Conclusion

The results of this study contribute to the discussion of the difference between comfort and discomfort. We argued that in using hand tools comfort and discomfort could be seen as two opposites on a continuous scale, because we found the same descriptors underlie comfort and discomfort. Based on the difference between our study about comfort factors in using hand tools and the study of Zhang et al. (1996) about comfort factors in sitting, we discussed that the theory of the difference between comfort and discomfort depends on the kind of product. Furthermore, the results of our study show that functionality is most related to comfort in using hand tools, followed by physical interaction and appearance. These results can be of help in the design of comfortable hand tools. In addition, the results give us input to develop a questionnaire to evaluate comfort in using hand tools.

3.6 References

Aghazadeh, F., Mital, A., 1987. Injuries due to hand tools; results of a questionnaire. Applied ergonomics, 18 (4): 273-278.

Berguer, R., Gerber, S., Kilpatrick, G., Remler, M., Beckley, D., 1999. A comparison of forearm and thumb muscle electromyographic responses of the use of laparoscopic instruments with either a finger grasp or a palm grasp. Ergonomics, 42 (12): 1634-1645.

Björing, G., Johansson, L., Hägg, G., 2002. Surface pressure in the hand when holding a drilling machine under different drilling conditions. Applied Ergonomics, 29 (5): 255-261.

Branton, P. 1969, Behavior, body mechanics and discomfort. Ergonomics, 12 (2): 316-327.

Chaffin, D.B., Andersson, G.B.J., Martin, B.J., 1999. Occupational biomechanics. 3rd edition, John Wiley & Sons, Inc., New York.

Chang, H.H., Wang, M.J..J., 2000. Evaluating factors that influence hand-arm stress while operating an electric screwdriver. Applied Ergonomics, 31 (3): 283-289.

Chang, S.R., Park, S., Freivalds, A., 1999. Ergonomic evaluation of the effects of handle types on garden tools. International Journal of Industrial Ergonomics, 24 (1): 99-105.

Chao, A., Kumar, A.J., Emery, C.T.N.D., Nagarajarao, K., You, H., 2000. An ergonomic evaluation of cleco pliers. In: Ergonomics for the New Millennium. Proceedings of the IEA 2000/HFES 2000 congress. San Diego, 28 July- 4 August, 2000: 4-441-4-442.

Ciriello, V.M., Snook, S.H., Webster, B.S., 2001. Psychophysical study of six hand movements. Ergonomics, 44 (10): 922-936.

Eikhout, S.M., Bronkhorst, R.E. and Grinten, M.P. van der., 2001. Evaluation of a new scraper. Proceedings of the 45th HFES congress 2001, Minneapolis (US): HFES: CD rom: 722-726

Fellows, G.L., Freivalds, A., 1991. Ergonomics evaluation of a foam rubber grip for tool handles. Applied Ergonomics, 22 (4): 225-230.

Fransson-Hall, C. Kilbom, A., 1993. Sensitivity of the hand to surface pressure. Applied Ergonomics, 24 (3): 181-189.

Freund, F., Takala, E.P., Toivonen, R., 2000. Effects of two ergonomic aids on the usability of an in-line screwdriver. Applied Ergonomics, 31 (4): 371-376.

Gurram, R., Rakheja, S., Gouw, G.J., 1995. A study of hand grip pressure distribution and EMG of finger flexor muscles under dynamic loads. Ergonomics, 38 (4): 684-699.

Habes, D.J., Grant, K.A., 1997. An electromyographic study of maximum torques and upper extremity muscle activity in simulated screwdriving tasks. International Journal of Industrial Ergonomics, 20 (4): 339-346.

Helander, M.G., Zhang, L., 1997. Field studies of comfort and discomfort in sitting. Ergonomics, 40 (9): 895-915.

Hertzberg, H.T.E., 1958. Seat comfort. In: Annotated Bibliography of Applied Physical Anthropology in Human Engineering, Hansen, R., Cnrnog, D.R. and Hertzberg, H.T.E. (eds). WADC Technical report 56-30. Wright-Patterson Airforce Based, Dayton. 297-300.

Jensen, C.V. and Bendix, T. 1992. Spontaneous movements with various seated-workplace adjustments. Clinical Biomechanics, 7 (2): 87-90.

Jianghong, Z., Long, T., 1994. An evaluation of comfort of a bus seat. Applied Ergonomics, 25 (6): 386-392.

Johansson, L., Kjellberg, A., Kilbom, A., Hagg, G., 1999. Perception of surface pressure applied to the hand. Ergonomics, 42 (10): 1274-1282.

Kadefors, R., Areskoug, Al, Dahlman, S., Kilbom, Å., Sperling, L., Wikström, L., Öster, J., 1993. An approach to ergonomic evaluation of hand tools. Applied Ergonomics, 24 (3): 203-211.

Kim, C.H., Kim, T.K., 2000. Maximum torque exertion capabilities of Korean at varying body postures with common hand tools. In: Ergonomics for the New Millennium. Proceedings of the IEA 2000/HFES 2000 congress. San Diego, 28 July- 4 August, 2000: 3-175-3-160.

Kumar, S., Narayan, Y, .,Bjornsdottir, S, 1999. Comparison of the sensitivity of three psychochophysical techniques to three materials handling task variables. Ergonomics, 42 (1): 61-73.

Liao, M.H., Drury, C.G., 2000. Posture discomfort and performance in a VDT task, Ergonomics, 43 (3): 345-359.

Lin, J.H., Radwin, R.G., Richard, T.G., 2001. Dynamic biomechanical model of the hand and arm in pistol grip power hand tool usage, Ergonomics, 44 (3): 295-312.

Looze, M.P. de, Kuijt-Evers, L.F.M., Dieën, J. van, 2003. Sitting comfort and discomfort and the relationships with objective measures. Ergonomics, 46 (10): 985-997.

Lowe, B.D., Freivalds, A., 1999. Effect of carpal tunnel syndrome on grip force coordination on hand tools. Ergonomics, 42 (1): 550-564.

Mano, H., Oliver, R.L., 1993. Assessing the dimensionality and structure of the consumption experience: Evaluation, Feeling, and Satisfaction. Journal of consumer research, 20 (3): 451-466.

Matern, U., 2001. Principles of ergonomic instrument handles. Minimally invasive therapy and applied technologies, 10 (3): 169-173.

McGorry, 2001. A system for the measurement of grip forces and applied moments during hand tool use. Applied Ergonomics, 32 (3): 271-279.

Niemelä, T., Leppänen, M., Päivinen, M., Mattila, M., 2000. Evaluation of an experimental testing system for non-powered hand tools. In: Ergonomics for the New Millennium. Proceedings of the IEA 2000/HFES 2000 congress. San Diego, 28 July- 4 August, 2000: 3-643-3-646.

Richards, L.G., 1980. On the psychology of passenger comfort. In: Human factors in Transport Research, volume 2. Oborne, D.J. Levis, J.A.(eds.), pp 15-23.

Rose, L., Ericson, M., Ortengren, R., 2000. Endurance time, pain and resumption in passive loading of the elbow joint. Ergonomics, 43 (3): 405-420.

Slater, K., 1985. Human comfort. Thomas, C.G., Springfield, IL,

Smith, C.A., Mirka, G.A., Myers, K..A., 2000. Ergonomic hand tool interventions for the furniture manufacturing industry. In: Ergonomics for the New Millennium. Proceedings of the IEA 2000/HFES 2000 congress. San Diego, 28 July- 4 August, 2000: 99-104.

Spielholz, P., Boa, S., Howard, N. (2001) A practical method for ergonomic and usability evaluation of hand tools: a comparison of three random orbital sander configurations. Applied occupational and environmental hygiene, 16 (11): 1043-1048.

Vergara, M. and Page, A. 2000. System to measure the use of the back rest in sitting-posture office tasks. Applied Ergonomics, 31 (3): 247-254.

Wilder, D., Magnusson, M.L., Pope, M., 1994. The effect of posture and seat suspension design on discomfort and back muscle fatigue during simulated truck driving. Applied Ergonomics, 25 (2): 66-76.

Wakula, J., Landau, K., 2000a. Ergonomic analysis of grapevine pruning and wine harvesting to define work and hand tools design requirements. In: Ergonomics for the New Millennium. Proceedings of the IEA 2000/HFES 2000 congress. San Diego, 28 July- 4 August, 2000: 635-637.

Wakula, J. Beckmann, T. Hett, M., 2000b. Stress-strain analysis of grapevine pruning with powered and non-powered hand tools. In: Ergonomics for the New Millennium. Proceedings of the IEA 2000/HFES 2000 congress. San Diego, 28 July- 4 August, 2000: 639-641.

Zhang, L., Helander, M.G., Drury, C.G., 1996. Identifying factors of comfort and discomfort in sitting. Human factors, 38 (3): 377-389.

Identifying predictors of comfort and discomfort in using hand tools

Chapter 4

Chapter 4

Abstract

The aim of the study was to identify predictors of comfort and discomfort in using hand tools. For this purpose the Comfort Questionnaire for Hand tools (CQH) was developed based on the results of a previous study. In the current study, four screwdrivers were evaluated on comfort (expected comfort at first sight and comfort after short time use) and discomfort (local perceived discomfort) using the CQH. The results show that expected comfort at first sight was predicted by aesthetics. Additionally, functionality and physical interaction and adverse body effects were the major predictors of overall comfort after short time use. Discomfort was predicted by adverse body effects only. We concluded that comfort and discomfort in using hand tools have partly the same underlying factors: discomfort feelings also affect the comfort experience.

Reprinted from Ergonomics, 48, Kuijt-Evers, L.F.M., Twisk, J.W.R., Groenesteijn, L., Looze, M.P. de, Vink, P. Identifying predictors of comfort and discomfort in using hand tools, 692-702., Copyright (2005), with permission from Taylor and Francis.

4 Identifying predictors of comfort and discomfort in using hand tools

4.1 Introduction

The use of hand tools frequently leads to feelings of discomfort (i.e., physical experiences of pain, fatigue, numbness, etcetera), which can reduce efficiency and job satisfaction of workers (Fellows and Freivalds, 1991). Therefore, employers are interested in hand tools for their employees which reduce discomfort. In addition, manufacturers recognize comfort (i.e. general feelings of well-being) as a major selling point, as it is thought to play an important role in product buying decisions (Vink et al., 2005). This results in a growing interest in well-designed hand tools which avoid discomfort and provide comfort for users.

Until now, the avoidance of discomfort has been a crucial issue in the design and in the evaluation of hand tools. (e.g., Dempsey et al., 2002; Chao et al., 2000; Chang, 1999; Li, 2003; Kong and Freivalds, 2003). However, comfort is seldomly considered in hand tool evaluations (Sperling et al.,1993; Freund et al., 2000). In our view it is important not only to reduce discomfort, but also to provide comfort. In a previous study (Kuijt-Evers et al., 2004), we defined a list of descriptors that were associated with comfort and to discomfort by hand tool users. The descriptors associated with comfort appeared to be the same as those that were associated with discomfort. The descriptors could be divided into six groups, which were in order of significance: 1) *functionality*, 2) *posture and muscles*, 3) *irritation and pain of hand and fingers*, 4) *irritation of hand surface*, 5) *handle characteristics*, and 6) (Kuijt-Evers et al., 2004). This study provides the (groups of) descriptors that hand tool users associate with comfort and discomfort. However, we do not know yet which of these descriptors are really predictors of comfort and discomfort during hand tool use.

The aim of the present study was to identify which (groups of) descriptors predict comfort and discomfort in hand tools. Another objective was to compare the underlying groups of descriptors of comfort and discomfort found in the current field study to the underlying groups of descriptors from the association study (Kuijt-Evers et al., 2004).

To this end, we developed the Comfort Questionnaire Hand tools (CQH) on the basis of the earlier findings (Kuijt-Evers et al., 2004). The items in the CQH concern the various descriptors of comfort/discomfort in using hand tools and an overall comfort rating. In the present study, subjects used four different screwdrivers and evaluated them with the CQH. To identify the comfort predictors, the relationship was determined between these descriptors and overall comfort. As Helander and Zhang (1997) found different underlying factors for comfort and discomfort in sitting, we also investigated the relationship between the descriptors and Localised Perceived Discomfort (LPD), which is a validated method to measure discomfort (Grinten, 1993).

4.2 Methods

4.2.1 Participants

A convenience sample was obtained by approaching visitors of a Do-It-Yourself (DIY) shop and employees of TNO Work and Employment. Twenty healthy volunteers, who frequently use screwdrivers, participated in this study (15 males and 5 females). The subjects gave their written informed consent. Table 4.1 shows the demographics of the sample.

Table 4.1 Demographics of the sample.

	Range	Mean	SD
Age (years)	25 – 63	44.5	12.3
Stature (cm)	165 – 200	181.9	9.0
Weight (kg)	54 – 105	80.9	13.5
Hand length (cm)*	16.6 - 21.5	19.4	1.3

* Meaured from top of the middlefinger to the distal crease of the wrist.

Expected comfort at first sight

	Very uncomfortable	•	A little uncomfortable	•	A little comfortable	•	Very comfortable
This hand tool is	1	2	3	4	5	6	7

Comfort Descriptors

This hand tool	Totally disagree	•	Disagree somewhat	•	Agree somewhat	•	Totally agree
Fits the hand	1	2	3	4	5	6	7
Is functional	1	2	3	4	5	6	7
Is very reliable	1	2	3	4	5	6	7
Is easy in use	1	2	3	4	5	6	7
Has a good force transmission	1	2	3	4	5	6	7
Has a solid design	1	2	3	4	5	6	7
Is safe	1	2	3	4	5	6	7
Causes pressure on the hand	1	2	3	4	5	6	7
Causes blisters	1	2	3	4	5	6	7
Is a high quality tool	1	2	3	4	5	6	7
Has a nice-feeling handle	1	2	3	4	5	6	7
Offers a high task performance	1	2	3	4	5	6	7
Causes body part ache	1	2	3	4	5	6	7
Provides a high product quality	1	2	3	4	5	6	7
Has a professional look	1	2	3	4	5	6	7
Has a functional colour	1	2	3	4	5	6	7
Needs low hand grip force supply	1	2	3	4	5	6	7
Has a good friction between handle and hand	1	2	3	4	5	6	7
Provides a relaxed working posture	1	2	3	4	5	6	7
Causes an inflamed skin of hand	1	2	3	4	5	6	7
Has a handle surface whith good roughness	1	2	3	4	5	6	7
Feels clammy	1	2	3	4	5	6	7
Is easy to take along	1	2	3	4	5	6	7
Has a nice colour	1	2	3	4	5	6	7
Causes pain	1	2	3	4	5	6	7
Causes numbness and lack of tactile feeling in hand	1	2	3	4	5	6	7
Causes cramped muscles	1	2	3	4	5	6	7

Comfort after use

	Very uncomfortable	•	A little uncomfortable	•	A little comfortable	•	Very comfortable
This hand tool is	1	2	3	4	5	6	7

Figure 4.1 The Comfort Questionnaire for Hand tools (CQH).

4.2.2 Apparatus

Comfort Questionnaire for hand tools

The Comfort Questionnaire for Hand tools (CQH) is based on the results of our previous study in which hand tool users rated 40 descriptors on their relation to comfort (Kuijt-Evers et al., 2004). 27 descriptors were selected for the CQH (Figure 4.1). The subjects rated the items on a 7-point scale (1= totally disagree, 7= totally agree). Finally, we added a question about expected comfort at first sight and a question about overall comfort after short time use. Answers to these questions were also given on a 7-point scale (1=very uncomfortable, 7=very comfortable).

Local Perceived Discomfort (LPD) of arm and hand

Local perceived discomfort was measured using a detailed hand-wrist map, with 23 regions and an arm map which consisted of two regions. A six pointscale was used to assess discomfort (ranging from 0 = no discomfort,…, to extreme discomfort, almost maximum = 5).

In the current study, perceived local discomfort was rated before and after each screwing task. For each region the increase in discomfort was calculated by subtracting the perceived discomfort rating after the task from the perceived discomfort before the task. The sum of the local discomfort increase of all regions together constitute the score of LPD.

As the frequency distribution of the LPD shows a large degree of skewness, a logarithmic transformation was performed on this variable. In further analysis only the transformed LPD was used as variable, which is called lnLPD.

Experimental setting

In this study four screwdrivers (Philips) were evaluated. The screwdrivers differed in handle diameter, handle shape, texture and colour. Subjects were asked to screw 6 screws into a wooden beam with each screwdriver, until the head of the screw touched the beam. The beam was prepared by gauging 24 holes of 10 mm with a diameter of 2 mm for men, and 24 holes of 30 mm with a diameter of 3 mm for women. Different sizes of pre-drill were used to take differences in hand strength into account. The screws (M4x5) were driven into the holes for some millimetres before the experiment started. The wooden beam was attached to a height adjustable table, which was fixed at hip height of the subject. This provides an elbow angle of about 110° when turning the screw into the wooden beam.

4.2.3 Protocol

First of all, the subjects rated expected comfort at first sight for each screwdriver by looking at all screwdrivers and holding them into their hands. After that, the first screwdriver was given to the subject. The subject was asked to screw six screws into the beam as quickly as possible without any brakes. The order of screwdrivers was systematically randomised among the subjects.

Before the subjects started to screw, their perceived discomfort was scored for each region. Then, the subject screwed the first six screws into the beam. The duration of the task was also measured. After the subject finished the six screws, perceived discomfort of each region was scored again. Additionally, the descriptors of the CQH were rated and – if necessary- the meaning of the descriptors were explained. At last, the subject rated the overall comfort after short time use. After a brake of at least five minutes, the next screw-task started. This procedure was repeated for all screwdrivers.

4.2.4 Data analysis

The ratings of the descriptors were correlated with the expected comfort at first sight, the overall comfort score after short time use and the lnLPD. Additionally, multiple regression (forward selection procedure) was used to identify which of the descriptors are the predictors of 1) expected comfort at first sight, 2) overall comfort after short time use and 3) lnLPD. After that, PCA with varimax rotation was performed to reduce the independent variables. The descriptors were classified into factors. The correlation between the factor scores of these factors with expected comfort at first sight, the overall comfort score after short time use and the lnLPD was calculated and a multiple regression (forward selection procedure) was performed to see which factors predict the 1) expected comfort at first sight, 2) overall comfort after short time use and 3) lnLPD.

The 80 data points (20 subjects x 4 screwdrivers) of expected comfort, overall comfort, LPD and descriptor ratings are not independent as one subject rated these variables four times each (i.e. for each screwdriver). Therefore, we used general estimation equations (GEE) to analyse our data, because this statistical technique takes into account the within-subjects correlation of our data (Diggle et al., 1994).

4.3 Results

4.3.1 Descriptors as predictors of comfort and discomfort in using hand tools

The correlation coefficients between the descriptors of the CQH and the expected comfort at first sight, the overall comfort after short time use, and discomfort (lnLPD) are shown in Table 4.2 on the next page. From the multiple regression was seen which of the descriptors predict expected comfort at first sight, overall comfort after short time use and discomfort. The results are shown in Table 4.3.

Table 4.3 Results of the multiple regression analysis; descriptors as predictors for comfort at first sight, comfort after short time use and discomfort.

Dependent variable	**Predictor**	**Beta**	**p**
Comfort at first sight	Has a professional look	0.34	p<.01
Comfort after short time use	Easy in use	0.36	p<.01
	Has a nice feeling handle	0.34	p<.01
	Needs low hand grip force supply	0.36	p<.01
	Is functional	-0.19	p<.05
	Causes cramped muscles	-0.11	p<.05
Discomfort (lnLPD)	Causes cramped muscles	0.37	p<.01
	Causes pressure on the hand	0.17	p<.01

Table 4.2 Standardized regressioncoefficients (beta) of descriptors of the CQH with measures of expected comfort, overall comfort after short time use, and discomfort (lnLPD). (** means p<.01, * means p<.05, - means not significant).

	Expected comfort	**Overall comfort**	**Discomfort**
Functionality and physical interaction	-	-	-
Is easy in use	0.24*	0.78**	-
Has a good force transmission	-	0.74**	-0.18*
Offers a high task performance	-	0.69**	-0.20*
Needs low hand grip force supply	-	0.76**	-0.20*
Fits the hand	0.24**	0.79**	-0.21*
Has a nice-feeling handle	0.29**	0.77**	-
Is functional	-	0.57**	-0.20*
Provides a high product quality	-	0.63**	-
Provides a relaxed working posture	-	0.67**	0.24**
Adverse body effects	-	-	-
Causes cramped muscles	-	-0.51**	0.43**
Causes pain	-	-0.48**	0.45**
Causes body part ache	-	-0.37**	0.32**
Causes numbness and lack of tactile	-	-0.39**	0.28**
Causes an inflamed skin of hand	-	-0.36**	0.34**
Causes pressure s on the hand	-		0.28**
Causes blisters	-	-0.39**	0.23**
Handle characteristics	-	-	-
Has a handle surface whith good	-	0.42**	-
Has a good friction between handle	-	0.62**	-0.19*
Feels clammy	-	-	-
Quality	-	-	-
Is safe	-	-	-0.24**
Is very reliable	-	0.45**	-
Is a high quality tool	-	0.32**	-
Colour	-	-	-
Has a functional colour	-	-	-
Has a nice colour	-	-	-
Aesthetics	-	-	-
Is easy to take along	-	-	0.19**
Has a professional look	0.40**	-	-
Has a solid design	-	-	-

4.3.2 Factors of comfort and discomfort in using hand tools

PCA of the descriptors revealed 6 major factors with eigenvalues greater than 1, explaining 73.2% of the variance. Table 4.4 (next page) shows the factor loadings greater than 0.4.While these results suggests 6 factors, the sharp decrease in eigenvalues after the fourth factor also suggests the predominance of the first four factors in the data.

The first factor contains descriptors like 'is easy in use', 'offers high force supply', fits the hand, has a nice-feeling handle. We labelled this factor *functionality and physical interaction*. Descriptors as 'causes pain', 'causes blisters', 'causes an inflamed skin of the hand' belong to the second factor, which we called *adverse body effects*. The third factor is about the *handle surface*, containing descriptors as 'has a handle with good roughness' and 'doesn't feel clammy'. Factor 4 contains descriptors of *quality*, like 'is reliable', 'is safe' and 'is of high quality'. Factor 5 and 6 were labelled *colour* and *aesthetics* respectively.

4.3.3 Factors as predictors of comfort and discomfort in using hand tools

The correlation coefficients between the factor scores of the six factors from the PCA and the expected comfort at first sight, the overall comfort, and local discomfort are shown in Table 4.5. Table 4.6 shows the results of the multiple regression analysis of the factors with expected comfort at first sight, comfort after short time use and discomfort (lnLPD).

Table 4.4 Factor loadings of the descriptors (PCA with varimax rotation) only the factor loadings > 0.4 are shown: factor 1 (*functionality and physical interaction*), factor 2 (*adverse body effects*), factor 3 (*handle characteristics*), factor 4 (*quality*), factor 5 (*colour*) and factor 6 (*aesthetics*).

	Factor 1	**Factor 2**	**Factor 3**	**Factor 4**	**Factor 5**	**Factor 6**
Is easy in use	0.877					
Has a good force transmission	0.857					
Offers a high task performance	0.839					
Needs low hand grip force supply	0.804					
Fits the hand	0.798					
Has a nice-feeling handle	0.761					
Is functional	0.731			0.470		
Provides a high product quality	0.725					
Provides a relaxed working posture	0.701					
Causes cramped muscles		0.875				
Causes pain		0.872				
Causes body part ache		0.781				
Causes numbness and lack of tactile feeling in hand		0.743				
Causes an inflamed skin of hand		0.564				
Causes pressure on the hand		0.557	-0.451			0.497
Causes blisters		0.431	-0.430			
Has a handle surface with good roughness			0.787			
Has a good friction between handle and hand	0.511		0.708			
Feels clammy			-0.651			
is safe				0.805		
Is very reliable	0.629			0.656		
is a high quality tool	0.463			0.533		
Has a functional colour					0.936	
Has a nice colour					0.908	
Is easy to take along						0.817
Has a professional look						0.580
Has a solid design						0.510

Tabel 4.5 Standardized regressioncoefficients (beta) of the factors with measures of expected comfort, overall comfort after short time use, and discomfort (lnLPD). (** means p<.01, * means p<.05.

	Expected comfort	**Overall Comfort**	**Discomfort**
Factor 1: Functionality and physical interaction	0.18	0.77**	-0.15
Factor 2: Adverse body effects	0.03	-0.30*	0.53**
Factor 3: Handle characteristics	0.08	0.17	-0.09
Factor 4: Quality	-0.10	-0.08	-0.18*
Factor 5: Colour	0.04	-0.05	0.05
Factor 6: Aesthetics	0.35*	0.25*	0.14

Table 4.6 Results of the multiple regression analysis; factors as predictors for comfort at first sight, comfort after short time use and discomfort.

Dependent variable	**Predictor**	**Beta**	**p**
Comfort at first sight	Aesthetics	0.63	p<.01
	Functionality and physical interaction	0.20	p<.05
Comfort after short time use	Functionality and physical interaction	0.75	p<.01
	Adverse body effects	-0.29	p<.01
	Aesthetics	0.18	p<.01
Discomfort (lnLPD)	Adverse body effects	0.53	p<.01

4.4 Discussion

4.4.1 Predicting descriptors of comfort en discomfort in using screwdrivers

The expected comfort is affected by the 'professional look' of a hand tool. This implies that a professional look may be important in product buying decisions, although it plays a minor role in comfort after short time use.

Five predictors of overall comfort were established (Table 4.3) All of these had the expected signs, except 'is functional'. This descriptor had a negative sign in the multiple regression, but in the univariate regression with overall comfort it had a positive sign. Probably, this is due to a high colinearity between the descriptors. The high colinearity may also be responsible for the absence of the descriptor 'fits the hand' in the prediction model, although it had the highest beta in the univariate regression. However, the forward selection method used in the multiple regression analysis, select the 'good' subsets of explanatory variables, although not necessarily the best (Everitt, 2002).

The descriptor 'causes cramped muscles' was the best predictor (out of two) of discomfort (Table 4.3). The results on discomfort (LPD) showed that most discomfort occurred in the fore arm. These feelings of discomfort came from the muscles, which suffered from fatigue after the screwing task. These findings illustrate that the recommended task can also influence the discomfort experience and indirectly, the comfort experience. Moreover, 'causes pressure in the hand' was the other predictor of discomfort. Which subscribes the local perceived discomfort in the hand measured by LPD.

4.4.2 Identifying factors of comfort and discomfort in using hand tools

In a previous study, six factors of comfort were identified in using hand tools: *Functionality*, *posture and muscles*, *pain in hand/fingers*, *hand surface*, *handle characteristics* and *aesthetics* (Kuijt-Evers et al., 2004). There are two major differences with the factors identified in the current study. Firstly, in the present study, one factor was seen which did not exist in the previous study: *Quality* (factor 4). This factor contains descriptors of the factor *functionality* of the previous study (i.e., safe and reliable). Secondly, most of the descriptors of factors 2 to 4 of the previous study (i.e., *posture and muscles*, *pain in hand/fingers*, *hand surface*) now belong to one factor: *Adverse body effects* (factor 2).

The first difference can be explained by the difference in questionnaire. In the previous study, subjects were asked to rate by association, to which degree the descriptors would be related to comfort. In the current study they were asked to asses different screwdrivers and to rate to what degree the screwdriver fit the descriptors. As both *quality* and *functionality* seems to be important for comfortable hand tool use, people considered these descriptors in the association study to be comfort-related in the same degree. In the current study, where subjects used a hand tool, subjects rated the descriptors of *quality* (reliable, quality, safe) high for all screwdrivers, but the rating of some descriptors of *functionality* were significantly different between the screwdrivers. For example, the descriptor 'has a good force transmission' was rated significantly higher for screwdriver 2 and 4 compared to screwdriver 1 and 3. The results of the previous study demonstrate that both quality and functionality are associated with comfort in the same way, but from the current study was seen that although a hand tool is of high quality, the functionality may be worse. Therefore, the PCA divided the descriptors of the factor *functionality* from the previous study into two different factors in the current study, which we labelled *functionality and physical interaction* on one side and *quality* on the other.

The second difference was more or less expected. All descriptors which are expected to be related to discomfort are classified into one factor (*adverse body effects*) instead of three different factors as in our previous study. This corresponds to the findings of Helander and Zhang (1997) who also found one factor corresponding to discomfort in sitting, which contained descriptors such as I have sore muscles, I have heavy legs, I feel pain, etc.)

Some factors did not change with respect to the previous study. The descriptors of factor 5 *handle characteristics* are still summarized in the same factor *handle characteristics* together with the descriptor 'handle doesn't feel clammy', which came from factor 4 of the previous study *handle surface*. The first factor *functionality and physical interaction* still contains the descriptors of functionality, but also some more descriptors that are related to physical interaction, like 'fits the hand' and 'provide a relaxed working posture'. In the previous study, most descriptors of factor 1 were descriptors of functionality. Therefore, this factor was called *functionality* in the previous study. As in the current study, more descriptors of physical interaction belong to factor 1, the name was changed into *functionality and physical interaction*.

4.4.3 Predicting factors of comfort and discomfort in using hand tools

Expected comfort at first sight was predicted by the factor aesthetics and the factor functionality and physical interaction. It was not surprising that aesthetics of a hand tool mainly predicts the expected comfort. However, the expected comfort was also related to the ratings on descriptors of functionality and physical interaction. Thus, for product buying decisions it seems to be important to give visitors of DIY-shops the opportunity to hold the hand tool in their hand for a few seconds to estimate the comfort.

What remains to be discussed is the comfort versus discomfort issue. First, Helander and Zhang (1997) found that in sitting comfort and discomfort are two separate entities with different underlying factors. This was not confirmed for hand tools in an earlier study of Kuijt-Evers et al. (2004). They found that hand tool users associated the same factors with comfort as with discomfort. From the present study it was seen that comfort and discomfort in using hand tools have partly the same underlying factors. Overall comfort was determined by descriptors of 1) *functionality and physical interaction*, 2) *adverse body effects* and 3) *aesthetics*, while discomfort was predicted by descriptors of *adverse body effects* only.

These findings are different from the results of studies about comfort in sitting which showed that comfort in sitting was mainly related to feelings of well-being and aesthetics (Zhang et al., 1996; Helander and Zhang, 1997) and discomfort feelings were associated with descriptors such as pain, cramped and numbness. Although, we also found a relationship between factor scores of *aesthetics* and overall comfort, *aesthetics* was of minor influence on overall comfort in using hand tools. Overall comfort is best predicted by *functionality and physical interaction* followed by *adverse body effects*. The factor *adverse body effects* was also related to discomfort. So, we found one factor to be related to both comfort and discomfort in using hand tools, but Helander and Zhang (1997) found different underlying factors for comfort (well being and aesthetics) and discomfort (biomechanics problems) in sitting. From these results it seems that discomfort in hand tool use determines the comfort experience, whereas discomfort does not influence comfort in sitting. However, discomfort has the same underlying descriptors in sitting as in using hand tools. In both seats and hand tools, discomfort feelings are associated with descriptors such as pain, cramped and numbness.

4.4.4 Meaning of the results for other kinds of hand tools

In this study, a screwdriver evaluation was used to identify the predictors of comfort and discomfort in hand tools. The question rises if these results can be generalized to other hand tools. In the current study for example, discomfort was mainly caused by the screwing task, as working with screwdrivers resulted in muscle fatigue of the fore arm. This explains the high correlation between the descriptor 'causes cramped muscles' and discomfort. However, when another task is performed with a different hand tool which does not recommend high force supply and lots of muscle activity, maybe other descriptors will be a better predictor. This implies that the relative importance of the descriptors can vary between different kinds of hand tools. However, we assume the predicting factors of expected comfort (i.e., *aesthetics*, and *functionality and physical interaction*) overall comfort after short time use (i.e., *functionality and physical interaction*, *adverse body effects*, and *aesthetics*) and discomfort (i.e., *adverse body effects*) can be applied to other kinds of hand tools as they are more general.

Not only the type of hand tool, but the properties of one of the evaluated hand tools as well can influence the prediction model. For example, if a property of a hand tool - which is related to a descriptor of the CQH - is of exceptional poor design, this can dominate the comfort and discomfort experience. For example, the handle diameter can dominate the rating on 'fits the hand', 'needs low force supply', and 'has a good force transmission' when the diameter is extremely small. This may also influence the overall comfort rating. In this way, a high correlation can be found between these descriptors and comfort. Other descriptors may be dropped from the prediction model for this reason. In the current study, this was not the case as we used standard screwdrivers. In future studies intended to identify predictors of comfort and discomfort in hand tools, special attention should be paid to select more or less standard editions of that kind of hand tool.

4.5 Conclusion

This study provides the descriptors and the factors (groups of descriptors) that predict the comfort in hand tool use as well as the extent to which they predict. Comfort in hand tools can partly be predicted from *adverse body effects* which determine discomfort, but the best predictor of comfort are descriptors of *functionality and physical interaction*. Therefore, when hand tools are evaluated on comfort, not only discomfort should be measured, but also aspects of functionality and physical interaction should be taken into account.

In order to design hand tools that provide much comfort, designers have to focus on functionality and physical interaction and avoiding discomfort. *Aesthetics* is especially important to expected comfort and can play a major role in product buying decisions. A comfortable screwdriver should be easy in use and functional. Additionally, the handle should feel nice and should provide a low grip force supply.

4.6 Acknowledgements

Special thanks to Intergamma b.v. who gave us the opportunity to perform our measurements in one of their DIY-shops, asking their visitors to participate in our study.

4.7 References

Chang, S.R., Park, S. and Freivalds, A., 1999. Ergonomic evaluation of the effects of handle types on garden tools. International Journal of Industrial Ergonomics. 24: 99-105.

Chao, A., Kumar, A.J., Emery, C.T.N.D., Nagarajarao, K., You, H., 2000. An ergonomic evaluation of cleco pliers. In: Ergonomics for the New Millennium. Proceedings of the IEA 2000/HFES 2000 congress. San Diego, 28 July- 4 August, 2000: 4-441-4-442.

Dempsey, P.G., McGorry, R.W., Leamon, T.B., O'Brien, N.V., 2002. Bending the tool and the effect on human performance: Further investigation of a simulated wire-twisting task. AIHA Journal, 63 (7): 586-593.

Diggle, P.J., Liang, K.-Y. and Zeger, S., 1994. Analysis of longitudinal data. Oxford Science Publications, Oxford.

Everitt, B.S., 2002. The Cambridge dictionary of statistics, 2nd edtion. Cambridge University Press, Cambridge.

Fellows, G.L., Freivalds, A., 1991. Ergonomics evaluation of a foam rubber grip for tool handles. Applied Ergonomics, 22 (4): 225-230.

Freund, J., Takala, E-P., Toivonen, R., 2000. Effects of two ergonomics aids on the usability of an in-line screwdriver. Applied Ergonomics, 31 (4): 371-376.

Grinten, M.P. van der, 1993. Manual for the methods of Locally Perceived Discomfort (LPD); Methods for assessment of physical load in research for ergonomic improvements (In Dutch). NIPG-TNO, Leiden.

Helander, M.G., Zhang, L., 1997. Field studies of comfort and discomfort in sitting. Ergonomics, 40 (9): 895-915.

Kong, Y-K, Freivalds, A., 2003. Evaluation of meat-hook handle shapes. International Journal of Industrial Ergonomics, 32 (1): 13-23.

Kuijt-Evers, L.F.M., Groenesteijn, L., Looze, M.P. de and Vink, P., 2004. Identifying factors of comfort in using hand tools. Applied Ergonomics. 35 (5): 453-458.

Li, K.W., 2003. Ergonomic evaluation of a fixture used for power driven wire-tyring hand tools. International Journal of Industrial Ergonomics. 32 (2): 71-79.

Sperling, L., Dahlman, S., Wikström, L., Kilbom, Å., Kadefors, R. 1993. A cube model for the classification of work with hand tools and the formulation of functional requirements. Applied Ergonomics. 24 (3), 212-220.

Vink, P., Overbeeke, C.J., Desmet, P.M.A. ,2005. Comfort experience. In: Comfort and design; principles and good practice. Vink, P. (ed.) CRC Press, Boca Raton. 1-12.

Zhang, L., Helander, M.G., Drury, C.G., 1996. Identifying factors of comfort and discomfort in sitting. Human factors, 38 (3): 377-389.

Comfort predictors for different kinds of hand tools: differences and similarities

Chapter 5

Abstract

This study investigates whether the same factors underlie comfort in using different kinds of hand tools (screwdrivers, paintbrushes and hand saws). The underlying factors of the hand tools are identified using Principal Component Analysis. The relationships between comfort descriptors (i.e. statements in end-users' own words that are related to comfort) and comfort factors (i.e. groups of comfort descriptors) with comfort experience are calculated. It is concluded that the same factors (functionality, physical interaction adverse effects on skin and in soft tissues) underlie comfort in different kinds of hand tools, however their relative importance differed. *Functionality and physical interaction* are the most important factors of comfort in using screwdrivers and paintbrushes (beta is 0.73 and 0.67 respectively) and *functionality* was the most important factor in using hand saws (beta=0.72). Moreover, the most important comfort descriptors differ between different kinds of hand tools. 'Has a nice feeling handle' (beta=0.27), 'fits the hand' (beta=0.43) and 'offers a high task performance' (beta=0.43) are the most important comfort descriptors in using screwdrivers, paintbrushes and hand saws respectively. Moreover, similarities are seen: 'Fits the hand' is associated with comfort in all studied hand tools. The results are applied in a flow chart, which designers can use to address the appropriate comfort descriptors in the hand tool design process.

This paper is in press by the International Journal of Industrial Ergonomics
Kuijt-Evers, L.F.M., Vink, P., Looze, M.P. de. Comfort predictors for different kinds of hand tools: differences and similarities. Reprinted with permission from Elsevier.

5 Comfort predictors for different kinds of hand tools: differences and similarities

5.1 Introduction

Hand tools are still the primary interface for operators at work, in spite of all the automation efforts made by modern industry (Christensen and Bishu, 2000). In the past, hand tool design was focused on tool function in order to improve task efficiency and allow for standardisation. The tool should perform the task for which it was designed and respond to the needs of the greatest possible number of users (Aptel et al., 2002; Marsot and Claudon, 2004). In recent years, emphasis is placed on the role of the user to do the job harmlessly, effortlessly and comfortably (Aptel et al., 2002; Marsot and Claudon, 2004). Especially, comfort is a topic of interest for manufacturers of hand tools, as it is thought to play a role in product buying decisions (Vink et al., 2005). Moreover, comfort can contribute to the task performance of the workers (Kuijt-Evers et al., 2006).

Before one can design a comfortable hand tool, it is important to know what end-users actually mean by comfort in using hand tools and how this can be addressed in the design process. The meaning of comfort in using hand tools to the end-users was investigated in a previous study (Kuijt-Evers et al., 2004). In that study, a list of 40 descriptors of comfort was composed. Those descriptors were associated with comfort by hand tool users and formulated in the end-users' own words, like: the hand tool fits the hand, has a good force transmission, and has a nice feeling handle (Kuijt-Evers et al., 2004). These comfort descriptors can help to focus on the most urgent customer needs during the design process.

For screwdrivers, the relative importance of these descriptors was determined (Kuijt-Evers et al., 2005). From the results of that study, it was seen that comfort in using screwdrivers was associated with 'ease in use', 'nice-feeling handle', 'low hand grip force supply', 'functionality' and 'causes cramped muscles' (The last descriptor was negatively associated with comfort). The underlying factors of comfort in using screwdrivers were determined by dividing the (interrelated) descriptors into factors using Principal Component Analysis (PCA). The most important factors for comfort pointed out to be *functionality and physical interaction*, and *adverse body effects*, while *aesthetics* was of minor influence.

The underlying factors of comfort in working with screwdrivers differ from those of comfort in sitting. Sitting comfort is mainly determined by feelings of well-being and relaxation (Zhang et al., 1996; Helander and Zhang, 1997), while biomechanical factors, like pain, fatigue and strain (Zhang et al., 1996), are not associated with comfort experience. These differences between office chairs and screwdrivers illustrate that different factors determine comfort in different kinds of products. This means that comfort predictors of one product can not be generalized for other products.

Therefore, it is interesting to know whether the underlying factors of comfort in working with screwdrivers would also determine comfort in other kinds of hand tools, like hammers, paintbrushes, pliers and hand saws. However, information is lacking about the meanings of the screwdriver evaluation study for other kinds of hand tools. Many differences exist across these kinds of hand tools which may affect the comfort predictors, like the intensity of the task (e.g., movement frequency and force exertion) or the grip (e.g., power grip, precision grip) (Mital and Kilbom, 1992).

The aim of the current study is to investigate whether the same factors (i.e., groups of descriptors) underlie comfort in different kinds of hand tools, namely screwdrivers, paintbrushes and hand saws. Moreover, the relative importance of the comfort descriptors and underlying factors are identified for each of these hand tools. In order to do so, the data of three hand tool evaluation studies were analysed. The main differences in using these hand tools can be summarized as follows. Firstly, the way the user holds the handles differs among these hand tools. A screwdriver is hold in a power grip, a paintbrush (mostly) in a precision grip and a hand saw in a pistol grip. Secondly, the force exertion (direction and magnitude) differs between the hand tools. For instance, users apply a high torque force on screwdrivers (resulting in shear forces between hand and handle). When using a paintbrush, the fingers provide the force to hold the paintbrush and the major muscle activity of the arm and shoulder is used to perform the required movement with (sometimes) high precision. In using hand saws, the exerted force is in line with the movement of the saw and results mostly in normal forces on the hand surface. Precision and force are two of the three demands in the cube model for the classification of work with hand tools (Sperling et al., 1993). By choosing screwdrivers, paintbrushes and hand saws as case studies, a wide range of hand tools is comprised as the demands on force and precision differ between the tools.

5.2 Methods

5.2.1 Experimental design

Case study 1: Screwdrivers

Four screwdrivers were evaluated on comfort by Do-It-Yourself enthusiasts (15 men and 5 women). The screwdrivers differed in handle diameter, handle shape, texture, colour and size of the tip of the screwdriver (Figure 5.1).

Figure 5.1 Four screwdrivers were evaluated in case study 1

Case study 2: Paintbrushes

Two paintbrushes were evaluated on comfort by professional painters. One paintbrush was a traditional paintbrush that the painters were used to. The second paintbrush was a prototype of a new design (Figure 5.2). The main differences with the traditional paintbrush were 1) the shape of the handle (more wavy), 2) the location of the centre of mass (located where the fingers held the brush), 3) the weight of the paintbrush (heavier) and 4) the material (PVC instead of beech wood).

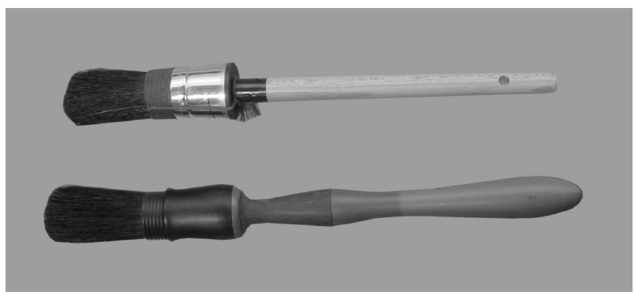


Figure 5.2 Two paintbrushes were evaluated in case study 2

Case study 3: Hand saws

Five hand saws were evaluated on comfort by carpenters. The five hand saws had a different sales segment and they differed in product characteristics, like hand grip, saw blade stiffness, teeth count and teeth shape (Figure 5.3).

Figure 5.3 Five hand saws were evaluated in case study 3

5.2.2 Subjects

Twenty DIY-enthusiasts (15 male, 5 female) and twenty professional painters (all male) volunteered in the screwdriver evaluation study and the paintbrush evaluation study, respectively. Twelve carpenters (all male) participated in the hand saw evaluation study. Table 5.1 shows the demographics of the samples.

Table 5.1 Demographics of the samples

		Range	Mean	SD
Screwdrivers	Age (years)	25 - 63	44.5	12.3
15 Male, 5 Female	Stature (cm)	165 - 200	181.9	9.0
	Weight (kg)	54 - 105	80.9	13.5
	Hand length (cm)*	16.6 - 21.5	19.4	1.3
Paintbrushes	Age (years)	16 - 59	35.1	8.9
20 Male	Stature (cm)	170 – 194	183.0	7.6
	Weight (kg)	54 – 110	83.5	13.8
	Hand length (cm)*	18.5 – 25.0	20.3	1.5
Hand saws	Age (years)	38 - 64	50.2	8.6
12 Male	Stature (cm)	169 - 190	179.6	5.5
	Weight (kg)	70 - 98	82.6	8.9
	Hand length (cm)*	17.6 - 21.5	20.1	1.2

* Measured from top of the middle finger to the distal crease of the wrist

5.2.3 Task

Case study 1: Screwdrivers

The subjects were asked to screw 6 screws into a wooden beam with each screwdriver, until the head of the screw touched the beam. The beam was prepared by gauging 24 holes of 10 mm with a diameter of 2 mm for men, and 24 holes of 30 mm with a diameter of 3 mm for women. Different sizes of pre-drill were used to take differences in hand strength into account. The screws (M4x5) were driven into the holes for some millimeters before the experiment started. The wooden beam was attached to a height adjustable table, which was fixed at hip height of the subject. This provides an elbow angle of about 110° when screwing.

After informing the subjects about the study and completing a written informed consent, the subjects were asked to screw six screws into the beam as quickly as possible without any rest breaks. The order of screwdrivers was systematically varied among the subjects to avoid fatigue effects. After the subjects finished six screws, the descriptors of the Comfort Questionnaire for Hand tools (CQH) were rated and – if necessary- the meaning of the descriptors was explained. At last, the subjects rated overall comfort. After a rest break of at least five minutes, the next screwing-task started. This procedure was repeated for all screwdrivers.

Case study 2: Paintbrushes

The professional painters used the prototype of the new paintbrush for some hours during their working day. They were all familiar with the traditional paintbrush, as they use it in their daily work. The painters were informed on the study. They were asked to paint with the prototype of the new paintbrush for at least 2 hours. At the end of their working day, they rated the descriptors of the CQH for both the prototype and their current paintbrush. If necessary, the meaning of the descriptors was explained. Finally, the painters rated overall comfort.

Case study 3: Hand saws

The carpenters had to fulfil a standardized task of crosscutting a wooden beam. For this purpose, a beam of bankirai wood (77x82 mm) was attached to a work-mate (height 59 cm). Bankirai wood was chosen because of its constant grains and absence of knots, which provide constant conditions for every saw for every subject. The place of the saw-cuts were drawn on the beam, with an intersection of 15 mm.

The carpenters were informed about the study and gave their written informed consent. Then, they had to saw five minutes with the first hand saw. After the sawing task was finished, the subjects rated the comfort descriptors and the overall comfort. Subsequently, they had a rest period of at least five minutes before the next sawing task started. The sawing task was repeated for each hand saw, resulting in five sawing tasks for each subject. The sequence of hand saws was systematically varied among the subjects in order to avoid fatigue effects.

5.2.4 Comfort Questionnaire for Hand tools (CQH)

The Comfort Questionnaire for Hand tools (CQH) was used in all three studies. The CQH is based on the results of a previous study in which descriptors associated with comfort in using screwdrivers were identified by end users, like 'fits the hand', 'has a good functionality', 'offers a high task performance' (Kuijt-Evers et al., 2005). For the current study 17 of these descriptors were selected (Figure 5.4). 10 descriptors were dropped from the questionnaire which was used in the previous study. There were two main reasons to drop comfort descriptors from the former CQH: Firstly, the former CQH was too long and subjects got bored at the end of the questionnaire (especially when evaluating more than two hand tools) and 2) more focus was needed on the most important descriptors.

The following descriptors were excluded from the revised CQH: 1) Descriptors which are hardly related to comfort (solid design, functional colour, nice colour, easy to take along), 2) descriptors which have too general meanings (causes pain, provides relaxed working posture, causes body ache), descriptors which are basic conditions for each hand tool (safe, reliable), and 4) descriptors which have the same meaning as other descriptors (has a good roughness). The subjects rated the descriptors on a 7-point scale (1= totally disagree, 7= totally agree). After that, they rated the overall comfort on a 7-point scale (1=very uncomfortable, 7=very comfortable).

Comfort Descriptors

This hand tool	Totally disagree	•	Disagree somewhat	•	Agree somewhat	•	Totally agree
Fits the hand	1	2	3	4	5	6	7
Is functional	1	2	3	4	5	6	7
Is easy in use	1	2	3	4	5	6	7
Has a good force transmission	1	2	3	4	5	6	7
Is a high quality tool	1	2	3	4	5	6	7
Has a nice-feeling handle	1	2	3	4	5	6	7
Offers a high task performance	1	2	3	4	5	6	7
Provides a high product quality	1	2	3	4	5	6	7
Looks professional	1	2	3	4	5	6	7
Needs low hand grip force supply	1	2	3	4	5	6	7
Has a good friction between handle and hand	1	2	3	4	5	6	7
Causes an inflamed skin of hand	1	2	3	4	5	6	7
Causes pressure on the hand	1	2	3	4	5	6	7
Causes blisters	1	2	3	4	5	6	7
Feels clammy	1	2	3	4	5	6	7
Causes numbness and lack of tactile feeling in hand	1	2	3	4	5	6	7
Causes cramped muscles	1	2	3	4	5	6	7

Comfort after use

	Very uncomfortable	•	A little uncomfortable	•	A little comfortable	•	Very comfortable
This hand tool is	1	2	3	4	5	6	7

Figure 5.4 The Comfort Questionnaire for Hand tools (translated from Dutch)

5.2.5 Data analysis

The ratings of the descriptors were correlated with overall comfort. Additionally, multiple regression (forward selection procedure) was used to identify which of the descriptors are the predictors of comfort for screwdrivers, paintbrushes and hand saws.

After that, PCA with varimax rotation was performed to reduce the independent variables. The descriptors were classified into factors. The correlation between the factor scores of these factors with overall comfort was calculated and a multiple regression (forward selection procedure) was performed to see which factors predict the overall comfort of screwdrivers, paintbrushes and hand saws.

The data points of the comfort descriptors and overall comfort are not independent as one subject rated these variables for each of the evaluated hand tools. For instance, DIY-enthusiasts rated the comfort descriptors and overall comfort four times (i.e., once for each screwdriver). The professional painters rated these variables two times when evaluating two paintbrushes and the carpenters rated them five times (once for each hand saw). Therefore, we used general estimation equations (GEE) to analyse our data, because this statistical technique takes into account the within-subjects correlation of our data (Twisk, 2003).

However, data analysis with the sophisticated GEE technique with a categorical outcome variable (like the rating scale of the CQH) is more problematic than with continuous or dichotomous outcome variables. Therefore, categorical variables may be treated as continuous variables in GEE analysis, especially when they are ordinal and have a sufficient number of categories (i.e., more than five) (Twisk, 2003). The other option is to use simple methods, but they do not correct for the within-subjects correlation of the data as we need in the current study. Therefore, we chose to treat the rating scales as a continuous variable.

5.3 Results

5.3.1 Descriptors as predictor of comfort in using hand tools

Table 5.2 shows the standardized regression coefficients of the univariate relationships between the comfort descriptors and overall comfort for screwdrivers, paintbrushes and hand saws. Some obvious results are described below.

Descriptors which are strongly associated (beta>0.5) (Cohen et al., 2003) with comfort in all of the studied hand tools are 'fits the hand', 'is functional', 'is easy in use', 'has a good force transmission', 'has a nice-feeling handle', 'offers a high task performance' and 'has a good friction between handle and hand'.

Differences in correlations exist for 'needs low hand grip force supply' and 'causes cramped muscles'. These descriptors are more related to comfort for screwdrivers (beta=0.76; beta=-0.51) and hand saws (beta=0.74; beta=-0.70) compared to paintbrushes (ns;ns). 'Is a high quality tool', 'looks professional' and 'causes peak pressures on the hand' are more related to comfort in using hand saws (beta=0.81; beta=0.53; beta=-0.46) than to comfort in using screwdrivers (beta= 0.32; ns;ns) and paintbrushes (beta=0.47; ns;ns).

Table 5.2 Standardized regression coefficients (beta) of descriptors of the CQH with measures of overall comfort (** means p<.01, * means p<.05, - means not significant)

	Beta		
CQH descriptors	**Screwdrivers**	**Paintbrushes**	**Hand saws**
Fits the hand	0.79**	0.77**	0.77**
Is functional	0.57**	0.72**	0.88**
Is easy in use	0.78**	0.69**	0.83**
Has a good force transmission	0.74**	0.59**	0.74**
Causes peak pressures on the hand	-	-	-0.46**
Causes blisters	-0.39**	-	-0.54**
Is a high quality tool	0.32**	0.47**	0.81**
Has a nice-feeling handle	0.77**	0.70**	0.68**
Offers a high task performance	0.69**	0.70**	0.89**
Provides a high product quality	0.63**	-	0.80**
Looks professional	-	-	0.53**
Needs low hand grip force supply	0.76**	-	0.74**
Has a good friction between handle and hand	0.62**	0.64**	0.70**
Causes an inflamed skin of hand	-0.36**		-0.50**
Feels clammy	-	-	-0.17*
Causes numbness and lack of tactile feeling in hand	-0.39**	-0.36*	-0.52**
Causes cramped muscles	-0.51**	-	-0.70**

Table 5.3 shows the results of the multiple regression for screwdrivers, paintbrushes and hand saws. The descriptor 'fits the hand' is part of all the multiple regression models.

This descriptor plays a role in the comfort experience of screwdrivers, paintbrushes and hand saws. 'Has a nice feeling handle' and 'has a good force transmission' contributes to comfort in using screwdrivers and paintbrushes. 'Causes cramped muscles' is associated with comfort in using screwdrivers and hand saws. However, the sign of beta of 'causes cramped muscles' was unexpected in the regression model of hand saws. Two other descriptors -which are not associated with comfort in using screwdrivers or paintbrushes- are strongly associated with comfort in using hand saws, that is: 'Offers a high task performance' and 'Is functional'.

Table 5.3 Results of the multiple regression analysis; descriptors as predictors for comfort in using screwdrivers, paintbrushes and hand saws

Dependent variable	**Predictors**	**Beta**	**p**
Comfort in using screwdrivers	Has a nice-feeling handle	0.27	<.01
	Has a good force transmission	0.24	<.01
	Fits the hand	0.22	<.05
	Is easy in use	0.18	<.01
	Causes cramped muscles	-0.12	<.05
Comfort in using paintbrushes	Fits the hand	0.43	<.01
	Has a good force transmission	0.29	<.01
	Has a nice-feeling handle	0.28	<.01
Comfort in using hand saws	Offers a high task performance	0.43	<.01
	Is functional	0.41	<.01
	Fits the hand	0.16	<.01
	Causes blisters	-0.12	<.01
	Causes cramped muscles	0.11	<.01

5.3.2 Factors of comfort in using hand tools

Screwdrivers

PCA of the descriptors revealed 4 major factors with eigenvalues greater than 1, explaining 70.9% of the variance. The sharp decrease in eigenvalues after the third factor suggests the predominance of the first three factors in the data. Table 5.4 shows the factor loadings greater than 0.4 of the first three factors.

Table 5.4 Comfort in working with screwdrivers: Factor loadings of the descriptors (PCA with varimax rotation) only the factor loadings > 0.4 are shown. Factor 1 = *Functionality and physical interaction*, factor 2 = *Adverse effects on the skin*, factor 3 = *Adverse effects in soft tissues*.

Screwdrivers	**Factor 1**	**Factor 2**	**Factor 3**
Has a good force transmission	0.868		
Offers a high task performance	0.853		
Is easy in use	0.851		
Is functional	0.815		
Needs low hand grip force supply	0.789		
Provides a high product quality	0.788		
Fits the hand	0.779		
Has a nice-feeling handle	0.697		
Is a high quality tool	0.550		
Causes peak pressures on the hand		0.750	
Has a good friction between handle and hand	0.465	-0.712	
Causes an inflamed skin of hand		0.600	0.425
Causes blisters		0.597	
Causes numbness and lack of tactile feeling in hand			0.835
Causes cramped muscles			0.827

We labelled the factors depending on the comfort descriptors that are included. The first factor was labelled *functionality and physical interaction* containing descriptors like ‘has a good force transmission’, ‘offers a high task performance’, ‘needs low hand grip force supply’ and ‘fits the hand’. Descriptors as ‘causes peak pressures’, ‘has a good friction between handle and hand’ and ‘causes blisters’ belong to the second factor, which we called: *Adverse effects on the skin*. The third factor contains descriptors like ‘causes numbness and lack of tactile feeling in hand’ and ‘causes cramped muscles’. This factor was called *Adverse effects in soft tissues*.

Paintbrushes

PCA of the descriptors of paintbrushes also revealed 4 major factors with eigenvalues greater than 1. These factors explained 70.6% of the variance. After the third factor, a sharp decrease in eigenvalues was seen, which suggests the predominance of the first three factors. The factor loadings of the first three factors are shown in Table 5.5.

Table 5.5 Comfort in using paintbrushes: Factor loadings of the descriptors (PCA with varimax rotation), only the factor loadings > 0.4 are shown. Factor 1 = *Functionality and physical interaction*, factor 2 = *Adverse effects in soft tissues and skin*, factor 3 = *Adverse effects on skin*.

Paintbrushes	**Factor 1**	**Factor 2**	**Factor 3**
Fits the hand	0.920		
Is easy in use	0.905		
Is functional	0.858		
Has a good friction between handle and hand	0.842		
Offers a high task performance	0.815		
Has a nice-feeling handle	0.764		
Has a good force transmission	0.677		
Is a high quality tool	0.520		
Causes numbness and lack of tactile feeling in hand		0.867	
Causes cramped muscles		0.818	
Feels clammy		0.680	
Causes blisters		0.641	
Needs low hand grip force supply			0.884
Causes peak pressures on the hand			0.644
Causes an inflamed skin of hand		0.488	-0.621

The factors are labelled *functionality and physical interaction*, *adverse effects in soft tissues and skin* (containing descriptors such as 'causes cramped muscles' and 'feels clammy'), and *adverse effects on skin* (contains descriptors like 'causes peak pressures on the hand' and 'causes an inflamed skin of the hand').

Hand saws

For hand saws, three major factors revealed from the PCA of the descriptors of hand saws. They explained 74.6% of the variance. Table 5.6 shows the factor loadings of the three factors.

Table 5.6 Comfort in using hand saws: Factor loadings of the descriptors (PCA with varimax rotation) only the factor loadings > 0.4 are shown. Factor 1 = *Functionality*, factor 2 = *physical interaction and adverse effects in soft tissues*, factor 3 = *Adverse effects on the skin*.

Hand saws	**Factor 1**	**Factor 2**	**Factor 3**
Is easy in use	0.895		
Is a high quality tool	0.890		
Has a good force transmission	0.870		
Provides a high product quality	0.869		
Is functional	0.842		
Offers a high task performance	0.785	0.459	
Looks professional	0.668		
Fits the hand	0.616	0.612	
Needs low hand grip force supply		0.821	
Causes numbness and lack of tactile feeling in hand		-0.737	
Causes cramped muscles		-0.729	
Has a good friction between handle and hand	0.413	0.684	
Has a nice-feeling handle	0.472	0.672	
Causes peak pressures on the hand		-0.561	
Feels clammy			0.859
Causes an inflamed skin of hand			0.770
Causes blisters			0.558

The factors are called *functionality* (containing descriptors such as 'is easy in use', 'has a good force transmission' and 'offers a high task performance'), *physical interaction and adverse effects in soft tissues* (containing descriptors like 'needs low hand grip force supply', 'has a nice feeling handle', 'causes cramped muscles') and *adverse effects on the skin* (Contains descriptors like 'causes an inflamed skin of the hand', 'causes blisters').

Comparison of PCA results of the three kinds of hand tools.

Figure 5.5 shows an overview of the comfort factors for each type of hand tool, which revealed from the PCA of the comfort descriptors for the three hand tools.

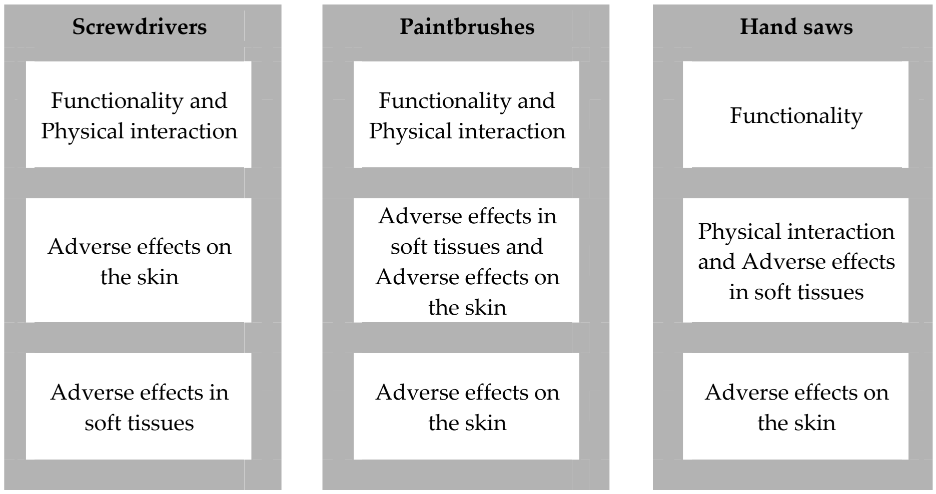


Figure 5.5 Overview of the factors of comfort in using screwdrivers, paintbrushes and hand saws.

From the results, it can be seen that descriptors relating the functionality of the hand tool and the physical interaction with the hand tool are classified into the same factor (called *functionality and physical interaction*) for screwdrivers and paintbrushes, while for hand saws, these descriptors are split up into two separate factors (namely, *functionality* and *physical interaction and adverse effects in soft tissues*). This means that the ratings on comfort descriptors relating functionality are not related to the ratings on comfort descriptors of physical interaction in the hand saw evaluation. Comfort descriptors relating adverse effects on the skin are combined in one factor, which is the same for all hand tools, except for paintbrushes. In that situation, ratings on descriptors relating to adverse effects on the skin are also related to adverse effects in soft tissues (in the *factor adverse effects in soft tissues and adverse effects on skin*). Descriptors relating to adverse effects in soft tissues are classified in the factor *adverse effects in soft tissues* (screwdrivers), combined with *adverse effects on the skin* and *physical interaction* (paintbrushes and hand saws respectively).

5.3.3 Factors as predictor of comfort in using hand tools

Table 5.7 shows the standardized regression coefficients of the univariate relationships between the factors and overall comfort for screwdrivers, paintbrushes and hand saws.

Table 5.7 Standardized regression coefficients (beta) of the factors from the PCA (groups of descriptors) with overall comfort (ns means not significant)

Hand tools	Factors of comfort	Beta	p
Screwdrivers	Functionality and physical interaction	0.75	<.01
	Adverse effects on the skin	-0.28	<.05
	Adverse effects in soft tissues	-0.22	ns
Paintbrushes	Functionality and physical interaction	0.67	<.01
	Adverse effects on soft tissues and skin	-0.12	ns
	Adverse effects on skin	-0.04	ns
Hand saws	Functionality	0.74	<.01
	Physical interaction and adverse effects on soft tissues	0.47	<.01
	Adverse effects on the skin	-0.21	<.01

The results of the multiple regression analysis are shown in Table 5.8. It appears that the factor *functionality and physical interaction* plays a major role in comfort in using screwdrivers and paintbrushes. For paintbrushes, this is also the only factor which is associated to comfort. The second important predictor of comfort in using screwdrivers is *adverse effects on the skin*. *Functionality* is the most important predictor of comfort in using hand saws, followed by *physical interaction and adverse effects in soft tissues*.

Table 5.8 Results of the multiple regression analysis; factors as predictors for comfort in using screwdrivers, paintbrushes and hand saws.

Hand tools	Dependent variable	Factors of comfort	Beta	p
Screwdrivers	Comfort	Functionality and physical interaction	0.73	<.01
		Adverse effects on the skin	-0.27	<.01
Paintbrushes	Comfort	Functionality and physical interaction	0.67	<.01
Hand saws	Comfort	Functionality	0.72	<.01
		Physical interaction and adverse effects on soft tissues	0.48	<.01

5.4 Discussion

The aim of the current study was to investigate whether underlying factors of comfort in hand tools differ or show similarities for different kinds of hand tools. To this end, the underlying comfort descriptors, the comfort underlying factors, and their relative importance were studied for screwdrivers, paintbrushes and hand saws.

As we wanted to study the underlying factors of comfort in using hand tools, the Comfort Questionnaire for Hand tools (CQH) was used, which is a subjective measurement. It is preferred to use a subjective measurement, as comfort is a construct of a subjectively-defined personal nature (Looze et al., 2003). Objective measurements (like contact pressure or muscle activity) are less suitable to measure comfort as they can only measure the physical aspects related to comfort (Kuijt-Evers et al., 2006) and do not result in a precise prediction of comfort experience of the end-users. Although objective measurements can be useful to indicate the physical workload in using hand tools, they do not necessarily match the end users' preference. This can be illustrated by a study of Kluth et al. (2004), who found that the most favorable and subjectively preferred angle-position to use a file indicated by the end-users, was not the optimum posture from physiological point of view. Therefore, subjective measurements are preferred, in order to fulfil the comfort-related customer needs.

The background of the end-users, who were involved in the hand tool evaluation studies differed across the hand tools. The screwdrivers were evaluated by Do-It-Yourself users, while the paintbrushes and the hand saws were tested by professional users. In another study on comfort in using screwdrivers, DIY-users and professionals associated the same descriptors with comfort (Kuijt-Evers et al., 2004). The reason that hardly differences were found between DIY-users and professionals for screwdrivers in that study may be that working with screwdrivers is a task that is also performed very frequently by DIY-users and that working with screwdrivers does not require special skills in contradiction to for instance painting. Moreover, professionals use more often powered screwdrivers for turning in screws. Therefore, DIY-users were involved in the screwdriver evaluation study and professionals participated in the paintbrush and hand saw evaluation.

Another aspect which may affect the application of the results of the current study is the tasks which were performed to evaluate the hand tools. This concerns the task-time as well as the experimental setting in the screwdriver and hand saw evaluation, which were performed in a laboratory setting. The tasks during these evaluations can be characterized as short and high intensive. In the field setting, workers will not be exposed to such a high intensity, as their activities vary across the day. For the purpose of our study -determining the underlying descriptors and factors of comfort in different kind of hand tools- it would even be better to concentrate the tasks on one part of the day. In this way, it is easier for the participants to compare the different tools, they can better rate the comfort descriptors directly after finishing the task, and they can really concentrate on working with the tool and their experience and are not distracted by other activities. However, the experimental setting could have influenced the results of the study. The performed tasks may not be representative for all tasks in the occupational situations. For instance, the screwdriver task consisted of turning screws horizontally into the wooden beam on an ideal working height. Maybe other comfort descriptors are important for the comfort experience when users are working above their head.

5.4.1 Descriptors as predictor of comfort

Seven out of the 17 descriptors were strongly (beta>0.5) associated with comfort in screwdrivers, paintbrushes and hand saws: 'fits the hand', 'is functional', 'is easy in use', 'has a good force transmission', 'has a nice-feeling handle', 'offers a high task performance' and 'has a good friction between handle and hand'. These descriptors can be entitled as very important and should always be considered as important customer needs in hand tool design.

However, some descriptors are important for hand saws and screwdrivers, but are not important for paintbrushes, like 'needs low hand grip force supply' and 'causes cramped muscles', which can be explained by task differences. It is obvious that sawing and screwing are accompanied by higher force exertions than painting. Therefore, these descriptors ('needs low hand grip force supply' and 'causes cramped muscles') are important for screwdrivers and hand saws and are not for paintbrushes. Hence, when designing hand tools which need force exertions, these descriptors should be taken into account.

Then, there are three descriptors which are strongly associated with comfort in using hand saws only: 1) 'is a high quality tool', 2) 'causes peak pressures on the hand' and 3) 'looks professional' are more related to comfort in using hand saws than to comfort in using screwdrivers and paintbrushes. This will be explained below.

The quality of the hand saw, especially the saw blade, is very important for the comfort experience, because it determines how easy the saw blade cuts the wood. This affects several items which underlie comfort in hand tools, like the task performance, the perceived functionality of the hand tool, and the occurrence of adverse body effects like peak pressures on the hand and cramped muscles. The work side (the saw blade of the tool) appears to play a more important role in comfort in using hand saws, than in using screwdrivers and paintbrushes as a bad designed saw blade directly results in feelings of discomfort and a lower productivity (Kuijt-Evers et al., 2006). Hence, the effect of the work-side of the tool on comfort experience may be different for different kind of hand tools.

The occurrence of peak pressures on the hand is also more important in hand sawing than in working with screwdrivers or painting. This can be explained by the normal forces on the palm of the hand when using a hand saw. In working with screwdrivers, the skin of the hand is exposed to shear forces, which do hardly result in peak pressures on the hand. Using paintbrushes does not need a forceful grip either does the performed movement. Therefore, peak pressures on the hand do not occur in painting. Hence, peak pressures are no issue in using screwdrivers and paintbrushes.

The association between the professional look of the hand saws and comfort is hard to explain because no association was found for screwdrivers and paintbrushes. However, we suppose that the work side of the hand tool has to do with it. The paintbrushes and the screwdrivers had different handles, but the work side (bristles and tip) did appear more or less the same. The saw blade of the hand saws looked clearly different from each other, which may have influenced the ratings of the carpenters on the descriptor: 'looks professional'. Although the appearance does not play a major role in comfort in using hand tools (Kuijt-Evers et al., 2005), it was seen that a professional look does play a main role in comfort at first sight (Kuijt-Evers et al., 2004) and hence, will be important in product buying decisions.

5.4.2 Underlying factors of comfort

The descriptors were divided into factors by PCA, to obtain the underlying factors of comfort. The results show that the underlying factors of comfort in using hand tools (i.e., screwdrivers, paintbrushes, hand saws) consist of 4 topics: *functionality*, *physical interaction*, *adverse effects on skin*, and *adverse effects in soft tissues*.

Some questions come up, when looking at these data. Firstly, it is remarkable that for hand saws, *functionality* was not classified into the same factor as *physical interaction* in contradiction with screwdrivers and paintbrushes. This depended on the kinds of saws, which were used during the tests. For instance, one of the saws was of high quality. It had a very nice shaped and nice feeling handle, which fitted the hand perfectly. Hence, all descriptors, which are associated with physical interaction, were rated highly. However, the blade was not suitable for cross cutting a wooden beam. The teeth were too small and the teeth count (number of teeth per inch) was too high. Actually, this saw blade was designed to cut plate material. The use of this hand saw resulted in a low task performance (objectively measured) (Kuijt-Evers et al., 2006) and low ratings on functionality, task performance and other descriptors, which determine the factor functionality, while the ratings on physical interaction (like 'fits the hand', 'has a nice feeling handle') were high. For the other hand tools (paintbrushes and screwdrivers), the ratings on descriptors of *functionality and physical interaction* were on the same level for all studied hand tools, either high or low depending on the tool. This explains why the ratings of the descriptors of functionality and physical interaction are related to each other (and therefore classified in the same factor) in using paintbrushes and screwdrivers, but are not related to each other in using hand saws (resulting in two different factors).

The former example illustrates a point of weakness of the methodology. The same figure was seen for the association between comfort descriptors of the hand tools on the one hand with comfort experience on the other hand. The properties of one of the evaluated hand tools can influence the prediction model. For instance, if a property of a hand tool -which is related to a descriptor of the CQH- is of exceptional poor design, this can dominate the comfort experience. For example, the shape of the handle can dominate the rating on 'causes peak pressures on the hand', when the shape has rather a square cross-section than a oval cross-section (compare hand saw B to hand saw E). This may also influence the overall comfort rating. In this way, a high correlation can be found between 'causes peak pressures on the hand' and comfort. Therefore, it was important to include different kinds of the current available hand saws, paintbrushes and screwdrivers, in order to cover the largest range of possible varieties in engineering characteristics within a type of hand tool but avoiding the extremes, as we did.

Secondly, the question arises why adverse body effects are split into different factors, namely *adverse effects on skin* and *adverse effects in soft tissues*. This is remarkable as in a previous study, only one factor (i.e., *adverse body effects*) contained both the adverse effects on skin and the adverse effects in soft tissues (Kuijt-Evers et al., 2005). Adverse effects on skin are descriptors like: 'feels clammy', 'causes blisters', and 'causes an inflamed skin'. These effects are mostly related to the material of the handle and the friction between handle and hand (present shear forces). Moreover, pressure forces on the skin (normal forces) can also contribute to adverse effects on the skin. Adverse effects in soft tissues are more related to the task which is performed. Cramped muscles and numbness and lack of tactile feeling occur by performing tasks which cause fatigue in specific body parts, like arm and shoulder. From this point of view it is obvious that adverse effects on the skin do not always occur in the same amount as adverse effects in soft tissues. Therefore they are separated in different factors.

The differences between the results from the PCA of the screwdriver data compared to the previous study (Kuijt-Evers et al., 2005), depend on the fact that the current study deals only with a selection (17) of the 27 descriptors used in the previous study.

5.4.3 Factors as predictors of comfort

The importance of the comfort factors differ between screwdrivers, paintbrushes and hand saws. However, *functionality* is strongly associated with comfort of all kinds of hand tools, followed by *physical interaction*. Additionally, *adverse body effects* also play a role in screwdrivers and hand saws: *Adverse effects on the skin* were associated with comfort in working with screwdrivers and *adverse effects in soft tissues* with comfort in using hand saws. Hence, it seems that the type of task and the force direction on the hand determine what kinds of adverse body effects play the most important role. For instance, *adverse effects on the skin* can be associated by the presence of shear and normal forces on the hand surface, while *adverse effects in soft tissues* occur when force exertions of arm and shoulder are needed.

The same figure was seen for comfort in sitting. The importance of the underlying factors differ between office chairs (Helander and Zhang, 1997) and racing bike saddles (Oudendijk and Delleman, 2004). Helander and Zhang (1997) found that comfort in sitting on office chairs was only affected by aesthetics and well-being. However, comfort in sitting on racing bike saddles was mainly associated by what Oudendijk and Delleman (2004) called 'feeling' (i.e., hurts on certain locations and feels nice), while the contribution of 'appearance' only became stronger when the problems on 'feeling' decreased (Oudendijk and Delleman, 2004).

5.4.4 Application of the results

The results of this study imply that comfort descriptors and comfort underlying factors which are valid for one hand tool, do not necessarily concern other kinds of hand tools. Therefore, we propose a flow chart to support designers and researchers to choose the appropriate descriptors as customer needs to be fulfilled by a hand tool (Figure 6). Only descriptors which are strongly (beta>0.5) or moderately (beta>0.3) (Cohen et al., 2003) associated with screwdrivers, paintbrushes or hand saws are mentioned in the flow chart. The first decision is based on the task (low or high intensity) which illustrates the difference between screwdrivers and hand saws on the one hand and paintbrushes on the other. The second decision is based on the force direction on the hand (shear forces or normal forces), which is the main difference between hand saws and screwdrivers.

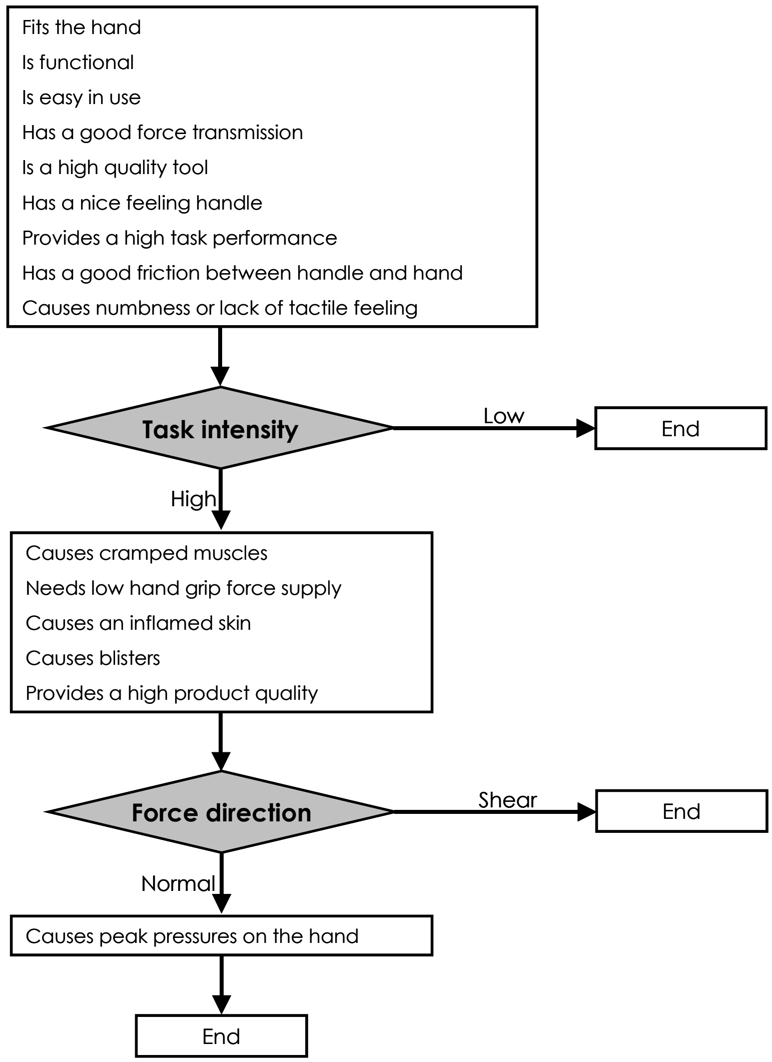


Figure 6 Flow chart to support designers and researchers to focus on the appropriate comfort descriptors in hand tool evaluation and design

This flow chart is based on findings of the current study and the differences between the studied hand tools. Therefore, it has to be validated with other kinds of hand tools and for different groups of end-users (DIY-users and professionals) in the future. Moreover, it has to be validated for occupational situations in which hand tools are used under different circumstances. In addition, designers should evaluate this flow chart, in order to get insight into the usability of this flow chart for addressing comfort in the hand tool design process.

5.5 Conclusion

We conclude that the same factors underlie comfort in different kinds of hand tools, specifically, the *functionality*, the *physical interaction*, the *adverse effects on the skin*, and the *adverse effects in soft tissues*. However, the importance of these underlying factors is different for different kinds of hand tools. The relative importance of the comfort descriptors also depends on the type of hand tool. A flow chart was proposed to assist designers and researchers in decision making about which descriptors should be taken into account. The decisions are based on the task intensity (movement frequency and force exertion) and the force direction.

5.6 Acknowledgements

We would like to thank the Dutch Ministry of Economic Affairs, Stichting Arbouw, Bahco Tools, and Copenhagen Gold for their support. Special thanks to Intergamma b.v. who gave us the opportunity to perform our measurements in one of their DIY-shops, asking their visitors to participate in the screwdriver study.

5.7 References

Aptel, M., Claudon, L., Marsot, J., 2002. Integration of ergonomics into hand tool design: principle and presentation of an example. International Journal of Occupational Safety and Ergonomics, 8 (1): 107-115.

Christensen, A.D., Bishu, R. 2000. Hand tool design: are biomechanical criteria the same as aesthetic criteria? A preliminary study. Proceedings of the IEA 2000/HFES 2000 Congress. 4-564-4-577.

Cohen, J., Cohen, P., West, S.G., Aiken, L.S. 2003. Applied multiple regression/correlation analysis for the behavioral sciences. 3th edition. Lawrence Erlbaum Associates, Inc. Mahwah, New Jersey, pp 52.

Helander, M.G., Zhang, L., 1997. Field studies of comfort and discomfort in sitting. Ergonomics, 40 (9): 895-915.

Kluth, K., Kelermann, H.G., Strasser, H., 2004. Assessment of the ergonomic quality of file handles using electromyographic and subjective methods. Occupational Ergonomics, 4 (2): 133-142.

Kuijt-Evers, L.F.M, Groenesteijn, L., Looze, M.P. de, Vink, P. 2004. Identifying factors of comfort in using hand tools. Applied Ergonomics 35 (5): 453-458.

Kuijt-Evers, L.F.M., Twisk, J.W.R., Groenesteijn, L., Looze, M.P. de, Vink, P. 2005. Identifying predictors of comfort and discomfort in using hand tools. Ergonomics. 48 (6): 692-702.

Kuijt-Evers, L.F.M., Bosch, T., Huysmans, M.A., Looze, M.P. de, Vink, P. 2006. Association between objective and subjective measurements of comfort and discomfort in hand tools. Applied Ergonomics (in press).

Marsot, J. and Claudon, L. 2004. Design and ergonomics. Methods for integrating ergonomics at hand tool design stage. International Journal of Occupational Safety and Ergonomics. 10 (1): 13-23.

Mital, A., Kilbom, Å., 1992. Design, selection and use of hand tools to elleviate trauma of the upper extremities: Part II – The scientific basis (knowledge base) for the guide. International Journal of Industrial Ergonomics, 10 (1-2): 7-21.

Oudendijk, M.L.W., Delleman, N.J. 2004. Comfort evaluation of racing bike saddles. TNO report TM-04-D013.

Sperling, L., Dahlman, S., Wikström, L., Kilbom, Å., Kadefors, R. 1993. A cube model for the classification of work with hand tools and the formulation of functional requirements. Applied Ergonomics. 24 (3), 212-220.

Twisk, J.W.R. 2003. Applied longitudinal data analysis for epidemiology; a practical guide. Cambridge: Cambridge University Press.

Vink, P., Overbeeke, C.J., Desmet, P.M.A. 2005. Comfort experience. In: Vink, P. Comfort and design; principles and good practice. CRCpress, Boca Raton.

Zhang, L., Helander, M.G., Drury, C.G. 1996. Identifying factors of comfort and discomfort in sitting, Human Factors. 38 (3): 377-389.

An application of QFD to the design of comfortable screwdrivers

Chapter 6

Chapter 6

Abstract

Quality Function Deployment is proposed as an effective design method to integrate ergonomic needs and comfort into hand tool design because it explicitly addresses the translation of customer needs into engineering characteristics. A crucial step during QFD concerns the linking of engineering characteristics to customer needs in the House of Quality by the design team. It is generally assumed that design teams are capable of accurately predicting the effect of a change in engineering characteristics on customer needs (also referred to as 'Whats'/'Hows' correlations). This paper explicitly tests this assumption by comparing the 'Whats'/ 'Hows' correlations estimated by a design team with the effect sizes observed in a systematic user evaluation study. Testing the assumption is important, because inaccurate estimates may lead to ineffective (re)design of hand tools and a waste of company resources. Results revealed that the design team's 'Whats'/'Hows' correlation estimates were not as accurate as is generally assumed. Twenty-five percent of the estimates differed significantly with those observed in the user evaluation study. Thus, QFD is a useful method to assist design teams in designing superior and more comfortable hand tools, but only on the condition that the effect of engineering characteristics on customer needs are validated, preferably by means of a systematic user evaluation study.

This paper is submitted to Applied Ergonomics
Kuijt-Evers, L.F.M., Morel, K.P.N., Vink, P., Eikelenberg, N.L.W. Can design teams accurately estimate the change in customer needs' perception produced by a change in engineering characteristics? An application of QFD to the design of comfortable screwdrivers.

6 An application of QFD to the design of comfortable screwdrivers

6.1 Introduction

Many hand tools have changed very little in the course of the 20th century (Haapalainen et al., 2000). During that time, hand tool design focused on tool functionality in order to improve task efficiency and allow for standardization. The tool should perform the task for which it was designed and corresponded to the characteristics of the greatest possible number of users (Aptel et al., 2002; Marsot and Claudon, 2004). The last ten years however, emphasis has shifted more towards the ergonomic needs of the user (to do the job harmlessly, effortlessly and comfortably (Aptel et al., 2002; Marsot and Claudon, 2004)). Simultaneously, various methodological tools to involve users and to integrate users' ergonomic needs into hand tool design have been put forward, such as the '11-point programme to design ergonomic hand tools' (Bobjer and Jansson, 1997), the 'spiral model of hand tool design' (Aptel et al, 2002), and Quality Function Deployment (QFD, Akao, 1990; Haapalainen et al., 2000; Marsot, 2005).

Of these tools, QFD appears to be the most suitable one, because it is the only tool that explicitly addresses the translation of customer needs (in this case customer requirements involving hand tool use) into engineering characteristics (in this case product properties of hand tools) by means of the 'House of Quality'. QFD has been applied earlier to hand tools by Marsot (2005) who used the House of Quality to design a boning knife, and by Haapalainen et al. (1999/2000) who evaluated pruning shears using the House of Quality.

Filling the House of Quality starts with the question: What do customers want? Their requirements are called customer needs. These are phrases which are used by customers to describe products and product characteristics (e.g., 'hand tool is light in use', 'hand tool can be used with gloves' (Haapalainen et al., 1999/2000)). Mostly, customer needs are collected from market research (Hauser & Clausing, 1988). The next question is: How can the product be changed to fulfil the customer needs? Now, the product is described in the language of the engineer. Along the top of the House of Quality, the design team lists those engineering characteristics that are likely to affect one or more of the customer needs (Hauser & Clausing, 1988). Examples are 'large force output' and 'suitable grip span' (Haapalainen, 1999/2000). The next step is to indicate the extent to which each engineering characteristic affects each customer need. This is usually done by assigning symbols or numbers (9=strong effect, 3= moderate effect, 1=some effect, 0= no effect) to each combination of customer need and engineering characteristic. In QFD terminology, the effects of a change in engineering characteristics on customer needs' perception are referred to as 'Whats'/'Hows' correlations (Akao, 1990; Hauser and Clausing, 1988; Hjort et al., 1992; Sullivan, 1986).

The linking of the customer needs to the engineering characteristics (that is estimating the 'Whats'/ 'Hows' correlations) is usually done by the design team. Based on these estimations, the design team gets insight into which engineering characteristics should be modified in order to better meet the requirements of the customers. The 'Whats'/'Hows' correlations give insight in the effect of a change in engineering characteristics on the perception of the customer needs. An error in estimating these effects, will propagate to successive stages during the design process (Han, et al., 2001). So, for a successful application of QFD, it is crucial that the design team's estimations of the 'Whats'/'Hows' correlations are accurate. Inaccurate estimations are likely to result in unsuccessful (re)designs as the design team may focus on the modification of engineering characteristics that are believed to strongly affect important customer needs, but that in fact do not or only minimally influence any of them.

Unfortunately, estimating 'Whats'/ 'Hows' correlations is a difficult step within QFD, which is characterized by high levels of uncertainty (Mitsufuji and Uchida, 1990; Haapalainen et al., 2000). Often, all input that design teams have to base their estimations on is their own experience, intuition, and determination (Mitsufuji and Uchida, 1990). Even if experience is high and intuition is good, 'there is no reliably established information concerning all correlation factors' (Haapalainen et al., 2000, p. 187).

Notwithstanding its importance, the accuracy of the estimations of the 'Whats'/'Hows' correlations between customer needs and engineering characteristics in hand tool design has not been studied before, as far as we know. The aim of the current study is to (1) determine to what extent the 'Whats'/'Hows' correlation estimates that design teams make are accurate (i.e., to what extent are design teams able to predict how a change of the engineering characteristics of a hand tool will change customers' perceptions of the use of that hand tool?); and (2) come up with a solution to validate the correlation estimates. This paper describes a case study on screwdriver design in which the design team's accuracy in estimating 'Whats'/'Hows' correlations is investigated. To this end, the design team's estimates 'Whats'/'Hows' correlations are compared with the effect sizes -- i.e., change in a response variable (in this case the customers' perceptions of the use of that hand tool) produced by a change in the explanatory variables (i.e., the engineering characteristics)-- obtained from a users' evaluation of a set of screwdrivers.

6.2 Using QFD to design a comfortable screwdriver

The empirical study reported here is about the design of a comfortable screwdriver. This object was chosen for three reasons: First, comfort is a particularly important topic for manufacturers of hand tools, as it is thought to play a significant role in product buying decisions (Vink et al., 2005). Second, comfort contributes to the task performance of the users of hand tools (Kuijt-Evers et al., 2006; Dempsey et al., 2002). Third, the experience of comfort in using a hand tool is difficult to predict by designers, mainly because comfort is a subjective personal experience in a particular environment (Looze, 2003). Therefore, when designing hand tools that provide comfort in its use, it is important to involve the end-user in the design process (Vink et al., 2005). Within QFD this can be done by including customer needs that are related to comfort and that have been collected from hand tool users themselves in the 'Whats' list of the House of Quality. This is the approach that was taken in the present study.

The present study consisted of two parts. In the first part, the design team drew up the engineering characteristics that would enable a set of predefined customer needs regarding the comfort of screwdriver handles to be satisfied. Next, the design team established the 'Whats'/'Hows' correlations between the customer needs and the engineering characteristics. The second part of the study consisted of an empirical study in which the effects of a change of the engineering characteristics on the perception of the customer needs were derived from users' evaluations of the comfort of five different screwdrivers. These two sets of effect sizes (i.e., the 'Whats'/'Hows' correlation estimates of the design team and the effect sizes derived from the user evaluations) were then compared with each other in order to assess to what extent the effects matched (i.e., the extent to which the design team's estimates were accurate).

6.2.1 'Whats' / 'Hows' correlations estimated by the design team (part 1)

The customer needs for a comfortable screwdriver were obtained by means of a procedure that is described in Kuijt-Evers et al. (2004) and Kuijt-Evers et al. (2005). In brief, this procedure included the following five steps. First, all potential comfort- and discomfort-related customer needs which were mentioned in the literature were collected by means of a systematic literature review. This resulted in a list of 58 customer needs for comfortable hand tools. Second, 22 experienced hand tool users (layman as well as professionals) produced their own set of comfort-related customer needs. This procedure did not reveal any new needs. Third, the same 22 hand tool users evaluated the list of 58 customer needs with regard to the degree to which these needs truly reflected comfort or discomfort in hand tool use. After this step, 36 customer needs remained, as more than 70 percent of the hand tool users associated them with comfort or discomfort. Fourth, 50 different hand tool users repeated this procedure, which resulted in a set of 27 customer needs. Finally, since the identified customer needs were for hand tools in general and derived without actually holding a hand tool, a screwdriver evaluation study was conducted in which the correlation between the customer needs and the comfort experience was established (Kuijt-Evers et al., 2005). Based on the results of that study, 14 customer needs were selected for inclusion in the House of Quality (see Table 6.1).

The engineering characteristics that are related to the 14 customer needs were drawn up by a design team, consisting of four industrial engineers, who have experience in using the House of Quality for different kinds of products. They were supported by a hand tool expert. For practical reasons (i.e., the user evaluation study), the number of engineering characteristics in the House of Quality was limited to four: (1) shape of the handle; (2) length of the handle; (3) presence of a guard; and (4) texture of the handle. These engineering characteristics were chosen because: (1) they could independently be varied between the handles (which means that there are no interactions in the roof of the House of Quality); (2) they could easily be produced by rapid prototyping, which was needed to make the prototypes for the user evaluation study.

After the customer needs and engineering characteristics had been identified, the members of the design team estimated the 'Whats'/'Hows' correlation (9 = strong effect, 3 = moderate effect, 1 = weak effect, or 0 = no effect) between each customer need and each engineering characteristic. When the estimates differed across members, they were discussed until consensus was reached.

6.2.2 Effect sizes derived from customers' evaluations (part 2)

Thirty-eight Do-It-Yourself (DIY) enthusiasts voluntary participated in this study (4 women and 34 men, mean age = 34.4 years). All of them had experience in working with screwdrivers. The study took place in a laboratory setting. Each subject evaluated 3 out of a set of 5 screwdrivers by turning one screw into and out of a pre-drilled wooden beam. One of the three screwdrivers was always the standard model (see below). The order in which the screwdrivers were presented was systematically varied across participants preventing the ratings to be affected by the sequence order. After using each screwdriver, participants were asked to evaluate it in terms of each of the customer needs from the House of Quality on a 5-point scale (1 = bad, 2 = weak, 3 = average, 4 = good, 5 = very good).

The set of five screwdrivers consisted of one screwdriver with a standard handle (as can be bought in the shop) and four with redesigned handles. All handles were made by rapid prototyping. For each of the four redesigned screwdrivers, one of the engineering characteristics was altered compared with the standard handle: (1) the shape of the cross-section of the handle was square instead of round; (2) the length of the handle was enlarged; (3) the presence of a guard was provided by adding a flange to the handle; and (4) the handle contained ribs to create a texture. The amount of change of the engineering characteristics was determined by ergonomic experts and based on the characteristics of currently available screwdrivers. Figure 6.1 shows the screwdrivers.

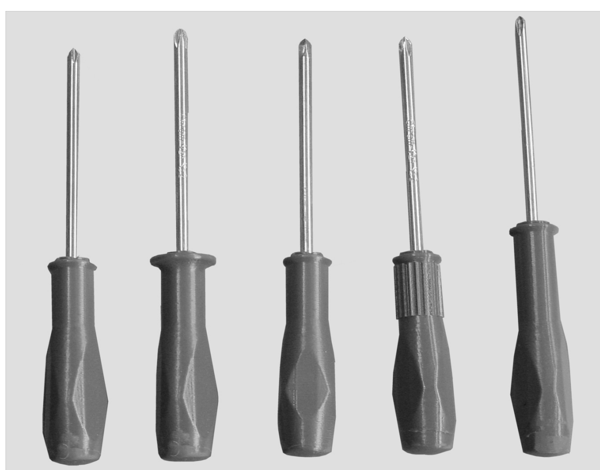


Figure 6.1 Prototypes of the screwdrivers. From left to right: standard handle, handle with supporting edge, handle with squared area, handle with ribs, enlarged handle.

As only one engineering characteristic was changed in each of the four prototypes with respect to the standard screwdriver, the influence of this specific characteristic on end-users' assessment of customer need fulfilment could be identified. For instance, when users would claim that the screwdriver with the enlarged handle better fulfilled the customer needs than the standard screwdriver, the superior performance could be attributed to the enlargement of the handle since this would be the only aspect that differed between the two screwdrivers.

In short, the first part of the study yielded design team estimates of the 'Whats'/'Hows' correlations between customer needs and engineering characteristics. The second part of the study yielded users' assessments of the degree to which four systematically altered screwdrivers fulfilled the set of 14 customer needs for comfortable screw drivers. In the next section, we will show how these data can be analyzed in order to assess the accuracy of the design team's estimates of the effects of a change of the engineering characteristics on the customer needs' perception.

6.2.3 Data analysis

In order to be able to compare the data from the user evaluation study with the estimates of the design team, the user evaluation scores had to be translated into effect sizes first. This was done as follows. The difference in user evaluations between each redesigned screwdriver and the standard screwdriver was calculated taking into consideration ceiling and floor-effects of the rating scale. An example will explain why this is necessary. Remember that each user evaluated three screwdrivers one by one. This means that the ratings for the second and third screwdrivers were affected by the rating(s) of the previously tested screwdriver(s). Therefore, the rating of the first screwdriver will affect the absolute maximum difference between the screwdrivers. For instance, if the rating of the first screwdriver was 3, the rating for the next screwdriver could be maximal 2 scale points higher because the highest possible rating was 5. However, when the first screwdriver was rated 4, and the user believed the next screwdriver to be 2 scale points better as in the first case, he could not express this differences on the rating scale, again because the maximum value was 5 (where a 6 would be the 'real' rating). The result of this is that some of the differences between the various screwdrivers are smaller than they should be due to the fact that the scale had definite end points.

To take these 'ceilings' and 'floors' into account, the relative difference in scores for each customer need between the standard and a redesigned screwdriver was calculated according to equations 1 and 2 (Twisk, 2003).

(1) when $Y_2 > Y_1$
$$\Delta Y = \frac{(Y_2 - Y_1)}{(Y_{max} - Y_1)}$$

(2) when $Y_2 < Y_1$
$$\Delta Y = \frac{(Y_2 - Y_1)}{(Y_1 - Y_{min})}$$

Y_1 represents the rating provided by a single user of one particular customer need (of the 14) for the standard screwdriver and Y_2 represents the rating of the same customer need for the redesigned screwdriver. Y_{max} is the maximum value ('ceiling') on the scale (i.e., 5) and Y_{min} is the minimum value ('floor') on the scale (i.e., 1). The relative difference (ΔY) represents the change in the user evaluation of a particular customer need as a result of a change in a specific engineering characteristic. To illustrate, if the engineering characteristic 'length of the handle' is changed from standard to enlarged, the degree to which a user's evaluation of a particular customer need (e.g., handle fits the hand) changes is ΔY. By calculating ΔY for each of the 14 customer needs for each of the four possible changes in the engineering characteristics and by taking the mean over all users, a matrix results with 56 cells that is comparable to the House of Quality 'Whats'/'Hows' matrix with 56 estimates (the 9-3-1-0 matrix) that the design team created. In fact, we argue that the ΔYs can be regarded as 'Whats'/'Hows' correlations. The effect of a change in an engineering characteristic on the perception of a customer need can be illustrated by a regression line as shown in Figure 6.2. This regression line can be described as: Y = a + bX + e, where Y is the predicted score (i.e., user evaluation of customer need), a is the intercept, b is the slope of the regression line (i.e. the correlation coefficient between X and Y), X is the predictor (i.e., change in engineering characteristic), and e is the error term. The slope of the regression line b is calculated as: $b = \Delta Y/\Delta X$. When $\Delta X = 1$, as is the case here when each engineering characteristic is changed relative to the standard screwdriver, ΔY will equal b and thus represents the correlation coefficient.

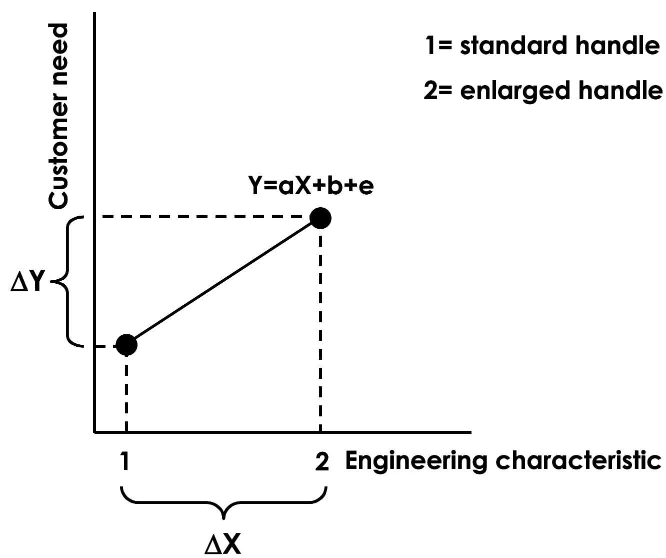


Figure 6.2 The relative difference between the ratings of the customer needs (ΔY) is the slope (a) of the regression line when ΔX=1

A final step that had to be taken before the correlation matrix that resulted from the user evaluation study could be compared with the correlation estimates matrix that the design team created, was the assignment of the former correlation coefficients to the same ordinal correlation categories (strong, moderate, weak, and no correlation) that were used by the design team. To this end, we followed the rules of thumb suggested by Cohen et al. (2003). Specifically, this meant that a mean correlation coefficient of $r > .5$, $.3 < r < .5$, $.1 < r < .3$, and $r < .1$ were qualified as strong (9), moderate (3), weak (1), or absent (0) respectively. A non-parametric Wilcoxon signed rank test was used to examine whether significant differences existed between the estimated 'Whats'/'Hows' correlations of the design team and the effect sizes obtained from the user evaluation study.

6.3 Results

The resulting matrices are shown in Table 6.1. For each pair of engineering characteristics and customer needs, the estimated 'Whats'/'Hows' correlations and the effects based on the users' evaluations are shown. The Z-values obtained from the Wilcoxon signed rank test show whether significant differences exist between the results from the design team estimations and the results obtained from the valdiation study.

Table 6.1 shows that 'fits in the hand', 'has a good force transmission', 'needs low hand-grip force supply' and 'has a good friction between handle and hand' was strongly affected by the 'shape of the handle'. 'Fits the hand' and 'has a good force transmission' was also strongly influenced by the 'texture of the handle'. The 'length of the handle' and the 'presence of a guard' only moderately affected the customer needs.

Comparing the two sets of data, 14 out of 56 (25 percent) differed significantly. Nine of these differences concerned over-estimations (i.e., the design team estimated a stronger effect than observed in the user evaluation study), five concerned under-estimations (i.e., the design team estimated a weaker effect than found in the user evaluation study).

The majority of differences between the estimations and the data from the user evaluation study were found for the texture of the handle. The design team predominantly over-estimated the effect that adding texture to the handle would have on users' evaluation of the customer needs. For instance, handle texture was thought to strongly affect 'handle feels nice', 'causes pressure on the hand', 'causes an inflamed skin', and moderately affect 'does not feel clammy' and 'has a professional look'. In reality, users' evaluations of these customer needs turned out to be only weakly affected by the addition of texture to the handle.

Table 6.1 Overview of estimated 'Whats'/'Hows' correlations by the design team and the 'real effects' (i.e., effect sizes based on the relative difference from the validation study) calculated as mean of the relative difference for all participants divided into categories. 4=strong, 3=moderate, 2=weak, 1 = no effect. The Z-values are obtained from the Wilcoxon signed rank test. * indicates a significant difference (p<.05) between the results of the design team estimations and the results obtaine from the validation study.

	Shape			**Length**			**Guard**			**Texture**		
	Estimation	**Validation**	**Z-value**	**Estimation**	**Validation**	**Z-value**	**Estimation**	**Validation**	**Z-value**	**Estimation**	**Validation**	**Z-value**
Fits the hand	4	4	-1.34	3	3	-1.24	1	3	-2.71*	2	4	-2.84*
Is functional	4	2	-1.89	1	2	-1.34	3	2	-2.03*	3	3	-1.84
Has a good force transmission	4	4	-1.41	3	3	0.00	1	3	-2.45*	3	4	-0.92
Handle feels nice	4	3	-1.41	2	2	-0.33	3	3	-0.44	4	2	-2.64*
Causes pressure on the hand	3	2	-1.93	1	3	-1.63	3	3	-1.39	4	2	-2.33*
Causes blisters	3	2	-1.84	2	2	-0.69	1	2	-1.86	4	3	-2.53*
Causes pain	2	2	-0.35	1	2	-1.63	2	2	-0.37	3	3	-0.46
Causes numbness or lack of tactile feeling in hand	2	2	-0.35	1	3	-1.89	1	2	-2.07*	3	2	-1.65
Needs low hand grip force supply	4	4	-1.41	2	3	-1.41	1	2	-1.86	3	3	-0.91
Causes cramped muscles	3	3	-0.96	1	2	-1.34	1	2	-1.63	2	2	-0.28
Has a good friction between handle and hand	2	4	-2.35*	1	2	-1.63	2	2	-0.28	4	3	-2.00*
Causes an inflamed skin	1	2	-1.34	1	1	-1.00	2	1	-1.94	4	2	-2.24*
Does feel clammy	1	2	-1.63	1	2	-1.60	1	1	-1.34	3	2	-2.76*
Has a professional look	4	2	-2.00*	3	3	-0.41	2	2	-0.80	3	2	-2.02*

Strong effects were also expected for 'causes blisters on the hand' and 'has a good friction between handle and hand', but these effects were only moderate according to the users. Only the effect of texture on 'fits the hand' was underestimated. The design team thought that texture would weakly affect 'fits the hand' but the user evaluation study showed a strong effect.

The presence of a guard was under-estimated for three customer needs: 'fits the hand', 'has a good force transmission', and 'causes numbness and lack of tactile feeling' were expected to be unaffected by the presence of a guard. However, the presence of a guard turned out to moderately and weakly affect these customer needs. In addition, the fact that a guard was present affected the functionality less than was expected (weak effect instead of the expected moderate effect).

The effect of the shape of the handle was estimated inaccurately for two customer needs. The effect on the friction between handle and hand was under-estimated by the design team (strong instead of weak effect) and the effect on 'has a professional look' was over-estimated (weak instead of strong effect).

For 'length of the handle' none of the 'Whats'/'Hows' correlations estimated by the design team differed significantly from the effect sizes observed in the user evaluation study.

6.4 Discussion

Recent studies on hand tool design, including the present one, have had design teams apply QFD, and in particular the House of Quality, in order to integrate ergonomics into the design of hand tools. A crucial step in the application of the House of Quality concerns the estimation of the 'Whats'/'Hows' correlations, that is, how a change of the engineering characteristics will change customers' perceptions. In general, it is assumed that design teams are capable of providing accurate 'Whats'/'Hows' correlations, because they are believed to possess the knowledge, experience, and intuitions that are required to do so. The purpose of the current study was to explicitly test the assumption that design teams are capable of accurately estimating 'Whats'/ 'Hows' correlations that are related to comfort-related customer needs. This is important, because inaccurate estimates may lead to ineffective (re)design of hand tools.

In order to be able to assess the accuracy of the 'Whats'/ 'Hows' correlation estimates made by a design team, a user validation study was conducted. In this study, users evaluated a set of five screwdrivers that were created by rapid prototyping. The set of screwdrivers consisted of a reproduction of a standard model that can be bought in the shop and four redesigns that each differed from the standard model on a different engineering characteristic. Users tested the different screwdrivers and indicated how well or bad they performed on a set of 14 measures that were related to comfort in use (e.g., fits the hand, causes blisters). Through this approach, we were able to determine how a particular change in the design of a screwdriver (e.g., changing the texture of the handle) affected users' evaluations of the comfort of the screwdriver. The set of observed correlation coefficients between each engineering characteristic and each customer need that resulted from the user evaluations could then be compared to the 'Whats'/'Hows' correlation estimated by a design team for the same set of needs and engineering characteristics.

Our results showed that 75 percent of the effects of a change in engineering characteristics on the customer needs' perception were accurately estimated, if we regard the user evaluations as the standard. The engineering characteristics presence of a guard and texture accounted for most of the inaccurate estimations. Specifically, the effect of a change in the guard on user evaluations of comfort was generally underestimated, whereas the effect of a change in texture on user comfort evaluations was consistently overestimated. Overestimation of 'Whats'/'Hows' correlations will lead to ineffective (re)designs and thus a waste of company resources, since effort will be invested to change design characteristics that only moderately or in the worst case not at all affect the end-user's comfort experience. The following example will illustrate what might happen when a design team underestimates 'Whats'/'Hows' correlations in the case of designing a comfortable screwdriver. In a study by Kuijt-Evers et al. (2005), it was found that the customer needs which are mostly related to comfort in working with screwdrivers are 'fits the hand' (beta=0.79), 'has a nice-feeling handle' (beta=0.77), 'needs low hand grip force supply' (beta=0.76) and 'has a good force transmission' (beta=0.74). In the current study, the design team underestimated the effect of a presence of a guard and a change in texture on the customer need 'fits the hand'. They expected 'no effect' and a 'weak effect' respectively (Table 1), whereas both effects turned out to be strong during the user evaluation study. The same pattern was observed for 'has a good force transmission' in relation to the shape of the handle. Based on these estimations, the design team would fail to adjust the shape, texture, and guard of the new screwdriver handle in such a way that it would significantly improve the comfort of the screwdriver.

The above example illustrates an important point: even though design teams are able to accurately predict 3 out of 4 'Whats'/ 'Hows' correlations (assuming that the performance of the design team in this study is representative of design teams in general), the 25 percent of inaccurate estimations could have severe consequences. Therefore, it appears to be highly recommendable to do user evaluation studies to validate design team estimates, unless the effects are already known (e.g., from previous studies). At the same time, however, performing such user evaluation studies introduces serious practical problems. When we take into consideration that a typical QFD application would include 30-100 customer needs in the House of Quality (Hauser and Clausing, 1988) and a similar number of engineering characteristics, it is obviously impossible to validate all the 'Whats'/'Hows' correlations between the customer needs and engineering characteristics in the way we did in our user evaluation study. A possible solution for this problem would be to focus on the most important customer needs and/or on the engineering characteristics that have an unknown effect on the customer needs.

The specific way we set up the user evaluation study enabled us to explicitly determine how a change in a particular engineering characteristic affected user comfort evaluations, but it also introduced a potential problem: for each engineering characteristic only one alternative to the standard screwdriver handle was included. The way in which the engineering characteristics were altered in the redesigned handles compared to the standard handle, determined the relative differences between the standard handle and the redesigned handles, and hence the effect of the change in engineering characteristic and on the change in customer needs in the eyes of the users. Different values for each of the engineering characteristics would probably have led to different effects. It is exactly for this reason that the change in engineering characteristics of the redesigned screwdriver handles in comparison with the standard handle was determined on the basis of existing variations in screwdriver handles that are currently available on the market. As such, these changes reflect realistic differences between screwdriver handles and would constitute realistic changes for the actual redesign of screwdriver handles in practice.

Another factor that needs closer attention is the duration of the user test. Users were asked to turn one screw into and out of a wooden beam. Their evaluations of the different screwdrivers were based on this short period of use. To what extent would user evaluations change if the time of use changes (e.g., turning 5 screws into and out of a wooden beam), so when discomfort is significantly increased? As discomfort is mostly affected by cramped muscles in working with screwdrivers (Kuijt-Evers et al., 2005), users would be expected to judge 'causes cramped muscles' and related customer needs (e.g., causes numbness and lack of tactile feeling) more negatively when turning more screws. However, these shifts in user evaluations would be the same for all screwdrivers. This is true, because contrary to what users appear to think, the design of the screwdriver itself or of its handle hardly influences the degree to which muscles cramp or hands turn numb (Kuijt-Evers et al., 2005). Cramped muscles are mainly caused by the screwing task itself. Therefore, lengthening the test duration would leave the differences in evaluations between the standard handle and the redesigned handles unchanged and would thus not affect our results.

6.5 Conclusion

Three main conclusions can be drawn from this study. First, although it is generally assumed that design teams that use QFD are capable of accurately predicting the 'Whats'/'Hows' correlations between customer needs and engineering characteristics, this assumption might not hold in reality. The design team in our study predicted only 75 percent of the correlations accurately. Although this might seem to be an acceptable performance, the 25 percent of errors (i.e., over- and underestimations) made is likely to have serious consequences in terms of missing out on opportunities to improve the product design or investing company resources in ineffective (re)design. Therefore, our second conclusion is that validation of a design team's 'Whats'/'Hows' correlation estimates should take place whenever possible, preferably by means of a systematic user evaluation study such as the one that was conducted here. Third, whereas QFD is a helpful tool to assist design teams in deciding which engineering characteristics to focus on in order to design a product that truly fits comfort-related customer needs, it will not tell them exactly how engineering characteristics should be changed to achieve this. For example, a design team may learn from QFD that 'a good friction between handle and hand' can be achieved by optimizing the shape of the handle, but they do not know what the shape should be like. This is a particularly complex issue, because the relationship between customer needs and engineering characteristics is not always linear; parabolic relationships occur frequently as well (Dawson and Askin, 1999). Experienced design teams will already know a lot about the exact way in which changes in engineering characteristics affect product performance regarding the customer needs. For such teams, QFD alone will do the trick. In all other cases, however, additional action from the design team is needed, before a truly superior new hand tool can be developed.

6.6 References

Akao, Y. 1990. An introduction to Quality Function Deployment. In: Akao, Y., Quality Function Deployment; Integration Customer Requirements into Product Design. Productivity Press, Cambridge, 1-24.

Aptel, M., Claudon, L., Marsot, J., 2002. Integration of ergonomics into hand tool design: principle and presentation of an example. International Journal of Occupational Safety and Ergonomics, 8 (1): 107-115.

Bobjer, O. and Jansson, C. 1997. A Research Approach to the Design of Ergonomic Hand Tools. The 11-Point Programme. In: From Experience to Innovation. P. Seppälä, T. Luopajärvi, C.H. Nygård, and M. Mattila (eds.) Proceedings of the 13th Triennial Congress of the International Ergonomics Association, Tampere, June 29- July 4. vol. 2. Helsinki: Finnish Institute of Occupational Health: 193–195.

Cohen, J., Cohen, P., West, S.G., Aiken, L.S. 2003. Applied multiple regression/correlation analysis for the behavioral sciences. 3th edition. Lawrence Erlbaum Associates, Inc. Mahwah, New Jersey, pp 52.

Dawson, D. and Askin R.1999. Optimal new product design using quality function deployment with empirical value functions. Quality and Reliability Engineering International 15: 17-32.

Dempsey, P.G., McGorry, R.W., Leamon, T.B., O'Brien, N.V., 2002. Bending the tool and the effect on human performance: Further investigation of a simulated wire-twisting task. AIHA Journal, 63 (7): 586-593.

Haapalainen, M., Kivistö-Rahnasto, J., Mattila, M., 1999/2000. Ergonomic design of non-powered hand tools : An application of quality function deployment (QFD). Occupational Ergonomics, 2 (3): 179-189.

Han, S.B., Chen, S.K., Ebrahimpour, M., Sodhi, M.S. 2001. A conceptual QFD planning model. International Journal of Quality & Reliability Management, 18 (8): 796-812.

Hauser, J., Clausing, D., 1988. The House of Quality; Design is a team effort, but how do marketing and engineering talk to each other? Harvard Business Review, 66 (3) May-June: 63-73.

Hjort, H., Hananel, D., Lucas, D., 1992. Quality Function Deployment and integrated product development. Journal of Engineering Design, 3 (1): 17-29.

Kuijt-Evers, L.F.M., Groenesteijn, L., Looze, M.P. de, Vink, P., 2004. Identifying factors of comfort in using hand tools. Applied Ergonomics. 35 (5), 453-458.

Kuijt-Evers, L., Twisk, J.W.R., Groenesteijn, L., Looze, M.P. de, Vink, P. 2005. Identifying predictors of comfort and discomfort in using hand tools. Ergonomics 48 (6): 692-702.

Kuijt-Evers, L.F.M, Bosch, T., Huysmans, M.A., Looze, M.P. de, Vink, P. 2006. Association between objective and subjective measurements of comfort and discomfort in hand tools. Applied Ergonomics. In press.

Looze, M.P. de, Kuijt-Evers, L.F.M., Dieën, J. van, 2003. Sitting comfort and discomfort and the relationships with objective measures. Ergonomics, 46 (10): 985-997.

Marsot, J. and Claudon, L., 2004. Design and ergonomics. Methods for integrating ergonomics at hand tool design stage. International Journal of Occupational Safetey and Ergonomics, 10 (1): 13-23.

Marsot, J., 2005. QFD: a methodological tool for integration of ergonomics at the design stage. Applied Ergonomics, 36 (2): 185-192.

Mitsufuji, Y. and Uchida, T. 1990. Using and promoting House of Qualitys. In: Quality Function Deployment; Integrating customer requirements into product design. Akao, Y. (ed.) Productivity Press, Cambridge. 53-81.

Sullivan, L.P. 1986. A system to assure that customer needs drive the product design and production process. Quality Progress: 39-50.

Twisk, J.W.R., 2003. Applied longitudinal data analysis for epidemiology. Cambridge University Press, Cambridge.

Vink, P., Overbeeke, C.J., Desmet, P.M.A. 2005. Comfort experience. In: Vink, P. (ed) Comfort and design; principles and good practice. CRCpress, Boca Raton. 1-12.

Association between objective and subjective measurements

Chapter 7

Abstract

In the current study the relationship between objective measurements and subjective experienced comfort and discomfort in using hand saws was examined. 12 carpenters evaluated five different hand saws. Objective measures of contact pressure (average pressure, pressure area and P-t integral) in static and dynamic conditions, muscle activity (EMG) of five muscles of the upper extremity, and productivity were obtained during a sawing task. Subjective comfort and discomfort were assessed using the Comfort Questionnaire for Hand tools and a scale for Local Perceived Discomfort (LPD). We did not find any relationship between muscle activity and comfort or discomfort. The P-t integral during the static measurement (beta=–0.24, $p<.01$) was the best predictor of comfort and the pressure area during static measurement was the best predictor of local perceived discomfort (beta=0.45, $p<.01$). Additionally, productivity was highly correlated to comfort (beta=0.31, $p<.01$) and discomfort (beta=–0.49, $p<.01$).

This paper is in press by Applied Ergonomics
Kuijt-Evers, L.F.M., Bosch, T., Huysmans, M.A., Looze, M.P. de, Vink, P., Association between objective and subjective measures of comfort and discomfort in hand tools. Reprinted with permission from Elsevier.

7 Association between objective and subjective measurements of comfort and discomfort in hand tools

7.1 Introduction

Tool design may play an important role in the development of work-related problems in the hand and forearm. By improving the ergonomic properties of hand tools the health of users and their job satisfaction might be positively affected (Kadefors et al., 1993). In order to recognize ergonomically well-designed and comfortable hand tools, many hand tool evaluation studies have been conducted. Most studies combined objective measurements (to measure physical load) with subjective experiences of the subjects (to measure comfort or discomfort; e.g., Kluth et al., 2004; Strasser et al., 1996; Groenesteijn et al., 2004; Chang et al., 1999; Li, 2003; Kong and Freivalds, 2003, Freund et al., 2000).

Subjective measurements are most common when hand tools are evaluated with respect to comfort and discomfort. Most of them are focussed on discomfort experience. Methods to assess discomfort are 1) assessing the intensity of discomfort using a map of the palmar side of the hand (Groenesteijn et al., 2004; Kilbom et al., 1993; Kuijt-Evers et al., 2005), 2) rating handle discomfort (Kong and Freivalds, 2003; Chang et al., 1999) and 3) rating discomfort of whole body and hand (Kilbom et al., 1993). In other studies, properties of hand tools are evaluated like general handiness, and suitability for longer work (Kluth et al., 2004; Freund et al., 2000; Strasser, 1996; Chang et al., 1999; Groenesteijn et al., 2004). Comfort experience is considered in only a few hand tool evaluation studies (Kuijt-Evers et al., 2005; Freund et al., 2000).

Subjective evaluations have some clear disadvantages: they require a large number of subjects and are therefore time-consuming (Lee et al., 1993), and they are influenced by personal preferences (Chen et al., 1994) (e.g., using always the same brand). Moreover, there are some common known sources of unreliability of using subjective measures, like time error and context effects (Annet, 2002). In some cases, factors which have nothing to do with comfort or discomfort may influence the results. Therefore, objective measurements are used in addition to subjective measurements (e.g., electromyography (EMG) (e.g., Strasser et al., 1996; Fellows and Freivalds, 1991; Freund et al., 2000; Habes and Grant, 1997; Niemelä et al., 2000; Chang et al., 1999; Kadefors et al., 1993), hand-wrist postures (Eikhout et al., 2001; Kadefors et al., 1993), and grip force distribution and grip force (Fellows and Freivalds, 1991; Chang et al., 1999; McGorry, 2003). All the above mentioned objective measures have proven to discriminate between hand tools. For example, differences in EMG were found between different types of masons' trowels, file handles, shovel handles and plate shears (Strasser et al., 1996; Kluth et al., 2004; Chang et al., 1999; Kilbom et al., 1993). A new designed scraper influenced hand-wrist postures (Eikhout et al., 2001) and grip force was found to discriminate between different types of plate-shears, meat cutting knives and shovel handles (Kilbom et al.,1993; McGorry et al., 2003; Chang et al., 1999).

In the previous paragraphs, we argued that subjective measurements are preferred when evaluating hand tools on comfort and discomfort, as comfort and discomfort are subjective feelings. However, as subjective measurements have some clear disadvantages, it would be interesting if we could measure comfort and discomfort objectively. However, information is lacking for the relationship between objective measurements and subjective comfort and discomfort experience in hand tool evaluation. Hence, the usefulness of objective measures for measuring comfort and discomfort are unknown. The main goal of the current study is to investigate the relationship between objective and subjective measures, by assessed comfort and discomfort.

Avoiding negative health effects and providing more job satisfaction for workers are not the only reason to pay attention to the design of comfortable hand tools. Employers also want their employees to achieve high work efficiency. Therefore, hand tools should stimulate high work efficiency too. Providing comfort and avoiding discomfort on the one hand and a high productivity on the other hand are not necessarily contradictive. Some studies suggest that hand tools which provide more comfort and less discomfort seem to be associated to a higher productivity (e.g., Eikhout, 2001). However, correlation coefficients are, as far as we know, not calculated yet. Hence, the second aim of the present study is to identify the relationship between comfort or discomfort and productivity when using hand tools.

To achieve both goals, a hand tool evaluation study was designed in which five hand saws were evaluated. The research questions are: 1) does a relationship exist between muscle activity (measured by EMG) and hand contact pressure (average pressure, pressure area and pressure-time (Pt-)integral) on the one hand and subjective ratings of comfort and discomfort on the other hand in using hand saws? 2) Is productivity related to subjective ratings of comfort and discomfort in using hand saws?

The results of this study can be helpful to interpret objective data in terms of comfort and discomfort and indicate the most relevant objective types of measurement for the evaluation of comfort and discomfort in using hand tools. Additionally, the results may subscribe the importance of focussing on comfort and discomfort in hand tool design, if relationships exist between productivity and more comfort and less discomfort.

7.2 Methods

7.2.1 Design

Five hand saws were evaluated by twelve subjects. The five hand saws have a different market sector and they differ in product characteristics, like hand grip, saw blade and teeth (Figure 7.1).

Figure 7.1 Five hand saws were evaluated in case study 3

The objective measurements were 1) EMG (%MVC) of five muscles during two measurements, 2) static and dynamic contact pressure (average pressure, pressure area and pressure-time integral), and 3) productivity. Comfort and discomfort (local perceived discomfort) were subjectively measured. An overview of the dependent and independent variables is given in Table 7.1 (next page).

7.2.2 Subjects

Twelve male (professional) carpenters participated in this study. The subjects gave their written informed consent. Table 7.2 shows the demographics of the sample.

Table 7.2 Demographics of the sample

	Range	**Mean**	**SD**
Age (years)	38 - 64	50.2	8.6
Stature (cm)	169 - 190	179.6	5.5
Weight (kg)	70 - 98	82.6	8.9
Hand length (cm)*	17.6 - 21.5	20.1	1.2
Hand width (cm)	7.7 - 10.2	9.3	0.8
Grip force (N)	27 - 51	38.3	6.9

* Measured from top of the middle finger to the distal crease of the wrist

Table 7.1 Overview of the independent and dependent variables

	Measurement	Independent variables		Dependent variables
Objective measurements	Muscle activity (EMG)	First measurement	Saw A	%MVC
			Saw B	%MVC
			Saw C	%MVC
			Saw D	%MVC
			Saw E	%MVC
		Second measurement	Saw A	%MVC
			Saw B	%MVC
			Saw C	%MVC
			Saw D	%MVC
			Saw E	%MVC
	Contact pressure	Static measurement	Saw A	Average pressure
				Pressure area
				P-t integral
			Saw B	Average pressure
				Pressure area
				P-t integral
			Saw C	Average pressure
				Pressure area
				P-t integral
			Saw D	Average pressure
				Pressure area
				P-t integral
			Saw E	Average pressure
				Pressure area
				P-t integral
		Dynamic measurement	Saw A	Average pressure
				Pressure area
				P-t integral
			Saw B	Average pressure
				Pressure area
				P-t integral
			Saw C	Average pressure
				Pressure area
				P-t integral
			Saw D	Average pressure
				Pressure area
				P-t integral
			Saw E	Average pressure
				Pressure area
				P-t integral

Table 7.1 (continued) Overview of the independent and dependent variables

	Measurement	Independent variables		Dependent variables
	Productivity		Saw A	Number of pieces cut
			Saw B	Number of pieces cut
			Saw C	Number of pieces cut
			Saw D	Number of pieces cut
			Saw E	Number of pieces cut
Subjective measurements	Comfort		Saw A	Rating 1 – 7
			Saw B	Rating 1 – 7
			Saw C	Rating 1 – 7
			Saw D	Rating 1 – 7
			Saw E	Rating 1 - 7
	Discomfort (LPD)		Saw A	Sum of ratings of regions
			Saw B	Sum of ratings of regions
			Saw C	Sum of ratings of regions
			Saw D	Sum of ratings of regions
			Saw E	Sum of ratings of regions

7.2.3 Tasks

Static task

The static task was performed to measure contact pressure in statical circumstances. During the static contact pressure measurement, the subject put the tip of the hand saw blade against the adapter of a digital force gauge (MecMesin, AFG 100). The force gauge was attached to a wooden plate which was mounted in a direction of 35° to the horizontal (Figure 7.2). The subjects were asked to generate an output force of 40 N, while holding the hand grip of the hand saw as they were used to, except that now the hand mat was attached in the palm of the hand. During 10 seconds, the contact pressure was measured.

Dynamic task

The dynamic task (used to measure EMG, dynamic pressure, productivity, comfort and discomfort) was a standardized task of crosscutting a wooden beam (Figure 7.3). For this purpose, a beam of bankirai wood (77x82 mm) was attached to a Workmate (height 59 cm).

Figure 7.2 Static contact pressure measurement

Figure 7.3 Dynamic contact pressure measurement

Bankirai wood was chosen because of its constant grains and absence of knots, which provide constant conditions for every saw for every subject. The place of the saw- cuts were drawn on the beam, with an intersection of 15 mm. The subjects were told to maintain the same body posture during all conditions.

7.2.4 Subjective measurements

Both comfort and discomfort experience were measured using subjective measurement techniques.

Comfort Questionnaire for hand tools

The Comfort Questionnaire for Hand tools (CQH) is based on the results of a previous study in which descriptors associated with comfort in using hand tools were identified by end-users (Kuijt-Evers et al., 2005), e.g. hand tool fits the hand, has a good functionality, has a high task performance. For the current hand saw evaluation study 17 of these descriptors were selected. The subjects rated the items on a 7-point scale (1= totally disagree, 7= totally agree). After the end-users rated to what extent the hand saw fulfils these descriptors, they rated overall comfort after short time use on a 7-point scale (1=very uncomfortable, 7=very comfortable).

Discomfort of arm and hand

Discomfort was measured using the Local Perceived Discomfort (LPD) method (Groenesteijn et al., 2004). This method consisted of a detailed hand-wrist map, with 23 regions and a map of the upper extremity which consisted of four regions. Feelings of pain, numbness and pressure, tiredness underlie discomfort. A six point-scale was used to assess discomfort (ranging from 0 = no discomfort,…, to 5 = extreme discomfort, almost maximum) per region.

7.2.5 Objective measurements

EMG

Muscle activity was measured by means of surface electromyography (EMG, porti 16/ASD system, TMS, Enschede). Bipolar Ag/AgCl (Medicotest) surface electrodes were placed with an inter-electrode distance of 25 mm at five muscles at the subject's dominant side: m. extensor carpi radialis, m. flexor carpi radialis, m. triceps brachii caput mediale, m. trapezius pars descendens and m. trapezius pars tranversa/m. romboideus major (electrode positions according to Franssen (1995)).

A reference electrode was placed on C7 spinous process. EMG signals were sampled at 1000 Hz during 10 seconds.

Contact pressure

Contact pressure was recorded using the Novel Pliance-x system. The hand mat (Elastisens HA 44, 70.4 x 70.4 mm cm, 16x16 sensors) was attached to the palm of the hand using double-sided adhesive tape (Figure 7.4). The data were recorded using the Pliance software. Contact pressure was measured for all sensors with a sample frequency of 10 Hz during 10 seconds in static as well as dynamic circumstances. The accuracy of the Novel pressure measurement equipment is very high (Hochmann et al., 2002; Poliack et al., 1999). Within the pressure range (5-200 kPa), a linear relationship exists between the applied and the observed pressures under increasing applied load. The hysteresis (difference in pressure readings while increasing and then decreasing pressure at the same rate) is small (Polliack et al., 1999). Hochmann (2002) found a hysteresis smaller than 5%. Drift errors (change in the relationship between applied and observed pressures over a period of time) are also small (Polliack et al., 1999).

Figure 7.4 The hand mat was attached to the hand using double-sided adhesive tape

Productivity

The productivity was expressed as the number of pieces of wood which were cut during three minutes. The unfinished last piece was registered as ¼, ½ and ¾ piece of wood, depending on the area which was cut.

7.2.6 Protocol

The subject was informed about the study. After that, some general information was noted. Subsequently, the hand mat was attached to the hand. In order to illustrate the hand mat's position on the hand a photo was taken. Before contact pressure was measured, the hand mat was set to zero holding the hand in the position like the hand grip of the saw was held. Then, the contact pressure was measured during the static and the dynamic sawing tasks.

After the contact pressure measurements, the preferred movement frequency when crosscutting the beam was obtained. The results of a pilot study showed that the preferred motion rhythm did not differ very much between the five hand saws. Therefore we decided to determine the motion rhythm using one saw. Hand saw B was chosen because this saw caused the fastest motion rhythm. Carpenters stated that it is easier to adapt to a faster motion rhythm than to slow down. The amount of cycli and the time the task took were recorded. From this, the preferred movement frequency could be calculated in movements a minute. This motion rhythm was given by a metronome during the EMG measurements in the sawing task, to maintain the same movement frequency using different saws.

Then, the electrodes were applied over the muscle bellies, after the skin was shaved, scrubbed and cleaned with alcohol. Subsequently, static maximum voluntary contractions were obtained for each muscle using manual resistance. The isometric contractions lasted 2-3 seconds. This was repeated three times for each muscle. The largest of these contractions for each muscle was called the maximum voluntary contraction of that muscle (MVC).

Before the sawing task started, the subject rated his LPD. Then, the subject had to saw five minutes. When sawing the first piece of wood, the EMG registration period started after the subject was accustomed to the motion rhythm of the metronome (EMG measurement 1). After the first piece of wood, the subject continued sawing during three minutes in his own rhythm (without metronome) to maintain the productivity. When the three minutes passed, the subject immediately stopped sawing the current piece and moved on to the next saw-cut. When sawing the first piece of wood after the three minute period, the subject again accustomed himself to the motion rhythm of the metronome and then again EMG was recorded (EMG measurement 2). After the saw-task was finished, the subjects rated their LPD and finished the CQH. Then, the subject had a rest period of at least five minutes. The saw-task was repeated for each hand saw, resulting in five sawing tasks for each subject. The order of hand saws was systematically varied among the subjects.

7.2.7 Data analysis

Discomfort (LPD)

Local perceived discomfort was rated before and after each sawing task. For each region the increase in discomfort was calculated by subtracting the perceived discomfort rating after the task from the perceived discomfort before the task. The sum of the local discomfort increase of all regions together constitutes the score of LPD. As the frequency distribution of the LPD shows a large degree of skewness, a logarithmic transformation was performed on this variable. In further analysis only the transformed LPD was used as a variable, which is called lnLPD.

EMG

An even number of saw cycli was cut from each 10 seconds lasting EMG measurement, with a minimum of 6 cycli. EMG signals were band pass filtered (10-400 Hz), rectified and filtered (fourth order Butterworth low pass 5 Hz).

Subsequently, the average EMG activity was calculated and normalized to the EMG level obtained during the MVCs.

Contact pressure

Static contact pressure

Pressure parameters were calculated in Matlab (The Mathworks). A cut-off pressure (20 kPa) was introduced to define pressure regions. A pressure region contains minimally 4 sensors having a pressure above the cut-off pressure. The average pressure, pressure area (area of all pressure regions together), and P-t integral were calculated.

Dynamic contact pressure

The dynamic pressure measurements were cut into 10 saw cycli. The same pressure variables were calculated as in the static contact pressure measurement.

7.2.8 Statistics

MANOVA repeated measures was performed to compare the hand saws with each other on EMG (%MVC) and contact pressure (average pressure, pressure area and P-t integral) as both measurements deal with more than one independent variable. The independent variables during the EMG measurement were the hand saws (A to E) and the measurement moment (begin and end of sawing task). The independent variables of the contact pressure measurement were the hand saws (A to E) and the type of measurement (static and dynamic). ANOVA repeated measurements was performed to compare the hand saws on productivity as the hand saws (A to E) were the only independent variable during the productivity measurement. p is based on degrees of freedom corrected with Greenhouse-Geisser's epsilon to compensate for the effects of violations of the sphericity assumption (Twisk, 2003). The results of the MANOVA and ANOVA will show if differences exist on EMG, contact pressure and productivity between the hand saws and between the measurements. However, based on these results it is not known between which groups (i.e., hand saws and measurements) the differences exist. Therefore a follow-up test is needed guarding against an increase in the probability of a type I error when performing multiple significance tests (Everitt, 2002). The Bonferroni follow-up was used for comparisons of the means between the groups. This is a highly conservative test, which means that it highly prevents for making the type I error and identifies fewer significant differences compared to other post-hoc tests (Thomas and Nelson, 1996).

Wilcoxon signed ranks test was used to see if the hand saws differ from each other on overall comfort and local perceived discomfort.

Linear regression analysis was performed to study the relationship between objective measurements (EMG, contact pressure, productivity) and subjective measurements (Overall comfort and lnLPD). We chose to perform a linear regression analysis (and not a multiple linear regression analysis including all objective measurements at the same time) as we wanted to investigate the predictive value of each objective variable separately. As one subject tested all five hand saws, these data points were not independent. Therefore, we used general estimation equations (GEE) to analyse our data, because this statistical technique takes into account the with-in subjects correlation of our data (Twisk, 2003). However, data analysis with the sophisticated GEE technique with a categorical outcome variable is more problematic than with continuous or dichotomous outcome variables. Until recently, only simple methods (which do not correct for the dependence of our data points) were available to analyse categorical outcome variables. Therefore, categorical variables are treated as continuous variables in GEE analysis, especially when they are ordinal and have a sufficient number of categories (i.e., more than five) (Twisk, 2003). In our study, the outcome variables (comfort and lnLPD) meet these requirements and therefore we considered our outcome variables as continuous variables in the GEE analysis.

7.3 Results

7.3.1 Comfort and discomfort

Differences between hand saws

Overall comfort after short time use was different between hand saws. Hand saw A, B, C and D were assessed as significantly more comfortable than hand saw E ($p<.01$). Hand saw E showed significantly more discomfort than the other hand saws ($p<.05$). The mean ranks of the comfort ratings and lnLPD are shown in Table 7.3.

Table 7.3 Mean ranks of the comfort ratings and the lnLPD for the five hand saws

Saw	Comfort (mean rank)	lnLPD (mean rank)
A	3.36	3.25
B	4.00	2.50
C	3.23	2.83
D	3.32	2.42
E	1.09	4.00

7.3.2 EMG

Differences between hand saws and moments of measurement

The differences in EMG between hand saws and moments of measurement were obtained for each muscle separately. The means of the %MVC are shown in Table 7.4. The EMG of the m. trapezius pars transversa/m. romboideus major was different among the various hand saws. However, Bonferroni as post-hoc test did not show between which hand saws the difference existed. No significant differences were found between hand saws for the m. extensor carpi radialis, the m. flexor carpi radialis, the m. triceps caput mediale, and the m. trapezius pars descendens. When comparing the first to the second EMG measurement, the m. trapezius pars descendens and the m. trapezius pars transversa/m.romboideus major were the only muscles showing a significant difference, namely a higher %MVC for the second measurement ($p<.01$).

Table 7.4 Means and standard deviations of the %MVC.

Muscle	**Saw**	**Measurement 1**		**Measurement 2**	
		%MVC		**%MVC**	
		Mean	**Std.**	**Mean**	**Std.**
m. Triceps brachii	A	11.4	5.6	12.8	5.8
	B	13.0	6.0	13.0	5.6
	C	12.6	5.7	13.1	6.0
	D	11.9	5.2	12.5	5.0
	E	14.9	6.7	13.9	5.1
m. Extensor carpi radialis	A	19.1	9.7	17.5	8.3
	B	20.6	9.7	18.1	8.4
	C	20.0	9.9	18.3	9.2
	D	19.0	9.6	16.7	7.9
	E	20.8	9.7	19.1	8.4
m. Flexor carpi radialis	A	24.7	13.8	21.8	14.6
	B	25.6	16.7	21.7	15.2
	C	25.8	15.2	21.6	13.9
	D	24.6	14.6	20.6	14.3
	E	22.8	14.2	20.2	14.1
m. Trapezius pars descendens	A	14.0	10.5	17.3	10.5
	B	14.9	8.8	15.7	8.9
	C	13.8	8.8	18.7	9.4
	D	13.6	8.2	17.1	8.0
	E	16.8	11.0	19.3	11.5
m. Trapezius pars transversa	A	18.7	7.9	20.9	8.1
	B	20.2	9.3	22.5	10.4
	C	19.5	7.5	22.4	9.2
	D	18.2	7.8	21.3	7.9
	E	21.6	9.4	24.1	8.9

Relationship with subjective measurements

Table 7.5 shows the standardized regression coefficients of the relationship between the mean %MVC of the five muscles (m. extensor carpi radialis, m. flexor carpi radialis, m. triceps brachii caput mediale, m. trapezius pars descendens and m. trapezius pars tranversa/m. romboideus major) and comfort and discomfort.

Table 7.5 Standardized regression coefficients of the relationship between EMG (%MVC) and overall comfort and lnLPD.

Dependant variable	**EMG measurement**	**Muscle**	**Beta**	**p**
Overall comfort	First measurement	m. extensor carpi radialis	0.08	n.s.
		m. flexor carpi radialis	-0.03	n.s.
		m. triceps brachii caput mediale	0.11	n.s.
		m. trapezius pars descendens	0.18	<.01
		m. trapezius pars transvers/m. romboideus major	0.02	n.s.
	Second measurement	m. extensor carpi radialis	0.05	n.s.
		m. flexor carpi radialis	-0.05	n.s.
		m. triceps brachii caput mediale	0.07	n.s.
		m. trapezius pars descendens	0.13	<.05
		m. trapezius pars transvers/m. romboideus major	0.04	n.s.
lnLPD	First measurement	m. extensor carpi radialis	-0.13	n.s.
		m. flexor carpi radialis	-0.25	n.s.
		m. triceps brachii caput mediale	-0.02	n.s.
		m. trapezius pars descendens	0.23	n.s.
		m. trapezius pars transvers/m. romboideus major	0.02	n.s.
	Second measurement	m. extensor carpi radialis	-0.01	n.s.
		m. flexor carpi radialis	-0.13	n.s.
		m. triceps brachii caput mediale	-0.04	n.s.
		m. trapezius pars descendens	0.34	<.05
		m. trapezius pars transvers/m. romboideus major	0.08	n.s.

Comfort was related to the mean %MVC of the m. trapezius pars descendens during the first (beta=0.18) and the second measurement (beta=0.13) with an explained variance of 1.6% and 3.2 % respectively. A higher muscle activity of the trapezius pars descendens corresponded with more comfort.

Discomfort was also related to the mean %MVC of the m. trapezius pars descendens during the second measurement (beta=0.34; explained variance of 11.5%). A higher muscle activity of this muscle corresponded with more discomfort.

7.3.3 Contact pressure

Differences between hand saws and measurements

Figures 7.5 to 7.7 show the average pressure, pressure area and the P-t integral of all hand saws for both the static and the dynamic measurement.

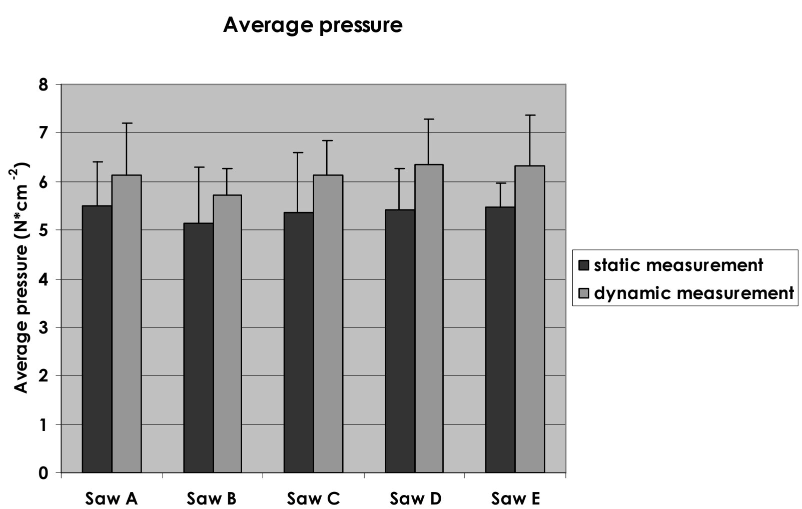


Figure 7.5 Average pressure on the palm of the hand during static and dynamic pressure measurements

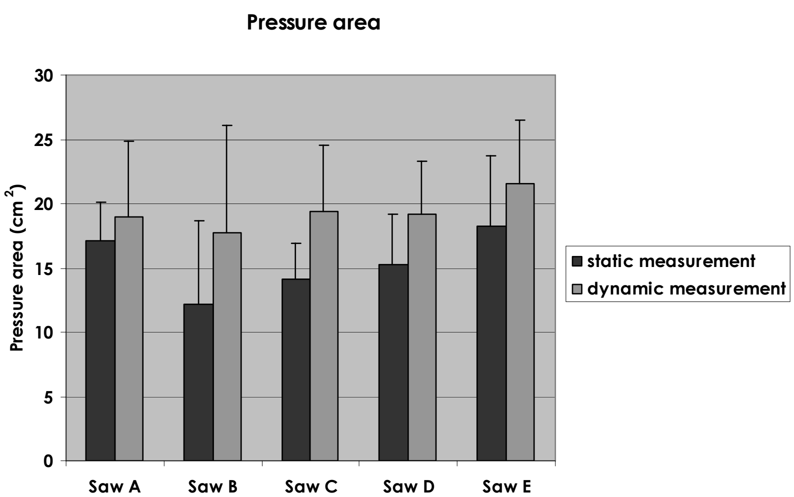


Figure 7.6 Pressure area on the palm of the hand during static and dynamic pressure measurements

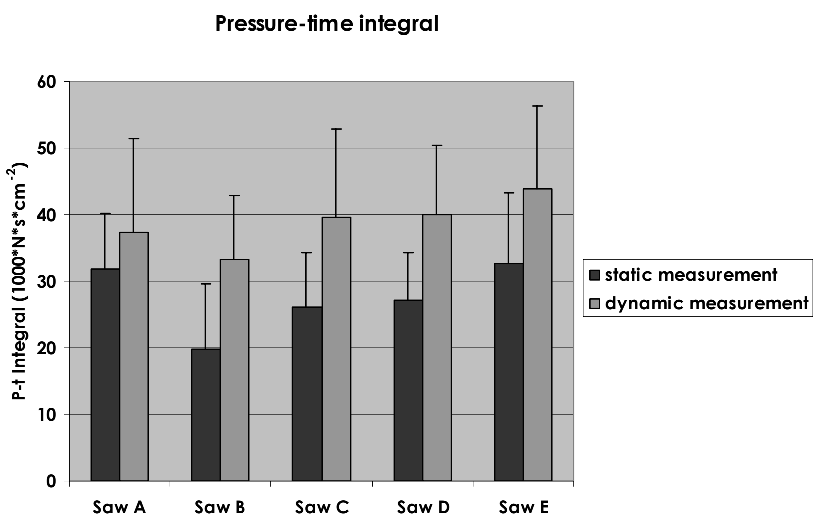
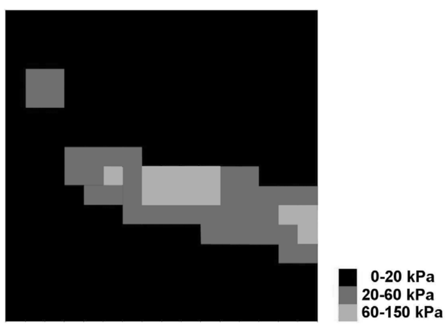


Figure 7.7 P-t integral of the pressure on the palm of the hand during static and dynamic pressure measurements

Significant differences between hand saws were found for average pressure (p<.05), pressure area (p<.01), and P-t integral (p<.01). For the average pressure, the Bonferroni post-hoc test did not show between which hand saws the differences existed. Additionally, the pressure area of hand saw E was significantly larger than the pressure area of hand saw B and D (both p<.05). Further, the P-t integral of hand saw B was significantly smaller than the P-t integral of A (<.05), C (p<.05) and E (p<.01). Figures 7.8a and b show the typical pressure area on the hand mat for hand saw B and E of one person.



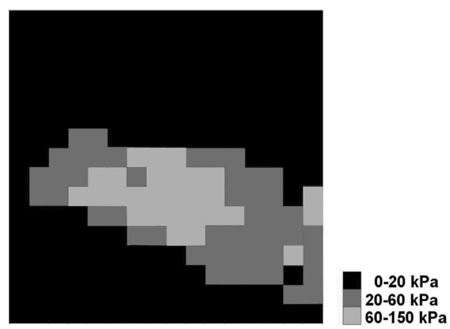


Figure 7.8a and 7.8b Pressure area of the hand saw in the hand for hand saw B and E respectively. The pressure area of hand saw E contains is larger (contains more sensors above the cutt-off pressure) than hand saw B.

Differences between static and dynamic measurement were found for all the contact pressure variables, i.e. average pressure (p<.05), pressure area (p<.01), and P-t integral (p<.01). The average pressure, pressure area, and P-t integral were higher during the dynamic measurement compared to the static measurement. This implies that the exerted force (40N) during the static measurement was an underestimation of the real output force which was exerted during sawing.

No interaction was found between hand saw and measurement for all the three pressure variables. The differences found between hand saws were independent of the type of measurement.

Relationship with subjective measurements

Table 7.6 shows the standardized regression coefficients of the relationship between the contact pressure variables (average pressure, pressure area and P-t integral) and comfort and discomfort for both the static and dynamic measurements.

Comfort was best predicted by the P-t integral during the static measurement (beta=–0.24), which resulted in an explained variance of 5.8%. The P-t integral was inversely related to the comfort experience, which means that a higher P-t integral corresponds to less comfort.

The best predictor of local perceived discomfort was the pressure area during the static pressure measurements (beta=0.45). The explained variance was 20.3%. A larger pressure area corresponds to higher discomfort. The same phenomenon was observed for the P-t integral during static measurements, although the standardized regression coefficient for the P-t integral was somewhat lower (beta=0.29) with an explained variance of 8.4%.

Table 7.6 Standardized regression coefficients of the relationship between contact pressure (average pressure, pressure area and P-t integral) and overall comfort and lnLPD for both static and dynamic measurements.

Dependant variable	**Pressure measurement**		**Beta**	**p**
Overall comfort	Static	Average pressure	-0.14	n.s.
		Pressure area	-0.20	n.s.
		P-t integral	-0.24	<.01
	Dynamic	Average pressure	-0.04	n.s.
		Pressure area	-0.17	n.s.
		P-t integral	-0.18	n.s.
lnLPD	Static	Average pressure	-0.05	n.s
		Pressure area	0.45	<.01
		P-t integral	0.29	<.01
	Dynamic	Average pressure	-0.05	n.s.
		Pressure area	0.17	n.s.
		P-t integral	-0.12	n.s.

Influence of size of the hand

The length and the width of the hand are confounding factors in the relationship between pressure area and discomfort. The length and the width of the hand affected the pressure area, but they were not related to discomfort.

7.3.4 Productivity

Differences between hand saws

Figure 7.9 shows the productivity of the carpenters with the different hand saws. Significant differences were found between saws ($p<.01$). When the carpenters used hand saw E, they cut significant fewer pieces of wood than with the other hand saws ($p<.05$). Additionally, they also cut significantly fewer pieces of wood with hand saw B than with hand saw C and D.

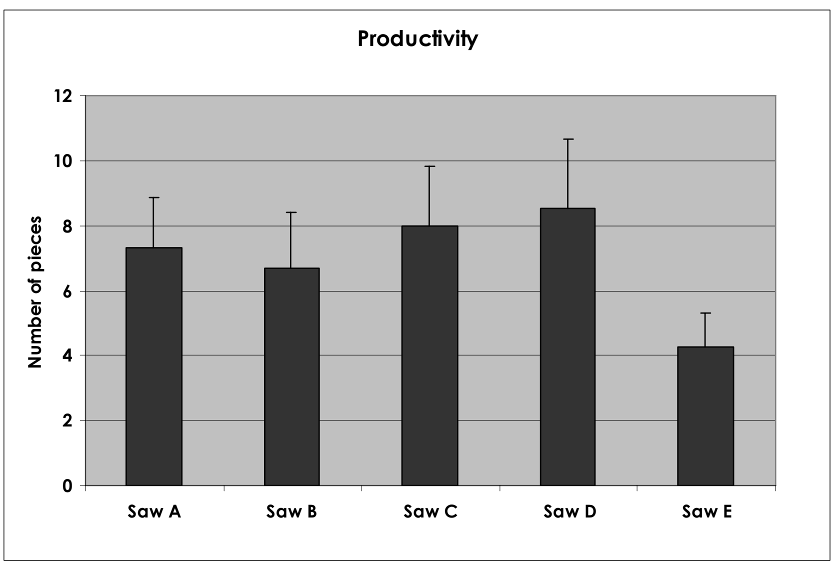


Figure 7.9 Productivity, number of wooden pieces cut in three minutes

Relationship with subjective measurements

Productivity was related to overall comfort (beta=0.31, p<.01) with an explained variance of 9.6% and inversely related to lnLPD (beta=–0.49, p<.01) with an explained variance of 24.0%. Hence, a higher productivity was achieved with hand saws which had a higher comfort rating. On the other hand, using hand saws which cause discomfort resulted in a lower productivity.

7.4 Discussion

In this study the relationships between objective measurements (i.e. contact pressure, EMG and productivity) and subjective comfort and discomfort experience were studied. Before the relationships were studied, the differences between the hand saws were considered. Although, the hand saws differed in design (the hand grip as well as the saw blade), they all look similar regarding quality, shape and size, except for hand saw E. In order to calculate the relationships it would have been better if more differences between hand saws existed. On the other hand, when these results are applied to hand tool evaluation studies nowadays, the differences between hand tools of the same kind will be very small and still it would be good if differences could be shown. In next sections, the relationships between objective measurements and experienced comfort/discomfort will be discussed.

7.4.1 Relationship between EMG and comfort/discomfort.

The results of the EMG measurements were contradictory. On the one hand, a small but positive relationship existed between the %MVC of the m. trapezius pars descendens and comfort (p<.01 and p<.05 for respectively the first and the second measurement) and on the other hand, a positive relationship existed with discomfort (p<.05). The latter was expected: a higher %MVC of the m. trapezius pars descendens should correspond to more discomfort. This hypothesis was based on a study of Hammarskjöld and Harms-Ringdahl (1992). They showed that the EMG median amplitudes increased after fatigue. We translated these results into our hypothesis: an increase in fatigue would also result in an increase of discomfort. The relationship between the %MVC and discomfort was found to be stronger (11.5 % explained variance) than the relationship between the %MVC and comfort (1.6% and 3.2% explained variance).

Two reasons can be given to explain that we did not find strong relationships between muscle activity and comfort or discomfort. The first reason is that the differences in %MVC were small (maximum about 3%) between the hand saws. Although, ANOVA repeated measures indicated that there were significant differences, Bonferroni as post-hoc test did not show between which hand saws the differences existed. Probably, people can not experience a difference in discomfort based on these small differences in %MVC. The second reason is that there are many factors which can influence muscle activity (i.e., adjusted movement trajectories, alternating activation of different muscles) in a dynamic task. We expect that in more static and/or precision tasks (like using dentist tools), EMG may be more associated with measuring comfort/discomfort as other studies have shown an increase of EMG activity with increased precision demands (Milerad and Ericson, 1994; Visser et al., 2004).

7.4.2 Relationship between contact pressure and comfort/discomfort

Static pressure measurement

Contact pressure variables were related to comfort and discomfort. The P-t integral during static pressure measurement was inversely related to comfort ($p<.01$). Pressure area and the P-t integral during static pressure measurement were both positively related to discomfort ($p<.01$). This is subscribed by a study of Chen et al. (1994). They studied the relationship between pressure under the foot and insole comfort. Subjects were asked to rank four insoles from least comfortable to most comfortable. They found that the P-t integral and the contact area of the foot were significantly smaller for the most comfortable insole compared to the least comfortable insole.

The findings of the current study and the study of Chen et al. (1994) seem to be contradictory with the common opinion that a force distribution over a large area leads to less discomfort. However, in our study the average pressure remains more or less constant between the hand saws. Hence, the same average pressure was exerted on a larger area when using the hand saw which caused most discomfort (i.e. hand saw E). Goonetilleke and Eng (1994) explained this phenomenon by spatial summation (which means that simultaneous stimulation of many sensory receptors is required to arouse a stimulation). Alternatively, a greater sensory response is experienced with a larger stimulated area. Based on this fact, Goontilleke and Eng (1994) argue that when sensations tend towards discomfort, a pressure distributed over a large area may increase discomfort opposed to the same pressure over a small area. Hence, the decision to distribute or concentrate forces is dependent on the magnitude of the pressure exceeding a critical pressure for given surface area, like the palm of the hand. Consequently, the relationship found between contact area and discomfort can not be applied to other hand tools right away as the pressure for the given surface area may be under the critical pressure for the palm of the hand.

For application to other hand tool evaluation studies or hand tool (re)design, first of all, the critical pressure for the specific contact area in the hand should be studied. Then the designer ought to know whether or not the pressure on the hand -when using the hand tool- will exceed this critical value. Subsequently, the designer knows whether he should enlarge or reduce the contact area of the design of the hand grip in order to avoid discomfort.

Dynamic pressure measurement

We did not find a relationship between dynamic pressure measurements and discomfort, while we did for static pressure measurements. From the results of MANOVA, it was seen that no interaction effect existed for saw and measurement. This means that the differences which were found between the saws were the same for the dynamic and the static measurements. This is remarkable because the five hand saws did not only have different hand grips, but they also differed in saw blade (i.e., surface material, teeth count, teeth size). During the static pressure measurements only the influence of the hand grip was measured, while in the dynamic pressure measurements a combination of hand grip and saw blade played a role. It was expected that the saw blade would affect the push force and affect the contact pressure during the dynamic measurements. However, the saw blade did not seem to have any influence.

From this, it can be concluded that the shape of the hand grip plays a major role in contact pressure in hand saws. As the contact area affects the discomfort experience, the static contact pressure measurement can be used to optimize the shape of the hand grip in order to avoid discomfort. The design of the saw blade (or the work side of the tool) can not be evaluated by contact pressure measurement, especially not when the hand grips differ. In that case, the hand grips will overrule the effects of the saw blade, such as this study illustrated.

In conclusion, static pressure measurement (i.e. contact area) could predict comfort/discomfort better than dynamic pressure measurement in sawing.

7.4.3 Relationship between productivity and comfort/discomfort

The results of this study showed that productivity is closely related to comfort and discomfort. The productivity was higher for hand saws that were assessed as more comfortable and the productivity was lower for hand saws which caused discomfort. The relationship between productivity and discomfort was earlier found in an evaluation study of scrapers (Eikhout et al., 2001). The scraper which needed fewer scrape motions was considered to be very comfortable by the painters and caused significantly less discomfort in the upper extremity. For hack saws, Das et al. (2005) also found a higher productivity with the hack saw which was subjectively assessed as better.

Groenesteijn et al. (2004) did not find any differences in productivity between the plier which was addressed as best-feeling by 80% of the subjects and the other pliers. They did not find any significant differences in local perceived discomfort either. Maybe the design of the pliers differed not enough to measure differences in productivity. However, the experienced work velocity was higher for the plier which was rated more comfortable than the others. This is an interesting finding with respect to the question if a more comfortable hand tool results in a higher productivity, or inversely, if a hand tool with which one can reach a higher productivity is experienced as more comfortable. It seems that the experience of productivity plays an important role in assessing comfort. This indicates that an (experience of) high productivity may affect the comfort experience in a positive way. This is subscribed by an earlier study in which a positive relationship (beta=0.69, $p<.01$) was found between the experience of high task performance and the overall comfort experience by using screwdrivers (Kuijt-Evers et al., 2005). Additionally, it seems obvious that when a hand tool causes discomfort (like sore muscles and pressure on the hand), one can not continue the task at high velocity or even without a break. Hence, feelings of discomfort can cause a decrease of productivity and (experiences of) high productivity may increase the comfort experience.

As a result, the focus on avoiding discomfort in hand tool design is not only important to avoid musculoskeletal complaints and improve job satisfaction of users, but is also important from a productivity point of view.

7.5 Conclusion

Based on our findings we conclude that EMG measurements can not be used as an objective measurement to subscribe subjective measured comfort or discomfort experience using hand tools for dynamic tasks. Contact pressure can not be used as a predictive measurement of comfort experience too. On the other hand, contact pressure (i.e., pressure area) is an appropriate objective measurement to support subjective findings on discomfort in using hand tools. Moreover, this contact pressure measurement can be useful to designers in hand grip design.

Additionally, from the productivity point of view, it is also important to design comfortable hand tools as they affect productivity in a positive way.

7.6 Acknowledgements

We would like to thank the Dutch Ministry of Economic Affairs, Stichting Arbouw and Bahco Tools for their support.

7.7 References

Annet, J. 2002. Subjective rating scales: science of art? Ergonomics, 45 (14): 966-987.

Chang, S.R., Park, S., Freivalds, A., 1999. Ergonomic evaluation of the effects of handle types on garden tools. International Journal of Industrial Ergonomics, 24 (1): 99-105.

Chen, H., Nigg, B.M., Koning, J. de, Relationship between plantar pressure distribution under the foot and insole comfort. 1994. Clinical Biomechanics, 9 (6): 335-342.

Côté, J.N., Mathieu, P.A., Levin, M.F., Feldman, A.G., 2002. Movement reorganization to compensate for fatique during sawing. Exp. Brain.Res., 146: 394-398

Das, B., Jongkol, P., Ngui, S., 2005. Snap-on-handles for a non-powered hacksaw : An ergonomics evaluation, redesign and testing. Ergonomics, 48 (1): 78-97.

Eikhout, S.M., Bronkhorst, R.E. and Grinten, M.P. van der., 2001. Evaluation of a new scraper. Proceedings of the 45th HFES congress 2001, Minneapolis (US): HFES: CD rom: 722-726

Everitt, B.S., 2002. The Cambridge dictionary of statistics. 2nd edition. Cambridge University Press, Cambridge: 50.

Fellows, G.L., Freivalds, A., 1991. Ergonomic evaluation of a foam rubber grip for tool handles. Applied Ergonomics. 22 (4): 225-230.

Franssen, J.L.M., 1995. Handboek Oppervlakte Elektromyografie. De Tijdstroom, Utrecht.

Freund, J., Takala, E-P., Toivonen, R., 2000. Effects of two ergonomics aids on the usability of an in-line screwdriver. Applied Ergonomics, 31 (4): 371-376.

Goonetilleke, R.S., Eng, T.J., 1994. Contact area effects on discomfort. Proceedings of the Human Factors and Ergonomics Society 38th Annual Meeting. 688-690.

Groenesteijn, L., Eikhout, S.M., Vink, P., 2004. One set of pliers for more tasks in installation work: the effects on (dis)comfort and productivity. Applied Ergonomics, 35 (5): 485-492.

Habes, D.J., Grant, K.A., 1997. An electromyographic study of maximum torques and upper extremity muscle activity in simulated screwdriving tasks. International Journal of Industrial Ergonomics, 20 (4): 339-346.

Hammarskjöld, E., Harms-Ringdahl, K., 1992. Effect of arm-shoulder fatigue on carpenters at work. European Journal of Applied Physiology, 64 (5): 402-409.

Hochmann, D., Diesing, P., Boenick, U. 2002. Evaluierung der messmethoden zur bewertung des therapeutischen nutzens von antidekubitys-systemen. Biomedizinische Technik. 47: Ergängzungsband, S. 816-35.

Kadefors, R., Areskoug, A., Dahlman, S., Kilbom, Å., Sperling, L., Wikström, L., Öster, J. 1993. An approach to ergonomics evaluation of hand tools. Applied Ergonomics. 24 (3): 203-211.

Kilbom, Å., Mäkäräinen, M., Sperling, L., Kadefors, R., Liedberg, L. 1993. Tool design, user characteristics and performance: a case study on plate shears. Applied Ergonomics. 24 (3): 221-230.

Kluth, K., Kelermann, H.G., Strasser, H., 2004. Assessment of the ergonomic quality of file handles using electromyographic and subjective methods. Occupational Ergonomics, 4 (2): 133-142.

Kong, Y-K, Freivalds, A., 2003. Evaluation of meat-hook handle shapes. International Journal of Industrial Ergonomics, 32 (1): 13-23.

Kuijt-Evers, L.F.M., Twisk, J.W.R., Groenesteijn, L., Looze, M.P. de, Vink, P. 2005. Identifying predictors of comfort and discomfort in using hand tools. Ergonomics, 48 (6): 692-702.

Lee, K.S., Ferraiuolo, P., Temming, J., 1993. Measuring seat comfort.Automotive Engineering. 101(7): 25-30.

Li, K.W., 2003. Ergonomic evaluation of a fixture used for power driven wire-tying hand tools. International Journal of Industrial Ergonomics. 32: 71-79.

McGorry, R.W., Dowd, P.C., Dempsey, P.G., 2003. Cutting moments and grip forces in meat cutting operations and the effect of knife sharpness. Applied Ergonomics, 34 (4): 375-382.

Milerad, E., Ericson, M.O., 1994. Effects of precision and force demands, grip diameter, and arm support during manual work: an electromyographic study. Ergonomics. 37: 255-264.

Niëmelä, T., Leppanen, M., Päivinen, 2000. Evaluation of an experimental testing system for non-powered hand tools. In: Ergonomics for the New Millennium. Proceedings of the IEA/HFES 2000 congres. 30 July-4 August, San Diego CA: 3-643-646.

Polliack, A., Landsberger, S., McNeal, D., Sieh, R., Craig, D., Ayyappa, E. 1999. Socket measurement systems perform under pressure. Biomechanics. June: 71-80.

Strasser, H., Wang, B., Hoffmann, A., 1996. Electromyography and subjective evaluation of hand tools: The example of masons' trowels. International Journal of Industrial Ergonomics, 18 (1): 91-106.

Thomas, J.R., Nelson, J.K., Research methods in physical activity. (Leeds, Human Kinetics): 158.

Twisk, J.W.R., 2003. Applied longitudinal data analysis for epidemiology. Cambridge University Press, Cambridge.

Visser, B., Looze, M.P de, Graaff, M.P. de, Dieën, J.Hv. van, 2004. Effects of precision demands and mental pressure on muscle activation and hand forces in computer mouse tasks. Ergonomics, 47 (2): 202-217.

Epilogue

Chapter 8

8 Epilogue

The main objective of this thesis was to provide knowledge to designers and researchers on comfort and discomfort in hand tool design and evaluation. In order to achieve this goal, three sub-goals were identified: to contribute to the theory of comfort and discomfort in using hand tools, to propose how comfort can be integrated in the design process, and to investigate how hand tools can be evaluated regarding comfort. This epilogue contains an overview of the results of the studies, a reflection on the focus of the thesis and the applied methodology, suggestions for designers and researchers on how to apply the results of this thesis in practice, and recommendations for future research.

8.1 Overview of results

8.1.1 Theory on comfort

The studies of chapter 3, 4 and 5 concern the theory of comfort in using hand tools. It was investigated if the same comfort descriptors underlie both comfort and discomfort. Additionally, the predictors of comfort at first sight, and the experienced comfort and discomfort after use were identified. Moreover, the hand tool specificity of the comfort predictors was studied.

In the first study, the participants rated the meaning of the respective comfort descriptors for the general feeling of comfort or discomfort, without actually using or holding a hand tool. From this study it was concluded that hand tool users associated the same descriptors with comfort as with discomfort. However, when the relationships between the ratings on comfort descriptors and factors with ratings of perceived comfort and discomfort were calculated in the screwdriver evaluation study, it was found that only one comfort descriptor (causes cramped muscles) and only one factor (adverse body effects) were associated with both comfort and discomfort. Moreover, comfort was related to some other comfort descriptors and factors. It was concluded that comfort and discomfort have one common underlying factor, i.e., adverse body effects. Apart from adverse body effects, comfort is mainly influenced by the functionality and physical interaction of the tool. Comfort at first sight is mainly predicted by aesthetics, followed by functionality and physical interaction. Discomfort is only predicted by adverse body effects.

The study on hand tool specificity indicated that the same factors underlie comfort in different kinds of hand tools, namely descriptors which are associated with functionality, physical interaction, adverse effects on skin, and adverse effects in soft tissues. However, the relative importance of the underlying factors is different. Moreover, the relative importance of the comfort descriptors also depends on the type of hand tool. Nevertheless, some comfort descriptors (e.g., 'fits the hand') are important for all kinds of hand tools. The comfort descriptors which are mostly related to the overall comfort are the comfort predictors. These comfort predictors represent the comfort-related customer needs, which are needed in the House of Quality of the Quality Function Deployment.

8.1.2 Hand tool design

The House of Quality of the Quality Function Deployment (QFD) was considered to be the best design approach to ensure attention for comfort in the design process. The House of Quality helps to translate the (comfort-related) customer needs into engineering characteristics. Mostly, the correlations between customer needs and engineering characteristics are based on experience, intuition and determination of the members of the design team. The study described in chapter 6 shows that the QFD method is an appropriate method to incorporate comfort during the design process, on the condition that the correlations between customer needs and engineering characteristics are supported by results of customer validation studies and/or a literature review. This is needed because the design team estimated the correlations wrong in 1/4 of the cases in the current study.

8.1.3 Hand tool evaluation

The Comfort Questionnaire for Hand tools was developed to investigate the comfort experience of hand tool users. This questionnaire consists of comfort descriptors (in the hand tool users own words) that are related to comfort in using hand tools. The final question is about the overall comfort of the hand tool. This questionnaire was used in three hand tool evaluation studies and finally comprised 17 comfort descriptors (chapter 5). In addition, it was investigated if comfort and discomfort experience could be predicted from objective measurements, like muscle activity and contact pressure. Firstly, it was found that muscle activity was not strongly related to either comfort or discomfort. Secondly, it was found that contact pressure was not strongly related to comfort. However, contact pressure was related to discomfort. Hence, discomfort experience can be predicted by contact pressure (i.e., pressure area), like in chair evaluation studies (Looze et al., 2003). It was concluded that the contact pressure, and more specifically pressure area, can be useful in hand tool evaluation studies as subjective measurements of discomfort can be supported by evidence of objective pressure measurements. Moreover, comfort and discomfort were associated with productivity, which indicates the importance of attention for comfort in hand tool design, as the attention for comfort in design is not only necessary from a health perspective but also needed from a productivity point of view.

8.2 Reflection on focus and methodology

Many aspects affect the comfort experience in using hand tools, which could not all be addressed in this thesis. Therefore, we chose to focus on non-powered hand tools and on the user-tool interaction. These choices are explained in this section.

8.2.1 Focus on non-powered hand tools

This thesis focuses on non-powered hand tools. This choice was made, in spite of the increasing usage of powered hand tools for many kinds of tasks. (Examples of these tools are electric screwdrivers, pneumatic pruning shears, and electric kitchen scissors). However, many people still use non-powered hand tools. We focused on non-powered hand tools for a methodological reason. For a better understanding of the interaction between the hand tool and the user, it is important that this interaction is not affected by other complicating factors like vibration and (undesired) reaction forces and moments caused by power sources (Lin et al., 2006).

8.2.2 Focus on hand tool-user interaction

The comfort experience of hand tool users is affected by the interaction between the task, the hand tool and the end-user, within an environment. The focus of this thesis was on the hand tool-user interaction. Therefore, the user-task interaction and the task-hand tool interaction were not studied, which explains why the task during the experiments was standardized (e.g., one work height, one force direction). The reason for this choice is that hand tool designers may not have the opportunity to redesign the workplace layout, because sometimes they may not be able to change the workplace as it is simply not possible (e.g., vineyard) or they are not allowed to (like in some production lines). Hence, the only possibility to improve the comfort experience of the end-user is by redesigning the hand tool. Therefore the focus of this research was on the user-tool interaction. Nevertheless, designers should always keep in mind that when they (re)design a hand tool, it will be used in several circumstances performing several tasks (Dempsey et al., 2004).

8.2.4 Focus on muscle activity (EMG) and contact pressure

In order to investigate if objective measurements can predict comfort and discomfort in using hand tools, muscle activity (EMG) and contact pressure were chosen as objective measurements. The reason to choose muscle activity as one of the measurements is that tendencies (without statistical evidence) of relationships between muscle activity and comfort or discomfort in using garden tools were observed (Chang et al., 1999; Fellows and Freivalds, 1991). Contact pressure (which is rarely measured in hand tool evaluation) appears to be the objective measure that has the most clear association with subjective comfort or discomfort ratings in sitting (Looze et al., 2003). Moreover, Goonetilleke (1998) states that pressure at the human interface can cause discomfort and it may also improve comfort in all kinds of products, including hand grips. For these reasons, contact pressure was also chosen as one of the objective measurements.

Wrist and arm postures measurements (goniometry) were not chosen, as postures are highly affected by the workplace layout (Dempsey et al., 2004). Furthermore, the hand grip direction did not vary between the studied hand saws (chapter 7). Therefore, the tool design did not affect the wrist posture. Hence, in this case the wrist posture could only be changed by the workplace layout and that was beyond the focus of this thesis. However, it is still important to concern wrist and arm postures in hand tool evaluation studies (and to avoid extreme postures in hand tool design), as Kee and Karwoski (2001) found that static joint postures (percentage of range of motion) of for instance wrist, elbow, shoulder, were highly correlated to the comfort score, and extreme joint postures (high percentage of range of motion) were accompanied by high discomfort levels (Kee and Karwowski, 2003).

8.3 Application of the results

8.3.1 Relevance to the industry

In the introduction, I stated that paying attention to comfort is necessary in the mid-price and high-price hand tool categories. It was also said that the shift from focus on functionality towards avoiding discomfort and providing comfort in hand tool design is a similar development as in office chair design. Although some hand tool manufacturers are still shifting from focussing on functionality to avoiding discomfort, other hand tool manufacturers shift from avoiding discomfort to providing comfort. The results of the current thesis support hand tool manufacturers who want to shift from avoiding discomfort to providing comfort. For instance, the underlying factors and comfort-related customer needs are now scientifically established. Hence, the designers and the manufacturers know with certainty what is important for providing comfort in using hand tools and can use this information during the design process. In addition, a method was developed to ensure comfort in the design process. That method consists of identifying the most important comfort-related customer needs using the Comfort Questionnaire for Hand tools. The applications of the results of the current thesis are described in this section. The results can be applied to both hand tool design and hand tool evaluation.

8.3.2 Applications for hand tool design

Choice of comfort-related customer needs

Designers can establish the comfort-related customer needs and their relative importance by using the Comfort Questionnaire for Hand tools. The importance of the comfort descriptors can be obtained from the strength of the relationship between the comfort descriptors and the comfort experience. The most important comfort descriptors can be considered as comfort-related customer needs for hand tools. If it is not possible to set up an experiment to establish the relationship between comfort descriptors and comfort experience, the flow chart (proposed in chapter 5) can be used to assist designers in choosing the appropriate comfort-related customer needs that should be taken into consideration during the design process. Moreover the House of Quality of the Quality Function Deployment can be used to establish the effect of changing an engineering characteristic on the customer needs perception. Chapter 6 describes a study in which these effects are investigated. The data collected in that study can be used as a starting point for filling up the House of Quality for other kinds of hand tools during the design process.

8.3.3 Applications for hand tool evaluation

Subjective methods to measure comfort and discomfort

Comfort and discomfort can be subjectively measured using the Comfort Questionnaire for Hand tools and using a body map for local perceived discomfort respectively. The Comfort Questionnaire for Hand tools can be used for different purposes. Firstly, it can be applied to investigate the most important comfort descriptors for a specific hand tool. This is important to know as the focus should be on these comfort descriptors during the design process. Next to that, it is also possible to recognize why one hand tool is experienced as more comfortable than the others, based on the differences in ratings of the comfort descriptors. These will give the designer starting points to improve the design of a hand tool in order to meet the standard of the competitors. At the end of the design process, the new design can be compared to the traditional design using the Comfort Questionnaire for Hand tools and the body map for local perceived discomfort.

Objective measures to measure comfort and discomfort

In hand tool evaluations, it may be usefull to have an indication of the force exertions on the hand grip (like pliers and hand saws) in order to decide which hand tool is the best. In those situations, it is recommended to use contact pressure measurements in addition to subjective measures. Furthermore, muscle activity may be important to comfort or discomfort in using hand tools that are used for precision tasks as other studies have shown an increase of muscle activity with increased precision demands (like dentist instruments) (Milerad and Ericson, 1994; Visser et al., 2004).

Choice of task

When evaluating a hand tool on comfort and discomfort it is recommended to evaluate the hand tool using different workplace layouts that are representative of the daily use of the hand tool. Additionally, all tasks that will be performed using the hand tool should be evaluated. For instance, masonry's trowels are used to scoop up the mortal, to carry the mortal, to spread out the mortal over the bricks, and to cut the bricks. In this case, all tasks should be evaluated.

8.4 Recommendations for future research

Finalizing the current thesis, some questions remain without an answer. Therefore, recommendations for future research with regard to hand tool design and hand tool evaluation are made in the current section.

8.4.1 Future research regarding hand tool design

The flow chart (proposed in chapter 5) to support designers in choosing the appropriate customer needs, is a first proposal. It is based on hand tool evaluation studies of screwdrivers, paintbrushes and hand saws only. It should be validated for other kinds of hand tools and it may be extended with more choices in order to cover all kinds of hand tools.

The Quality Function Deployment (and more specific the House of Quality) can be used to incorporate comfort in the hand tool design process. However, it is necessary to validate the estimations of the design team between customer needs and engineering characteristics. This may be very time consuming when it is needed in every hand tool design process. However, it seems that the effect of changing an engineering characterstic on the perception of the customer needs are common for different kinds of hand tools. This means that if these relationships are investigated for one type of hand tool, it may be applied to other kinds of hand tools. A future study is needed to investigate these relationships for other kinds of hand tools in order to confirm or reject this hypothesis.

Although the studies of the current thesis show which engineering characteristics are important for comfort in using hand tools, they are lacking information on how these engineering characteristics should be optimised. It is necessary to investigate how to optimize engineering characteristics, not only based on anthropometrics and maximal force exertion but with respect to comfort experience.

8.4.2 Future research regarding hand tool evaluation

The relationship between objective and subjective measures was only established for a hand tool which requires high forces and large movement trajectories. In that case contact pressure measurement was the only objective measurement that was related to discomfort. As argued before, it may be possible that muscle activity can be associated with comfort and discomfort in using hand tools that need precision and which are used under static circumstances. Therefore, it is recommended to also investigate the relationship between objective and subject measures for hand tools used for precision tasks under static circumstances, like dentist instruments.

The Comfort Questionnaire for Hand tools was developed to evaluate non-powered hand tools. It may also be applied to powered hand tools. However, comfort descriptors of powered hand tools should be added and the questionnaire should be validated again. Hence, before the Comfort Questionnaire for Hand tools is applied to powered hand tools, it should be investigated what descriptors are associated with comfort in using powered hand tools by end-users. In that way, the work done in the current thesis could be extended further than non-powered hand tools.

8.5 References

Chang, S.R., Park, S., Freivalds, A., 1999. Ergonomic evaluation of the effects of handle types on garden tools. International Journal of Industrial Ergonomics, 24 (1): 99-105.

Dempsey, P.G., McGorry, R.W., O'Brien, N.V. 2004. The effects of work height, workpiece orientation, gender, and screwdrivers type on productivity and wrist deviation. International Journal of Industrial Ergonomics, 33 (4): 339-346.

Fellows, G.L., Freivalds, A., 1991. Ergonomics evaluation of a foam rubber grip for tool handles. Applied Ergonomics, 22 (4): 225-230.

Goonetilleke, R.S. Designing to minimize discomfort. Ergonomics in Design. 6: 12-19.

Green, P.E., Krieger, A.M., Wind, Y.J., 2001. Thirty years of conjoint analysis: reflections and prospects. Interfaces. 31: s56-s73.

Kee, D., Karwowski, W., 2001. The boundaries for joint angle of isocomfort for sitting and standing males based on perceived comfort af static joint postures. Ergonomics, 44 (6): 614-648.

Kee, D., Karwowski, W., 2003. Ranking systems for evaluation of joint and joint motion stressfulness based on perceived discomfort. Applied Ergonomics. 43 (2): 167-176.

Lin, J-H., McGorry, R.W., Dempsey, P.G., Chang, C-C., 2006. Handle displacement and operator responses to pneumatic nutrunner torque buildup. Applied Ergonomics, 37 (3): 367-376.

Looze, M.P. de, Kuijt-Evers, L.F.M., Dieën, J. van, 2003. Sitting comfort and discomfort and the relationships with objective measures. Ergonomics, 46 (10): 985-997.

Milerad, E., Ericson, M.O., 1994. Effects of precision and force demands, grip diameter, and arm support during manual work: an electromyographic study. Ergonomics, 37 (2): 255-264.

Pullman, M.E., More, W.L., Wardell, D.G., 2002. A comparison of quality function deployment and conjoint analysis in new product design. Journal of Product Innovation Management, 19 (5): 354-364.

Visser, B., Looze, M.P de, Graaff, M.P. de, Dieën, J.H. van, 2004. Effects of precision demands and mental pressure on muscle activation and hand forces in computer mouse tasks. Ergonomics, 47 (2): 202-217.

Summary

Summary

Comfort in Using Hand Tools; Theory, Design and Evaluation

Hand tools, like knifes, forks, and scissors are used by many people in their daily life. Moreover, many professional workers use hand tools to perform their jobs (e.g. construction workers, carpenters, cooks, surgeons). The use of hand tools is very often accompanied by feelings of discomfort, i.e., physical experiences of pain, fatigue, numbness, etcetera. Feelings of discomfort can reduce job satisfaction and productivity and can cause musculoskeletal disorders on the longer term. Therefore, hand tool design and evaluation were mainly focused on the decrease of discomfort in the past. Hand tools were required to respond to the needs of the greatest possible number of users, and be as cheap as possible. Nowadays, the scope changes to providing comfort, i.e. general feelings of pleasantness and well-being. New product manufacturing techniques are developed, which make it possible to customize products. Because of these developments on customization, it is possible to more easily adapt the design to personal preferences. In near future, this will give the opportunity to provide comfort in tool design. Therefore, comfort is and may become a more important issue in hand tool design with respect to these developments. Manufacturers and hand tool distributors already recognise comfort as a major selling point. However, knowledge is lacking about 1) comfort and discomfort in using hand tools and their underlying attributes, 2) ensuring attention to comfort in the design process, and 3) the evaluation of hand tools with regard to comfort.

The main objective of this thesis is to provide knowledge to designers and researchers on comfort and discomfort in hand tool design and evaluation. Chapter 1 addresses why it is important to provide knowledge about this topic to designers and researchers. The second chapter of this thesis describes the state of science and indicates the gaps in the current knowledge. Chapter 3 to 7 concern experiments

which gain new knowledge on comfort and discomfort in using hand tools, hand tool design, and hand tool evaluation. The thesis ends with an epilogue (chapter 8) which reflects on the methodology, the results and their applications.

In the first introductory chapter, the importance of the focus on comfort and discomfort in hand tool design is argued and the sub-goals of the thesis are described, namely 1) to contribute to the theory on comfort and discomfort in using hand tools, 2) to propose methods to incorporate comfort in hand tool design and 3) to investigate how comfort can be evaluated in hand tool use. In addition, an outline of the thesis is given based on a conceptual frame work, which illustrates the relationship between product properties of hand tools and comfort experience of end-users. As end-users do not evaluate hand tools on comfort experience in terms of product characteristics (but in terms of performance), the relationship between product properties and comfort experience can not be directly established. Therefore, a step between product properties and comfort experience is needed to get information about the underlying reasons of end-users' comfort experience. This step consists of descriptors of performance of hand tools. These descriptors will be referred to as comfort descriptors. Hence, comfort descriptors are descriptions (in the end-users' own words) that are related to comfort in using hand tools.

Chapter 2 gives an overview of the state of science on the three main topics of this thesis: comfort theory, hand tool design, and hand tool evaluation. This chapter is based on a literature survey, which shows that there are different definitions of comfort but that some issues are generally accepted: comfort is a subjective feeling and a reaction to the environment affected by factors of various nature (physical, physiological and psychological). Another part of the discussion in the literature focuses on the differences between comfort and discomfort. Comfort and discomfort are both construct variables, which are underlied by several elements. The question is whether the underlying elements are the same for comfort and discomfort (and are two opposites on one scale) or have different

underlying elements (and have to be considered on two separate scales). This seems to depend on the product.
The survey also showed that different methods are used in hand tool design. Some general design methods have been described in the literature, such as the participatory design process (which is a design process that allow users to have a large amount of input into product design) and the basic design cycle (which is a model that illustrates the steps of the design process and its cyclic character). Quality Function Deployment (and as part of it the House of Quality) has been presented in different hand tool design studies. The House of Quality is a design tool which helps the designers to translate the customer needs into engineering characteristics and to focus on the appropriate engineering characteristics to achieve maximal effort when (re)designing a product. Therefore, this also seems to be an appropriate tool to incorporate comfort in the hand tool design process. Finally, methods are described, which have been specifically developed for hand tool design (like the 11-point program).

In addition, the literature showed that many hand tool evaluation studies have been conducted in recent years. Most of them use subjective (to establish e.g., discomfort, workload, preference) as well as objective measurements (like muscle activity, grip force). For assessing discomfort (with hand or body map), the literature provides validated methods, but comfort has hardly been studied. No suitable method was found to measure comfort. Moreover, it is unknown if objective measures can be used to predict the comfort experience in hand tool use.

Chapter 3 concerns an investigation into the underlying descriptors of comfort and discomfort in using hand tools (like fits the hand, has a nice feeling handle) and their relative importance. 58 Possible underlying descriptors were collected by a literature survey and interviews. 22 hand tool users rated these descriptors with respect to either comfort or discomfort. The remaining list with comfort descriptors was validated by 50 other hand tool users, who indicated the relationship between the comfort descriptors and comfort/discomfort in general, without actually using or holding a hand tool. The comfort descriptors were divided into 6 main factors using Principal Components Analysis. It was concluded that comfort and discomfort could be seen as two opposites on a continuous scale, because the same descriptors were related to comfort as well as discomfort. In addition, functionality of the hand tool was thought to be most closely related to comfort and discomfort in using hand tools according to the hand tool users, followed by the factors that deal with physical interaction. The hand tool users did not actually use or hold a hand tool when indicating the relationships during this study. The results of this study contribute to the development of a questionnaire to evaluate hand tools on comfort (in the next chapter).

Chapter 4 describes the development of the first version of the Comfort Questionnaire for Hand tools (CQH) and the use of the CQH in a screwdriver evaluation study. The aim of this study was to identify the predictors of comfort and discomfort in using hand tools. It was not only studied which comfort descriptors and factors are associated with comfort and discomfort, but also to what extent they are related to comfort and discomfort. Therefore, the relationships were calculated between the comfort descriptors (i.e., statements in end-users' own words that are related to comfort) and factors (i.e., groups of interrelated comfort descriptors retrieved from Principal Components Analysis), and comfort and discomfort on the other hand. 20 Do-It-Yourself hand tool users volunteered in this study. They evaluated four screwdrivers, which differed clearly, on expected comfort at first sight, and comfort and discomfort after turning 6 screws into a wooden beam. Comfort was measured using the CQH, which consists of ratings of expected comfort, comfort descriptors, and overall comfort on a 7-point scale. Discomfort was measured using a hand/arm map to assess local perceived discomfort. The results show that expected comfort is mainly associated with a 'professional look', and comfort after use is determined by 'ease in use', 'nice-feeling handle' and 'low hand grip force supply'. Discomfort was predicted by 'causes cramped muscles' and 'causes pressure on the hand'. Principal Components Analysis of the comfort descriptors revealed 6 major factors: 1) *functionality and physical interaction*, 2) *adverse body effects*, 3) *handle surface*, 4) *quality*, 5) *colour*, and 6) *aesthetics*. Expected comfort was mainly predicted by aesthetics. Comfort after use was related to *functionality and physical interaction* and *adverse body effects*. *Aesthetics* played a minor role. *Adverse body effects* was the only factor which determined discomfort. It was concluded that comfort and discomfort have one common underlying factor (i.e., *adverse body effects*). However, in order to design hand tools that provide comfort to the end-user, it is not only necessary to avoid adverse body effects (i.e., discomfort), but also to provide a good functionality and physical interaction. Moreover, aesthetics play a role in product buying decisions as it was highly associated with expected comfort.

The aim of the study addressed in chapter 5 was to investigate whether the same comfort descriptors and factors underlie comfort in using different kinds of hand tools. Data from three studies were used, in which screwdrivers, paintbrushes and hand saws were evaluated by use of the Comfort Questionnaire for Hand tools. The underlying factors of comfort in using the hand tools were identified using Principal Components Analysis. The relationships between comfort descriptors and factors with comfort experience were calculated. It was concluded that the same factors (*functionality*, *physical interaction*, *adverse effects on skin and adverse effect in soft tissues*) underlie comfort in different kinds of hand tools, although their relative importance differed. *Functionality and physical interaction* is the most important factor of comfort in using screwdrivers and paintbrushes and *functionality* was the most important factor in using hand saws. Moreover, the most important comfort descriptors differ between different kinds of hand tools. ‘Has a nice feeling handle’, ‘fits the hand’ and ‘offers a high task performance’ are the most important comfort descriptors in using screwdrivers, paintbrushes and hand saws respectively. Similarities are also seen: ‘Fits the hand’ is associated with comfort in all studied hand tools. The results of this study were applied in a flow chart, which designers can use to choose the appropriate comfort descriptors (i.e., customer needs for comfortable hand tools) in the hand tool design process.

Chapter 6 concerns the question whether the Quality Function Deployment (QFD) and especially, the House of Quality, is suitable to incorporate comfort in screwdriver design. In order to do so, it was investigated to what extent the 'Whats'/'Hows' correlations that the design teams has to make are accurate (i.e., to what extent are design teams able to predict how a change of the engineering characteristics of a hand tool will change customers' perceptions of comfort in using hand tools). Firstly the comfort-related customer needs are listed followed by describing the engineering characteristics. After that, the design team estimated the 'Whats'/'Hows' correlations. A case study on screwdriver design was performed to investigate if the design team can estimate the effects of changing engineering characteristics (product properties) on the perception of customer needs (comfort descriptors) in the House of Quality accurately. The estimated 'Whats'/'Hows' correlations of the House of Quality were compared to the correlations from a customer validation study. The results showed that 75% of the 'Whats'/'Hows' correlations were well estimated. The consequence of the wrong estimations may be that the design team focuses on the wrong engineering characteristics during the design process and important keys necessary to fulfil the customer needs are missed. It was concluded that the House of Quality can be used to set priorities in designing comfortable products on the condition that the 'Whats'/'Hows' correlations between customer needs and engineering characteristics are confirmed by a customer validation study or otherwise.

Hand tool evaluation very often comprises subjective and objective measurements. The subjective measurements are mostly used to assess discomfort or personal preferences, while the objective measurements indicate the physical workload. Subjective measurements have some clear disadvantages, like some common known sources of unreliability. Therefore, it would be interesting if we could obtain support for subjective measurements of comfort and discomfort by objective measurements. The aim of chapter 7 was to investigate the relationship between objective measures and subjective measures of comfort and discomfort. Moreover, the relationship between productivity and comfort and discomfort was established. 12 carpenters evaluated five different hand saws. Objective measures of contact pressure (average pressure, pressure area and P-t integral) in static and dynamic conditions, muscle activity (EMG) of five muscles of the upper extremity, and productivity were obtained during a sawing task. Subjective comfort and discomfort were assessed using the Comfort Questionnaire for Hand tools and a hand/arm/shoulder map respectively. The pressure area during static measurement was the best predictor of discomfort (20.3% explained variance). Hence, pressure data can support subjective measurements of discomfort. Moreover, this contact pressure measurement can be useful to designers in hand grip design. From the productivity point of view, it is also important to design comfortable hand tools as they affect productivity in a positive way.

The epilogue in chapter 8 gives an overview of the results of this thesis, a reflection on the methodology, suggestions for designers and researchers in practice and recommendations for future research. The most important results are described below.

- Comfort and discomfort have one common underlying factor: adverse body effects. Moreover, comfort is mainly affected by functionality and physical interaction. Expected comfort at first sight is mainly predicted by aesthetics, but (expected) functionality and physical interaction also play a role. Moreover, the same factors underlie comfort in different kinds of hand tools, although the importance of these factors varies between hand tools. In addition, different comfort descriptors are associated with comfort in different kinds of hand tools. However, the comfort descriptor 'fits the hand' and the factor *functionality* are important for all kinds of hand tools.
- The House of Quality (a part of the Quality Function Deployment) seems to be an appropriate design method to incorporate comfort in the design process, on the condition that the estimation of 'Whats'/'Hows' correlations between customer needs and engineering characteristics are supported by a customer validation study and/or literature review.

- The Comfort Questionnaire for Hand tools can be used to assess comfort in using hand tools subjectively. Objective measures like muscle activity and contact pressure can not predict subjective comfort experience. However, discomfort was associated with contact pressure.

Designers and researchers can apply the results of this thesis to hand tool design and evaluation. The Comfort Questionnaire for Hand tools can be used by designers and researchers for several purposes: 1) to investigate the most important comfort descriptors (i.e., customer needs) for a specific type of hand tool, 2) to find starting points for hand tool design improvement, and 3) to compare different kinds of the same type of hand tool with each other on comfort. Moreover, in hand tool evaluation and design, the different tasks performed with the hand tool, the various end-users, as well as the environment should be addressed, as comfort experience is an interaction between user, task, and tool in the environment.

Lottie F.M. Kuijt-Evers

Samenvatting

Samenvatting

Comfort bij gebruik van handgereedschap; theorie, ontwerp en evaluatie

Tijdens het dagelijkse leven gebruiken veel mensen handgereedschappen, zoals messen, vorken en scharen. Daarnaast worden handgereedschappen veelvuldig gebruikt in verschillende beroepsgroepen. Denk hierbij bijvoorbeeld aan timmerlieden, bouwvakkers, chirurgen en koks. Vaak gaat het gebruik van handgereedschap gepaard met lichamelijk ongemak (discomfort). Dit is echter onwenselijk, want het optreden van discomfort kan leiden tot een verlaagde arbeidstevredenheid en een verlaging van de productiviteit. Daarnaast zijn er aanwijzingen dat het optreden van discomfort op langere termijn lichamelijke klachten kan veroorzaken. Dit zijn de redenen dat ontwerpers veel aandacht schenken aan het voorkomen van discomfort. Ten gevolge van de concurrentie tussen handgereedschapfabrikanten en nieuwe ontwikkelingen in het productieproces, zoals customization (het ontwikkelen van producten voor een individu), verandert de focus in de ontwerpwereld van het voorkómen van discomfort naar het bieden van comfort. Er ontbreekt echter kennis over 1) wat gereedschapgebruikers verstaan onder comfort en discomfort bij het gebruik van handgereedschap en wat de onderliggende factoren zijn, 2) hoe het ontwerpproces moet verlopen zodat comfort gewaarborgd wordt in het eindontwerp en 3) hoe handgereedschappen geëvalueerd kunnen worden op comfort en discomfort.

Het doel van dit proefschrift is het ontwikkelen van kennis over comfort en discomfort bij gebruik van handgereedschap ten behoeve van ontwerpers en onderzoekers die zich bezighouden met het ontwerpen en evalueren van handgereedschap. Het eerste hoofdstuk beschrijft waarom het belangrijk is dat kennis ontwikkeld wordt op dit gebied. Daarna wordt in het tweede hoofdstuk de stand der kennis beschreven en worden hiaten in het kennisgebied aangeduid. In hoofdstuk 3 tot en met 7 worden experimenten beschreven die bijdragen aan de theorievorming rond comfort en discomfort bij handgereedschap, handgereedschapontwerp en handgereedschapevaluatie. Het proefschrift wordt afgesloten met een epiloog, waarin de belangrijkste resultaten van het onderzoek worden samengevat, een reflectie op de onderzoeksmethoden wordt gegeven en de gemaakte keuzes worden toegelicht. Tevens worden hier de toepassing van de resultaten van het onderzoek beschreven en aanbevelingen gedaan voor toekomstig onderzoek.

De inleiding van dit proefschrift in hoofdstuk 1 geeft aan waarom het belangrijk is dat kennis ontwikkeld wordt over comfort en discomfort bij het gebruik van handgereedschap. Daarnaast worden de subdoelen van dit proefschrift beschreven: 1) het bijdragen aan de theorievorming over comfort en discomfort bij het gebruik van handgereedschap, 2) het voorstellen van een ontwerpmethode om aandacht voor comfort in het ontwerpproces te borgen en 3) het onderzoeken hoe comfort bij het gebruik van handgereedschap getest kan worden. Ten slotte wordt een overzicht van het proefschrift gegeven dat gebaseerd is op een conceptueel model. Dit model geeft de relatie weer tussen producteigenschappen van handgereedschap en de comfortbeleving van eindgebruikers. Eindgebruikers beoordelen het comfort van een handgereedschap echter meestal niet op de afzonderlijke producteigenschappen (zoals de scherpte van een schaar of de stroefheid waarmee deze beweegt), maar op de prestatie (de schaar glijdt door het papier, de schaar gaat goed de bocht om). Daarom is het nodig om de relatie tussen de producteigenschappen en de comfortbeleving te beschrijven via een tussenstap die informatie geeft waarom eindgebruikers een bepaalde comfortbeleving hebben. Aangezien de meeste eindgebruikers het comfort van gereedschap beoordelen op basis van de prestatie, bestaat deze stap uit beschrijvingen die de prestatie van het gereedschap weergeven. Deze beschrijving worden in dit proefschrift 'comfort descriptoren' genoemd. Comfort descriptoren zijn beschrijvingen (in de eigen woorden van de eindgebruiker) die gerelateerd zijn aan comfort bij het gebruik van handgereedschap.

Hoofdstuk 2 biedt een overzicht van de stand der kennis op de drie deelgebieden van dit proefschrift: comforttheorie, gereedschapontwerp en gereedschapevaluatie. In het eerste deel over comforttheorie wordt ingegaan op de verschillende definities van comfort en het gebrek aan consensus hierover in de (wetenschappelijke) literatuur. Een aantal punten staat echter niet ter discussie. Zo wordt comfort gezien als een subjectief gevoel dat optreedt in reactie op de omgeving en dat wordt bepaald door verschillende invloeden (bv. psychologische, lichamelijke en fysiologische invloeden). Daarnaast beschrijft de wetenschappelijke literatuur de discussie over hoe comfort zich tot discomfort verhoudt. De vraag is of comfort door dezelfde aspecten bepaald wordt als discomfort. Als dat zo is zijn comfort en discomfort twee uitersten op eenzelfde schaal. Echter indien de aspecten die comfort bepalen anders zijn dan de aspecten die discomfort bepalen, zullen comfort en discomfort apart beoordeeld moeten worden op verschillende schalen.

Het tweede deel van het literatuuronderzoek gaat over de ontwerpmethoden die gebruikt worden bij het (her)ontwerpen van handgereedschap. Het blijkt dat diverse ontwerpmethoden gangbaar zijn. Een tweetal algemene methoden wordt beschreven, zoals de participatieve ontwerpaanpak en de ontwerpbasiscyclus. De participatieve ontwerpaanpak is een methode waarbij eindgebruikers betrokken worden in het ontwerpproces en een grote invloed hebben op het eindproduct dat ontworpen wordt. De ontwerpbasiscyclus is een model voor de cyclische basisstructuur van het ontwerpproces. Het illustreert de verschillende stappen waaruit een ontwerpproces bestaat en de herhaling van deze stappen die noodzakelijk is om tot een ontwerp te komen. De Quality Function Deployment, en als onderdeel hiervan: het Kwaliteitenhuis, wordt regelmatig beschreven in relatie tot gereedschapontwerp. Deze methode houdt rekening met zowel de technische als de ergonomische eisen die aan een product gesteld worden. Bovendien helpt het de ontwerpers bij het vertalen van de gebruikerseisen in producteigenschappen. Het lijkt een waardevolle methode om comfort in het ontwerpproces te waarborgen. Ten slotte, zijn er nog ontwerpprocessen die

speciaal voor het ontwerp van handgereedschap ontwikkeld zijn. Ook deze processen worden beschreven.
Tevens kwam uit het literatuuronderzoek naar voren dat er zeer veel handgereedschapevaluaties plaatsgevonden hebben de afgelopen jaren. Tijdens deze evaluaties voeren gebruikers diverse taken uit met het gereedschap. Daarbij worden metingen verricht om bijvoorbeeld de lichamelijke belasting te bepalen. Op deze wijze kunnen verschillende uitvoeringen van hetzelfde handgereedschap met elkaar vergeleken worden. Deze evaluaties bestaan veelal uit subjectieve en objectieve meetmethoden. Subjectieve meetmethoden (waarin de gebruikers om een beoordeling wordt gevraagd) worden bijvoorbeeld gebruikt voor het vaststellen van het ervaren discomfort, de voorkeur voor een bepaald gereedschap en de mate van ervaren arbeidsbelasting. Objectieve meetmethoden (waarbij 'harde' gegevens -onafhankelijk van de persoonlijke mening van de gebruiker- worden verzameld met diverse meetinstrumenten) worden ingezet om bijvoorbeeld de spieractiviteit of de knijpkracht tijdens het knippen met een zijsnijtang te bepalen. Voor het bepalen van discomfort zijn geschikte (subjectieve) meetmethoden beschreven in de literatuur, zoals de Lokaal Ervaren Ongemak (LEO) methode, waarbij gebruikers per lichaamsgebied aangeven of en in welke mate ze ongemak ervaren. Voor het bepalen van het ervaren comfort zijn geen geschikte meetmethoden gevonden in de literatuur. Bovendien is geen informatie gevonden over een mogelijk verband tussen objectieve meetmethoden (spieractiviteit, druk op de hand) en subjectief ervaren comfort en discomfort.

Hoofdstuk 3 beschrijft een onderzoek waarin de onderliggende aspecten en het relatieve belang ervan voor comfort en discomfort bij handgereedschap geïnventariseerd zijn. Tijdens een literatuurstudie zijn alle begrippen verzameld die gebruikers kunnen associëren met comfort en discomfort bij handgereedschap. De mate waarin eindgebruikers vinden dat deze begrippen gerelateerd zijn aan comfort werd onderzocht. De eindgebruikers gaven aan in welke mate zij vonden dat deze begrippen geassocieerd zijn met comfort of discomfort bij gebruik van handgereedschap in het algemeen, zonder daarbij werkelijk een handgereedschap in de hand te hebben. Dit resulteerde in een lijst van begrippen die door gebruikers geassocieerd worden met comfort en discomfort: de zogenaamde comfort descriptoren. Het blijkt dat dezelfde begrippen met comfort als met discomfort geassocieerd worden. De comfort descriptoren werden in 6 hoofdgroepen verdeeld (met behulp van een statistische techniek: hoofdcomponenten analyse). Daarbij komen de comfort descriptoren die aan elkaar gerelateerd zijn in één groep, ook wel factor genoemd. De factor die het meest gerelateerd was aan comfort, is de factor *functionaliteit* (welke comfort descriptoren bevat als 'gemakkelijk in gebruik', 'functioneel') gevolgd door drie andere factoren die allemaal te maken hadden met de *fysieke interactie* (zoals 'drukpunten op de hand'). De resultaten van dit onderzoek vormden de basis voor het ontwikkelen van de comfortvragenlijst handgereedschap.

Hoofdstuk 4 beschrijft de ontwikkeling van de eerste versie van de comfortvragenlijst handgereedschap. Deze vragenlijst werd vervolgens getest tijdens een schroevendraaierevaluatie. Het doel van het onderzoek was het achterhalen wat de voorspellers (comfort descriptoren en factoren) zijn voor comfort en discomfort bij handgereedschap. Daarom is het verband bepaald tussen de score op de comfort descriptoren en de factoren enerzijds met de beoordeling van het comfort en discomfort anderzijds. 20 Doe-het-zelvers beoordeelden 4 schroevendraaiers nadat ze 6 schroeven in een houten balk gedraaid hadden. Het verwachte comfort, comfort na gebruik en het discomfort zijn beoordeeld. Hieruit bleek dat het verwachte comfort met name bepaald wordt door hoe het gereedschap eruit ziet, maar ook door hoe het aanvoelt in de hand. Het comfort na gebruik wordt vooral bepaald door de functionaliteit en de lichamelijke interactie tussen handgreep en hand. Daarnaast speelt het optreden van lichamelijk ongemak een rol. Discomfort wordt in zijn geheel bepaald door het optreden van lichamelijk ongemak. Hieruit volgt dat ontwerpers niet alleen moeten focussen op het voorkómen van discomfort, maar dat ook aandacht geschonken moet worden aan de functionaliteit en de hand-handvat interface. Het uiterlijk blijkt een belangrijke rol te spelen bij aankoop, maar daarna niet meer.

Het doel van het onderzoek in hoofdstuk 5 was om te achterhalen of dezelfde comfort descriptoren en factoren belangrijk zijn voor comfort bij verschillende gereedschappen. Hiervoor zijn de data van drie evaluatiestudies (schilderskwasten, schroevendraaiers en zagen) opnieuw geanalyseerd. De onderliggende factoren zijn voor alle gereedschappen bepaald met behulp van de hoofdcomponenten analyse. Daarnaast zijn de verbanden tussen comfort descriptoren en factoren aan de ene kant en comfortbeleving aan de andere kan bepaald. Uit de resultaten komt naar voren dat comfort descriptoren verdeeld worden in dezelfde factoren voor de verschillende gereedschappen (functionaliteit, fysieke interactie, discomfort aan het huidoppervlak, discomfort in dieperliggend weefsel). Echter de invloed die de factoren hebben op de comfortbeleving verschilt per gereedschap. Ook de belangrijkste comfort descriptoren zijn verschillend voor onderzochte gereedschappen. Daarnaast zijn er overeenkomsten gevonden tussen de gereedschappen. Zo blijkt een 'goede ligging in de hand' voor alle gereedschappen belangrijk te zijn. De resultaten van dit onderzoek zijn weergegeven in een stroomdiagram. Op basis hiervan kunnen ontwerpers kiezen welke gebruikerseisen belangrijk zijn voor comfort bij een bepaald type gereedschap.

In hoofdstuk 6 wordt onderzocht of de Quality Function Deployment (QFD) een geschikte methode is om comfort in handgereedschapontwerp te waarborgen. Het belangrijkste daarvoor is dat het ontwerpteam de effecten van veranderingen in producteigenschappen op de beoordeling van de gebruikerseisen (comfort descriptoren) goed kan voorspellen. Het is namelijk van belang om te weten welke producteigenschappen veranderd moeten worden om de grootste verbetering op het gebied van comfort te bereiken. Daarom is in dit hoofdstuk onderzocht of een ontwerpteam in staat is deze effecten (ook wel 'wat'/'hoe'correlaties genoemd) die nodig zijn om het Kwaliteitenhuis van de QFD methode in te vullen, goed te schatten. Het ontwerpteam is gevraagd het Kwaliteitenhuis in te vullen voor het ontwerp van een comfortabele schroevendraaier door op basis van hun kennis en ervaring de 'Wat'/'Hoe' correlaties te schatten zoals het gebruikelijk is. Vervolgens is middels een gebruikersonderzoek bepaald of deze effecten goed geschat zijn. Hieruit bleek dat in 75% van de gevallen de effecten goed geschat zijn. In de overige gevallen was het geschatte effect anders dan het werkelijke effect zoals vastgesteld in het gebruikersonderzoek. Door deze foute schattingen kan het gebeuren dat ontwerpers de verkeerde prioriteiten stellen tijdens het ontwerpproces. Daarom is het belangrijk om bij gebruik van het Kwaliteitenhuis ten einde comfort in handgereedschapontwerp te waarborgen, de 'Wat'/'Hoe' correlaties te onderbouwen met bijvoorbeeld een gebruikersevaluatie of literatuuronderzoek.

Handgereedschapevaluaties combineren vaak subjectieve en objectieve meetmethoden. Subjectieve meetmethoden hebben echter enkele nadelen. Daarom is het interessant om te kijken of er ook objectieve meetmethoden zijn, die in zulke mate gerelateerd zijn aan comfort en discomfortbeleving dat ze als voorspellende methode gebruikt kunnen worden. In hoofdstuk 7 wordt een onderzoek beschreven waarin vijf handzagen geëvalueerd werden. Hierbij werden zowel objectieve (spieractiviteit en druk op de hand) als subjectieve metingen (comfort en discomfort) uitgevoerd. De relaties tussen de uitkomsten van de twee objectieve metingen en subjectief gemeten comfort en discomfort werden bepaald, alsmede de relatie tussen productiviteit enerzijds en comfort en discomfort anderzijds. Comfort blijkt niet voorspeld te kunnen worden op basis van spieractiviteit en druk op de hand. De mate van druk op de hand was als enige gerelateerd aan discomfort (20,3% verklaarde variantie). Drukmeting op de hand kan derhalve ingezet worden om de resultaten van subjectief gemeten discomfort te bevestigen. Daarnaast kan deze methode aanwijzingen geven voor het optimaliseren van handvatten. Bovendien blijkt uit dit onderzoek dat gereedschap dat comfort biedt tijdens gebruik niet alleen belangrijk is vanuit gezondheidskundig oogpunt, maar ook vanuit economisch perspectief, aangezien de productiviteit verhoogd werd bij gebruik van de zaag die meer comfort bood.

Tot slot volgt in hoofdstuk 8 een epiloog waarin een overzicht van de belangrijkste resultaten en een reflectie op de gebruikte methoden gegeven wordt. Daarnaast worden toepassingen van de resultaten voor de ontwerppraktijk beschreven alsmede aanbevelingen gedaan voor toekomstig onderzoek.

De belangrijkste bevindingen van de proefschrift staan hieronder beschreven:

- Comfort en discomfort hebben één gezamenlijke onderliggende factor, namelijk lichamelijke ongemak. Daarnaast wordt comfort bepaald door de functionaliteit van het handgereedschap en de fysieke interactie tussen handgereedschap en hand. Verwacht comfort op het eerste gezicht wordt voornamelijk bepaald door het uiterlijk, maar ook de fysieke interactie speelt hier een rol. Comfort bij verschillende soorten gereedschap wordt door dezelfde factoren beïnvloed, maar het individuele aandeel van een factor is verschillend voor verschillende gereedschappen. Ook de comfort descriptoren die het comfort bepalen zijn verschillend voor verschillende gereedschappen. De overeenkomsten zijn dat voor alle gereedschappen een 'goede ligging in de hand' belangrijk is, alsmede de functionaliteit.
- The Quality Function Deployment (en met name het Kwaliteitenhuis) is een geschikte methode om comfort in het ontwerpproces te borgen, mits de 'Wat'/'Hoe' correlaties onderbouwd worden met gebruikersonderzoek en/of literatuuronderzoek.
- De comfortvragenlijst handgereedschap is ontwikkeld en kan gebruikt worden om handgereedschap te evalueren op comfort. Objectieve metingen (van spieractiviteit en druk op de hand) kunnen comfortbeleving niet voorspellen. Echter, discomfort was wel gerelateerd aan druk op de hand.

Ontwerpers en onderzoekers kunnen de resultaten van dit proefschrift gebruiken bij de ontwikkeling en evaluatie van handgereedschap. De comfortvragenlijst handgereedschap is hierbij een belangrijk onderdeel. Deze kan gebruikt worden om 1) de belangrijkste comfort descriptoren (en dus gebruikerseisen) te achterhalen voor een bepaald gereedschap, 2) aanknopingspunten te bieden voor verbetering van een bestaand gereedschap op basis van de scores op de individuele comfort descriptoren en 3) verschillende gereedschappen met elkaar te vergelijken op het gebied van comfort. Daarbij zullen bij handgereedschapontwerp en –evaluatie altijd de verschillende taken die uitgevoerd worden met het gereedschap, de verschillende gebruikers die het handgereedschap gaan gebruiken en de omgeving waarin het handgereedschap gebruikt gaat worden meegenomen moeten worden, want de comfortbeleving van handgereedschap blijft een interactie tussen de gebruiker, de taak en het gereedschap in de omgeving.

Lottie F.M. Kuijt-Evers

Dankwoord

Dankwoord

Een proefschrift schrijven doe je niet alleen. Gelukkig maar! Op deze plek wil ik verschillende mensen bedanken die een bijdrage geleverd hebben aan dit project.

Dit proefschrift is het resultaat van een knap staaltje teamwork binnen TNO. Daarvoor wil ik een aantal collega's heel erg bedanken. Ten eerste wil ik mijn promotoren Peter Vink en Michiel de Looze bedanken voor hun begeleiding en inhoudelijke bijdragen aan dit proefschrift. Door hun "dubbelfunctie" konden ze zich goed inleven in de beperkingen en mogelijkheden die het uitvoeren van een promotieonderzoek binnen het bedrijfsleven met zich meebrengt.

Maar er zijn nog meer (ex)collega's die een bijdrage geleverd hebben. Liesbeth, Tim, Nicole en Laura, jullie hebben geholpen bij het uitvoeren, opzetten en het schrijven van publicaties, waarvoor dank! Henny, dankzij jou ziet ook het Engels er nu verzorgd uit. Bedankt dat je tijd geïnvesteerd hebt om alles te controleren. Ben, jou wil ik bedanken voor alle hulp bij het bedenken en bouwen van de meetopstellingen. En natuurlijk voor alle keren dat je als proefpersoon meegedaan hebt aan de pilots.

Maaike, ook jou wil ik eigenlijk in het rijtje collega's zetten, al ben je dat nu officieel niet meer. Behalve dat je inhoudelijk betrokken was bij een van de onderzoeken uit mijn proefschrift, heb je vooral een belangrijke rol gespeeld in de weg ernaar toe. Dat begon in Den Haag, bij de opleiding Bewegingstechnologie. Daarna gingen we samen naar de VU om Bewegingswetenschappen te studeren, met voor mij als hoogtepunt onze gezamelijke stages. Promoveren doen we dan weer apart van elkaar, maar ik wil je wel graag naast me hebben als paranimf!
Voor het bedrijfsleven geldt ook: zonder geld geen project en zonder klant geen geld. Sandra, daarom ben ik ook jou veel dank verschuldigd. Voor het merendeel

van de projecten waarover ik in dit proefschrift schrijf, heb jij de financiering geregeld. Ik ben dan ook erg blij dat je mijn paranimf wilt zijn.

Verder wil ik ook het management van TNO bedanken, met name Steven d'Hondt en Robin Bronkhorst. Zij hebben me drie maanden vrijgesteld van werk bij TNO, waardoor ik de kans had om aan de TU Delft in alle rust mijn proefschrift af te ronden. Daarvoor wil ik natuurlijk ook Daan van Eijk bedanken, die mij gedurende deze periode in dienst nam van de afdeling Applied Ergonomics and Design van de Faculteit Industrieel Ontwerpen.

Er zijn nog meer mensen buiten TNO die ik wil bedanken. Jos Twisk wil ik bedanken voor zijn bijdrage aan de statistische dataverwerking en voor alle keren dat hij mijn vragen daarover beantwoord heeft. Kaj Morel heeft me enorm geholpen met zijn kennis over de QFD methode. Het was heel inspirerend samen een publicatie te schrijven, te meer omdat onze achtergrond totaal verschillend is.

De leden van de promotiecommissie (prof. Dr. Jaap van Dieën, Prof. Dr. Cees Overbeeke, Prof. dr. Cees de Bondt, Prof. Ir. Daan van Eijk) wil ik bedanken voor hun kritische blik en waardevolle aanwijzingen om dit proefschrift te laten worden tot wat het nu is. I would like to thank Dr. Lena Sperling from Lund University, Sweden. She was one of the researchers of the Swedish hand tool project in the 90's and I am really grateful that she wanted to participate in my promotion commission.

Verder wil ik ook alle timmermannen, schilders en doe-het-zelvers die ik heb laten zagen, schilderen en schroeven bedanken voor hun inspanningen en hun tijd. Ik hoop dat de spierpijn achteraf dragelijk was.

“Oos” Pap en “oos” Mam wil ik bedanken voor de basis die ze me gaven. “Meer dan je best kun je niet doen”, is iets wat ik vaak gehoord heb, net als “goed gereedschap is het halve werk”. Beide uitspraken hebben de afgelopen jaren regelmatig door mijn hoofd gespeeld!

Tenslotte wil ik Eduard, Tom en Daan bedanken. Jullie leren mij te relativeren en laten me telkens weer beseffen wat nu écht belangrijk is. Jullie zijn “100 op de schaal van lief”.

Het was mooi!

Lottie

Publications

Publications

Publications part of this thesis:

Kuijt-Evers, L.F.M., Groenesteijn, L., Looze, M.P. de, Vink, P., 2004. Identifying factors of comfort in using hand tools. Applied Ergonomics, 35 (5): 453-458.

Kuijt-Evers, L.F.M., Twisk, J.W.R., Groenesteijn, L., Looze, M.P. de, Vink, P., 2005. Identifying predictors of comfort and discomfort in using hand tools. Ergonomics, 48 (6): 692-702.

Kuijt-Evers, L.F.M., Bosch, T., Huysmans, M.A., Looze, M.P. de, Vink, P.. Association between objective and subjective measures of comfort and discomfort in hand tools. Applied Ergonomics. In press.

Kuijt-Evers, L.F.M., Vink, P., Looze, M.P. de. Comfort predictors for different kinds of hand tools: differences and similarities. International Journal of Industrial Ergonomics. In press.

Kuijt-Evers, L.F.M., Morel, K.P.N., Vink, P., Eikelenberg, N.J.W. Can design teams accurately estimate correlations between customer needs and engineering characteristics? An application of QFD to the design of comfortable screwdrivers. Applied Ergonomics. Submitted.

Other publications (2001-2006):

Delleman, N.J., Huysmans, M.A., Kuijt-Evers, L.F.M., 2001. Postural behaviour in static gazing sidewards. Proceedings Conference and Exhibition "Digital Human Modeling for design and engineering", June 26-28, 2001, Arlington VI. Warrendale, PA: SAE International 2001: 2093-2097.

Looze, M.P. de, Kuijt-Evers, L.F.M., Dieën, J.H. van, 2003. Sitting comfort and discomfort and the relationships with objective measures. Ergonomics, 46 (10): 985-997.

Kuijt-Evers, L.F.M., Krause, F., Vink, P., 2003. Aspects to improve cabin comfort of wheel loaders and excavators according to operators. Applied Ergonomics, 34 (3): 265-272.

Kuijt-Evers, L.F.M., 2004. Determinants of comfort and discomfort in using hand tools. In: K. Bendix Olsen and O.J. Teller (eds) Proceedings of the Nordic Ergonomics Society 36th Annual Conference "NES 2004". Hotel conwell, Kolding, Denmark 16-18 August 2004.

Kuijt-Evers, L.F.M., 2005. Relationships of contact pressure with subjective experience of comfort and discomfort in using hand saws. In: Ergonomics as a tool in future development and value creation. Proceedings. NES 2005, 37th Annual Conference. Veierstad B, Fostervold KI, Gould KS, Bakkeli W, (eds.) Oslo 10-12 October 2005.

Kuijt-Evers, L.F.M., Buffinga, J., 2006. Ontwerp van een nieuwe vorkheftruckstoel. Tijdschrift voor Ergonomie, 31 (1): 4-9.

Kuijt-Evers, L.F.M., Eikhout, S.M., 2006. Signaal uit de praktijk: De innovatieve metseltroffel. Tijdschrift voor Ergonomie, 31 (4): 20-22.

Kuijt-Evers LFM, Bosch T., 2006. Contact pressure measurement in hand tool evaluation studies. In: Meeting Diversity in Ergonomics. Proceedings IEA2006 Congress. Pikaar R.N., Koningsveld, E.A.P., Settels, P.J.M. (eds). Elsevier, Oxford. CD-rom: art0303.

Kuijt-Evers, L.F.M., Eikhout, S.M., 2006. Development process of a new masoner's trowel. In: Meeting Diversity in Ergonomics. Proceedings IEA2006 Congress. Pikaar, R.N., Koningsveld, E.A.P., Settels, P.J.M. (eds). Elsevier, Oxford. CD-rom: art0571

Kuijt-Evers, L.F.M., 2006. Comfort and discomfort in using hand tools: the hand tool-user-task interaction. In: Meeting Diversity in Ergonomics. Proceedings IEA2006 Congress. Pikaar R.N., Koningsveld, E.A.P., Settels, P.J.M. (eds). Elsevier, Oxford. CD-rom: art0434

Groenesteijn, L., Kuijt-Evers, L.F.M., Eikhout, S.M., 2006. Ergonomic evaluation of bricklayer trowel prototypes in a field setting. In: Meeting Diversity in Ergonomics. Proceedings IEA2006 Congress. Pikaar R.N., Koningsveld, E.A.P., Settels, P.J.M. (eds). Elsevier, Oxford. CD-rom: art0292.

Book chapters

Vink, P., Kuijt-Evers, L.F.M., 2002. Rekening houden met participanten: participatieve ergonomie. In: Comfortabel en slim werken, Vink, P. (ed.). Kerkebosch, Zeist. 25-35.

Groenesteijn, L., Kuijt-Evers, L.F.M., Koningsveld, E.A.P., Wijma, J., 2003. Werkboek fysieke belasting: deel 4 uit de reeks werkboeken Arboconventant Gemeenten. Stichting Arbeidsmarkt- en Opleidingsfonds Gemeenten, Den Haag.

Kuijt-Evers, L., Krause, F., 2003. What would operators like to see. In: Krause F, Bronkhorst RE, Looze MP de, eds. Comfortable earth moving machinery: knowledge and experiences from the Eurocabin porject. TNO Work and Employment, Hoofddorp. 107-111.

Vink, P., Looze, M.P. de, Kuijt-Evers, L.F.M., 2005. Theory of Comfort. In: Comfort and Design: Principles and Good Practice, Vink, P. (ed). CRC Press, Boca Raton (etc.). 13-32.

Kuijt-Evers, L.F.M., Looze, M.P. de, 2005. Integral design of small forklift trucks. In: Advanced Cabin Design. How to Improve Comfort and Performance by Progressive Cabin Design, Bronkhorst, R.E., Looze M.P. de, (eds.) TNO Work and Employment, Hoofddorp: 13-24.

Eikhout, S.M., Groenesteijn, L., Koningsveld, E.A.P., Kuijt-Evers, L.F.M., 2006. Ontwerpen van handgereedschappen. In: Handboek Ergonomie 2006, Voskamp, P., Scheijndel, P.A.M. van, Peereboom, K.J., (eds). Kluwer, Alphen aan den Rijn , 723-741.

About the author

About the author

Lottie Kuijt-Evers was born on the 16th of February in 1975 in Weert, the Netherlands. From 1987-1993, she attended secondary school at the 'Philips van Horne Scholengemeenschap' in Weert. After she passed the final exams, she started to study 'Human Kinetic Technology' at the 'Haagse Hogeschool'. She learned to find technical solutions to solve problems that are related to human movement, and to adapt products to human ability. In 1997 she graduated and then she began her Master studies at the Faculty of Human Movement Sciences at the 'Vrije Universiteit' in Amsterdam. During her Masters, she expanded her research skills and she specialised in the field labour (ergonomics). In 2000, she graduated with a study on the effect of repetitive pinching on the nerve conduction velocity at the Faculty of Human Movement Sciences (VU Amsterdam) and with a study on movement strategies in horizontally static gazing at TNO Human Factors (Soesterberg). In the mean time, she worked one day a week as associate education manager at the 'Postdoctorale Beroepsopleiding (PDBO) Ergonomie'.

In October 2000, she started to work for TNO Work and Employment in Hoofddorp as a researcher/consultant. Her areas of research and consultancy include physical workload, comfort, and the design of workplaces, hand tools and chairs. For instance, she designed a new masoner's trowel, applied her knowledge on comfort in sitting for a new fork-lift chair design, and developed (research based) ergonomics guidelines for cleaning windows using window washing poles. She published articles on several topics in Applied Ergonomics, Ergonomics, and the International Journal of Industrial Ergonomics. Furthermore, she belongs to the editorial board of the 'Tijdschrift voor Ergonomie' (The Dutch Journal of Ergonomics. The recent years, the focus of her research was on comfort and discomfort in using hand tools, which resulted in the current thesis. During that period, she also worked at the Faculty of Industrial Engineering of the Delft University of Technology to finalize her thesis.