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Abstract

Manufacturers are seeking solutions for gaining an advantage over their competitors. Improvement of ergonomics and usability of consumer products can give increased market value and has a major impact on the users' safety and pleasure as well as the performance and productivity of work. In the competitive marketplace manufacturing firms are forced to design better performing products at a remarkably rapid pace. This creates new challenges for the integration and testing of ergonomics and usability.

The objective of this study was to find ways to integrate ergonomics and usability issues into the process of development and design of consumer products using hand tools as an example. The purpose was to find ways to support the development and design process in order to be able to create more usable products.

Four different approaches supporting a user-centred process of designing consumer products in the area of ergonomics and usability are described: 1) collection of ergonomic design criteria based on existing information and classifying them to be used as supportive material in hand tool design, for example with the Quality Function Deployment method (QFD); 2) use of a questionnaire and risk analysis method to investigate the ergonomics and usability of hand tools used by electricians working on telecommunications and electricity transmission masts in a cold climate; 3) assessment of the ergonomics and usability of hand tools by electromyography (EMG) and subjective opinions during the process of designing a garden pruners; 4) investigating the force demands during simulated cutting using lacquered, chromium-coated and polytetrafluoroethylene- (PTFE) coated cutting hand tool blades. The first two approaches can be used as pre-screening methods for gaining information which can be applied in product design. The latter two are more direct methods based on the measurement of certain product characteristics and provide results and improvement suggestions for particular design cases.

Ergonomic design criteria for pliers-like hand tools were found and collected from literature. The data is presented as a detailed list and classified to be used as supportive material for hand tool design, for example in conjunction with the QFD method. It was possible to investigate the usability and ergonomics of hand tools using a questionnaire and a risk analysis. The falling of hand tools was ranked as the main risk in working on telecommunications and electricity transmission masts in a cold climate. Physiological and subjective methods were used to assess the usability and ergonomics of garden pruners during the process of designing a new tool. By performing the measurements in two parts and comparing different tools and prototypes, it was possible to integrate ergonomics and usability into the design process. PTFE-coated blades were found to create the lowest force demands compared with chromium-coated and lacquered blades.

The main benefit of these different approaches was that they provided information which could be applied in different settings in further design cases as well as direct results applicable in current product design. As a result of the research, more ergonomic and usable hand tools were supplied to the market.

Keywords Ergonomics, usability, human factors, design, hand tool, safety, telecommunications, electricity transmission, PTFE

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Tampere, April 2002

Minna Päivinen

Appendices

Abbreviations

Ag	Silver
AgCl	Silver chloride
CAD	Computer Aided Design
Cr	Chromium
3D	Three-dimensional
EEE	Experimental Ergonomic Evaluation
EMG	Electromyography
EN	European Standard
FG	Focus Group
HOQ	House of Quality
IEA	International Ergonomics Association
ISO	International Organization for Standardization
LMD	Localised Muscular Discomfort
m.	Musculus (lat.), muscle
Mo	Molybdenum
MTS	Material Testing System
MVC	Maximal Voluntary (isometric) Contraction of a muscle
% of MVC	Percentage of Maximal Voluntary Contraction
PPT	Pain-Pressure Threshold
PTFE	Polytetrafluoroethylene
QFD	Quality Function Deployment
ROC	Rating of Hand Tool Characteristics
RPE	Rating of Perceived Exertion
SAE	Self Addressed Envelope
SD	Standard Deviation
SFS	Suomen standardisoimisliitto ry; Finnish Standards Association
TiN	Titanium nitride
(Ti, Zr)N	Titanium-zirconium nitride
V	Vanadium
VAS	Visual Analogue Scale

VR	Virtual Reality
ZrN	Zirconium nitride

Key Definitions

The following definitions are given to clarify the meaning of the main terms used in this study context.

Accident	Unplanned event giving rise to ill-health, injury, damage or other loss (BS 8800)
Consumer product	Saleable or marketable commodity used by people; see also *product*
Context of use	Users, tasks, equipment and the physical and social environments in which a product is used (SFS-EN ISO 9241-11)
Design	To plan a system or a product for a specific purpose; to create or execute according to a plan
Effectiveness	Accuracy and completeness with which users achieve specified goals (SFS-EN ISO 9241-11)
Efficiency	Resources expanded in relation to the accuracy and completeness with which users achieve goals (SFS-EN ISO 9241-11)
EMG	Electromyography; recording of the electrical activity of a muscle (Lamb and Hobard 1992), the graphical presentation of the time varying electrical potentials of muscle(s) (Kroemer et al 1994)
Ergonomics	Ergonomics (or human factors) is the scientific discipline concerned with the understanding of interactions among

	humans and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimise human well-being and overall system performance. Human-system interaction design considerations include physical, cognitive, social, organizational and environmental factors (http://www.iea.cc)
Extend	To move adjacent body segments so that the angle between them is increased
Flex	To move a joint in such a direction as to bring together the two parts which it connects
Goal	Intended outcome; an end towards which effort is directed
Hand tool	An implement used to modify raw material for use and which compensates for human inadequacies and limitations while performing manual tasks. All tools are extensions of the human body and help to increase the speed, power and accuracy nature has given us (Cacha 1999, Signo and Jackson 1999)
Hazard	A source of possible injury or damage to health (SFS-EN 292-1)
Human factors	see Ergonomics
Impedance	The opposition in an electrical circuit to the flow of an alternating current

Incident	Unplanned event, which has the potential to lead to accident (BS 8800)
Motor unit	The smallest functional unit of the neuromuscular system; an anterior horn cell, its axon and all of the muscle innervated by the axon (Soderberg 1992a)
Product	A result of a manufacturing process; an item to be used for its properties and functions; from a functional viewpoint, products protect, support and/or take over particular human activities or extend human capabilities (Kanis 1998)
Prototype	An original and usually operational model of a new type or design of construction developed for testing; a trial model
Reliability	Something to be relied on. Also used to define the ability of a machine or components or equipment to perform a required function under specified conditions and for a given period of time without failing (Milton and Arnold 1990, SFS-EN 292-1)
Repeatability	The degree to which the study is repeatable, i.e. giving the same results in consecutive trials (Kanis 1997b, Kanis 1997c)
Risk	A combination of the probability and the degree of the possible injury or damage to health in a hazardous situation (SFS-EN 292-1)
Risk assessment	An estimation of the probability and the degree of the possible injury or damage to health in a hazardous

	situation in order to select appropriate safety measures (SFS-EN 292-1)
Satisfaction	Freedom from discomfort, and positive attitudes towards the use of a product (SFS-EN ISO 9241-11)
Subject	A person involved in an experiment; a person that is studied in a trial
Task	Activities required to achieve a goal (SFS-EN ISO 9241-11)
Tribology	The branch of science and technology concerned with interacting surfaces in relative motion and with associated matters (as friction, wear, lubrication and the design of bearings)
Usability	Extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use (SFS-EN ISO 9241-11)
Usability testing	Any of those techniques in which users interact systematically with a product or system under controlled conditions to perform a goal-oriented task in an applied scenario and some behavioural data are collected (Wichansky 2000). In this study also methods which support the design process with the aim of improving usability
User	Person who interacts with the product (SFS-EN ISO 9241-11)

User-centred design	Designing based upon the physical and mental characteristics of its human user (Pheasant 2001)
User trial	An experimental investigation in which a sample of people test a prototype version of the product in controlled conditions (Pheasant 2001)

1 Introduction

There is a constant need for manufacturers to seek ways to gain advantage over their competitors. An increasing number of manufacturers are recognising not only the importance of ergonomics but also its potential for market advantage (Butters and Dixon 1998). The ability to make gains in the traditional way of improving products' technological level or by lowering manufacturing costs is being continually eroded (Green and Jordan 1999). Thus, user-centred design has become an issue of increasing commercial importance.

Good ergonomics (human factors) is seen as a central principle of good design. Manufacturers see the ergonomics input to the design process as giving their products a competitive edge in the marketplace. Customers have come to expect and demand products that are easy to use. To succeed, a product or system must provide satisfactory interaction with its user or customer on both a functional and cultural level (Popovic 1997). Quantification of ergonomics and usability issues takes these into a concrete domain that can be understood by others involved in the product creation process. (Green and Jordan 1999)

In today's fast changing and intensely competitive marketplace with rapid technological evolution manufacturing companies are forced to design better performing and less expensive consumer products at a remarkably rapid pace. Design methods for the reduction of this time have been developed. (Krishnan et al 1995, 1997, Popovic 1997, Willén 1997, Sabbaghian and Eppinger 1998) This creates new challenges for the implementation of usability testing into the design process, which can be one source of recovering the "hidden" loss of quality. During these processes it must be possible to set up and implement a user study within a short period of time (Kahmann and Henze 1999).

Ergonomic methods are often used in two principal ways: to conduct basic ergonomic research that adds to the body of ergonomic knowledge and to assist in the design and development of products (Chapanis 1995). In basic ergonomic research the goal is often description, but in design or development the emphasis is strongly on prediction (Chapanis 1995). The objective of ergonomic research and improvements is to reduce the risk of injury while simultaneously increasing the effectiveness of manual operations (Norris and Wilson 1999).

By implementing ergonomics and usability issues in product design, the user's well-being can be improved by decreasing e.g. the risk of musculosceletal disorders (Meagher 1987, Kadefors et al 1993a, Kilbom et al 1993a, Sperling et al 1993a). The improvement of the ergonomics and usability of a product can have a positive effect on the user's health by decreasing local muscular discomfort, biomechanical strain and use of force and by improving user comfort and safety. Also work performance and efficiency as well as productivity and quality of work can be improved (Meagher 1987, Chaffin and Andersson 1991, Buchholz et al 1992, Kadefors et al 1993a, Kilbom et al 1993a, Sperling et al 1993b, Ulin et al 1995, Tudor 1996, Kardborn 1998).

Consumer products include an extremely heterogeneous group of products. Hand tools represent one branch of widely used consumer products. A tool can be defined as "an implement used to modify raw material for use". One of man's most distinctive characteristics is the ability to shape and mould the physical world around him. Human beings create things, which is essential to the development of culture and technology. All tools are extensions of the human body and help to increase the speed, power and accuracy nature has given us. (Cacha 1999, Signo and Jackson 1999)

The oldest tools made of stone and wood were found in Kenya and are estimated to be about 2.6 million years old. With the twin developments of agriculture and animal domestication, roughly 10000 years ago, the many demands of a settled way of life led to a higher degree of tool specialization. One of the major incidents was development of the iron-bladed felling axe in the Middle Ages, which made possible the vast forest clearance of northwestern Europe and the development of medieval agriculture. (www.eb.co.uk, Encyclopædia Britannica) The development of hand tools led to the development of human cultures and we will always be dependent on them. In the modern world hand tools still play an important role in the future development of our culture and technology.

Ergonomics (or human factors) was defined by International Ergonomics Association (IEA) as the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimise human well-being and overall system performance. Human-system interaction design considerations include physical, cognitive, social, organizational and environmental factors (http://www.iea.cc). Cacha (1999) has made a distinction between human factors and ergonomics in the case of hand tools. In his opinion human factors can be regarded as dealing, though not exclusively, with psychological issues such as behaviour, sensation, perception, information storage and retrieval and decision making. Ergonomics on the other hand deals, though not exclusively, with anatomical and physical issues. From this point of view human factors issues in hand tool use and design can be regarded as having a mission of improving efficiency and safety, and ergonomics the mission of controlling musculoskeletal diseases and cardiovascular diseases as well as increasing comfort, safety and efficiency. In this thesis the term ergonomics is used to represent both ergonomics and human factors according to the definition given by IEA.

The term usability is often used to refer to the capability of a product to be used easily. According to SFS-EN ISO 9241-11, usability can be defined as the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use. By incorporating features and attributes known to benefit the users in a particular context of use, the usability of products can be improved. (SFS-EN ISO 9241-11)

Usability can be considered to overlap with the definition of ergonomics, but on the other hand gives a more precise way of looking at the relationship between users and products. In this study the terms ergonomics and usability are used in conjunction, since usability by itself tends to look at the process of a user using a product while ergonomics provides a wider perspective by considering improvement in overall system performance in a user-centred way and contributes to the design of interacting systems.

2 Literature review

2.1 Ergonomics and usability

Ergonomics can be defined as the scientific discipline concerned with interactions among humans and other elements of a system in carrying out a purposeful activity. Ergonomics aims to improve human well-being and overall system performance by optimising human-system compatibility. Human-system interaction design considerations include physical, cognitive, social, organizational and environmental factors. (http://www.iea.cc)

Ergonomics was also described as the theoretical and fundamental understanding of human behaviour and performance in purposeful interacting socio-technological systems and the application of that understanding to design of interactions in the context of real settings (Wilson 2000). The role of ergonomics can be identified through a holistic approach 1) to fundamentally understand purposive interactions between people and artefacts and especially to consider the capabilities, needs, desires and limitations of people in such interactions and 2) to contribute to the design of interacting systems, maximising the capabilities, minimising the limitations and trying to satisfy the needs and desires of the human race (Wilson 2000, Karlsson 2001).

Ergonomics methods and data can have a major impact on systems when they are incorporated into products at the earliest phase of system development (Casey 1991). These issues are often concretised by using the concept of usability.

According to SFS-EN ISO 9241-11, usability can be defined as an extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use. The standard defines usability in the context of ergonomic requirements for office work with visual display terminals. The main principles can carefully be applied in other usability issues as the standard gives guidance on usability in the form of general principles and techniques. The guidance can be used in procurement, design, development, evaluation and communication of information about usability. It is necessary to measure the performance and satisfaction of users working with a product in order to determine the level of usability achieved. It is emphasised that the measurement of usability is important in view of the complexity of the interactions between the user, the goals, the task characteristics and the other elements of the context of use. A product can have significantly different levels of usability when used in different contexts. (SFS-EN ISO 9241-11)

Usability defined in terms of the quality of a work system necessarily depends on all factors which can influence the use of a product in the real world. These factors include organizational aspects such as working practices and the location or appearance of a product and individual differences between the users, including those due to cultural factors and preferences. This broad approach to usability has the advantage that it concentrates on the real purpose of design of a product. It also ensures that a product meets the needs of real users carrying out real tasks in real technical, physical and organizational environment. (SFS-EN ISO 9241-11)

The terms usage, usability and functionality were defined also in the following way by Green (1999). Usage involves the mapping of perception or cognition and user actions via conceptual models, physical models and prototypes or actual products. Usability is the impact of the mixture of human characteristics and mental models on product performance. Functionality on the other hand can be seen as extending these to include impact on quality of life, whether the product is bought or used at all, and involving notions such as joy in using, effective performance, perceived stigmatisation, actual or perceived safety. (Green 1999)

Usability approaches tend to look at products as tools with which users achieve tasks effectively, efficiently and with a certain level of satisfaction (SFS-EN ISO 9241-11). The human factors profession has operationalised satisfaction in a manner that is limited to the avoidance of physical or cognitive discomfort (Jordan 1999b). A holistic approach to usability was also introduced as in reality products have a wider role in people's lives and the next challenge is to look at people, products and relationships rather than users, products and tasks. If only product, user and the environment of use are being looked at, there is a danger of dehumanisation. (Green and Jordan 1999)

The challenge is to look at factors which can affect the quality of relationship between person and product. Products can be regarded as "living objects" with which people have relationships. (Green and Jordan 1999) Products are objects which can make people happy or angry, proud or ashamed, secure or anxious (Jordan 1999b). People-product relationships are likely to be affected by the look and the feel of a product, the fit of technical specification and performance with a user expectations and the emotions and values that are associated with a product. It is thus important to look at the emotional and hedonic benefits that products can offer people and to investigate what the implications of these will be for design and evaluation. (Green and Jordan 1999)

In the context of usability Jordan (1998, 1999a, b) proposed the concept of "pleasure" that products can bring to the users. In the case of products, pleasure can be defined as the emotional, hedonic and practical benefits associated with them. The pleasure of a product can be classified into four types:

- Physio-pleasure – pleasures to do with the body and the senses,
- Socio-pleasure – pleasures to do with inter-personal and social relationships,
- Psycho-pleasures – pleasures to do with the mind and
- Ideo-pleasures – pleasures to do with values.

As the view of the "pleasure" concept emerged the methodological issues must also be considered. Jordan (1999b) proposed that some of the methods already used in ergonomics research could be applied, including for example interviews, focus groups and questionnaires.

According to the definition of ergonomics, the discipline can be considered to express a broad view regarding the improvement of human well-being and overall system performance, including physical, cognitive, social, organizational and environmental factors (http://www.iea.cc). Usability on the one hand is considered to be the extent to which a product can be used by the users to achieve a goal with effectiveness, efficiency and satisfaction. Or on the other hand usability is defined in terms of the quality of a work system necessarily depends on all factors which can influence the use of a product in the real world. These factors include organizational aspects such as working practices and the location or appearance of a product, as well as individual differences between the users, including those due to cultural factors and preferences. (SFS-EN ISO 9241-11)

2.2 Designing for ergonomics and usability

Design is prediction concerned with how things ought to be. It is aimed at changing an existing situation into a preferred one. Designers attempt to predict the behaviour of a product and its users, using their knowledge and expertise. The most innovative phase in design is its conceptual phase, in which most decisions are made. With advanced product development and manufacturing, more detailed product concepts are needed. Designers need knowledge of the users and their behaviour, which can be obtained from 1) research, 2) evaluation of similar products, 3) evaluation of related products and 4) evaluation of predicted products. (Popovic 1997)

User-centred design can seem a time-consuming and expensive affair. However, if the process of product development is considered as a whole, quite the opposite is true. User-centred design shortens overall development time by reducing the number of expensive changes required late in the design process. (den Buurman 1997, Wichansky 2000) It was also found that most customers were willing to pay up to 10 to 15 per cent more for ergonomic products (Willén 1997). User-centred design results in improved product quality in a market that is becoming increasingly more discriminating both with respect to usefulness and usability (den Buurman 1997). Product quality refers to the performance, overall design and interface design of the product/system, the manufacturing process and the product life cycle (Popovic 1997). The next generation of customers will to a greater extent seek out and choose products that, besides fulfilling the basic demands of quality, will also add to their quality of life and general comfort (Axelsson 2001).

There is more and more need to use participatory design, usability studies and user studies in product design concerning user interfaces. Each product should be seen as a component in an individual-technology-task-environment-organization system (Kirvesoja 2001). User-centred design was described by Pheasant (2001) as a way to accomplish the best possible match between the product and its users in the context of the task to be performed (Figure 1).

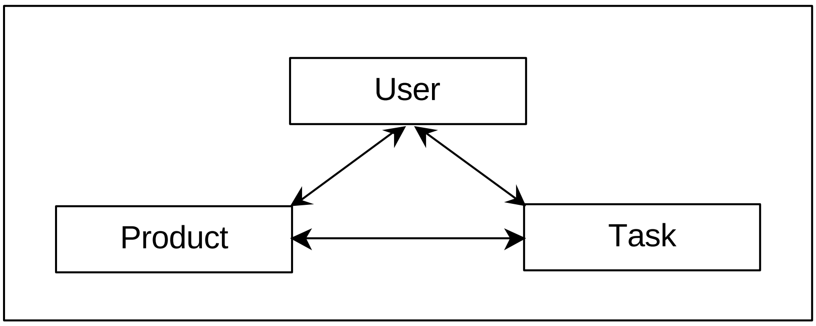

Figure 1. User-centred design consisting of the product, the user and the task in interaction (Pheasant 2001).

Planning for usability as a part of the design and development of products involves systematic identification of requirements for usability, including usability measures and verifiable descriptions of the context of use. These provide design targets, which can be the basis for verification of the resulting design. To specify or measure usability, it is necessary to identify the goals and to decompose effectiveness, efficiency and satisfaction and the components of the context of use into sub-components with measurable and verifiable attributes (Figure 2). (SFS-EN ISO 9241-11)

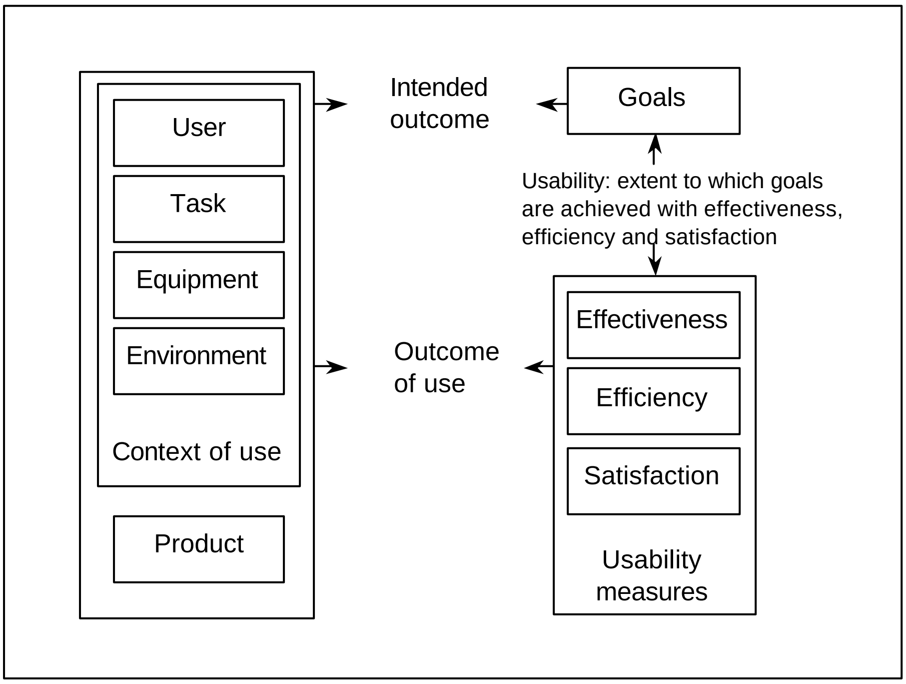

Figure 2. Usability framework (SFS-EN ISO 9241-11).

Information about product usage can be implemented in most phases of the design process (Marinissen 1993). The nature of the design project determines which kinds of methods, strategies and knowledge are required. The selection of the appropriate method will depend on design goals and on which design constraints have to be evaluated. (Popovic 1997)

2.3 Usability testing

Wichansky (2000) has defined usability testing, especially in the context of software testing, as any of those techniques in which users interact systematically with a product or system under controlled conditions to perform a goal-oriented task in an applied scenario and some behavioural data are collected.

A product has no intrinsic usability, only a capability to be used in a particular context. The study of a particular user-product interaction may be related to such diverse data as:

- sensory capacities and anthropometrics, physiological functions, e.g. heart rate and oxygen consumption and human performance like exertable forces and reaction times and
- the activities of humans when actually using a product, e.g. perceptions, cognitions and actions and physical actions including the effort involved and the possible experiencing of inconvenience. (Rooden and Green 1997, Kanis 1998)

Also the term “convenience” has been brought up in the area of evaluation of consumer product ergonomics. The term encompasses all aspects of living with one’s choice, including familiarisation, the appropriateness of the functionality, comfort, anthropometric fit, adjustability and ease of maintenance. (Butters and Dixon 1998)

There are several techniques for studying the usability of products. A general overview of the user trial process was presented by Kahmann and Henze (1999) (Figure 3). Marinissen (1993) proposed that user tests can be applied in various phases of a design process.

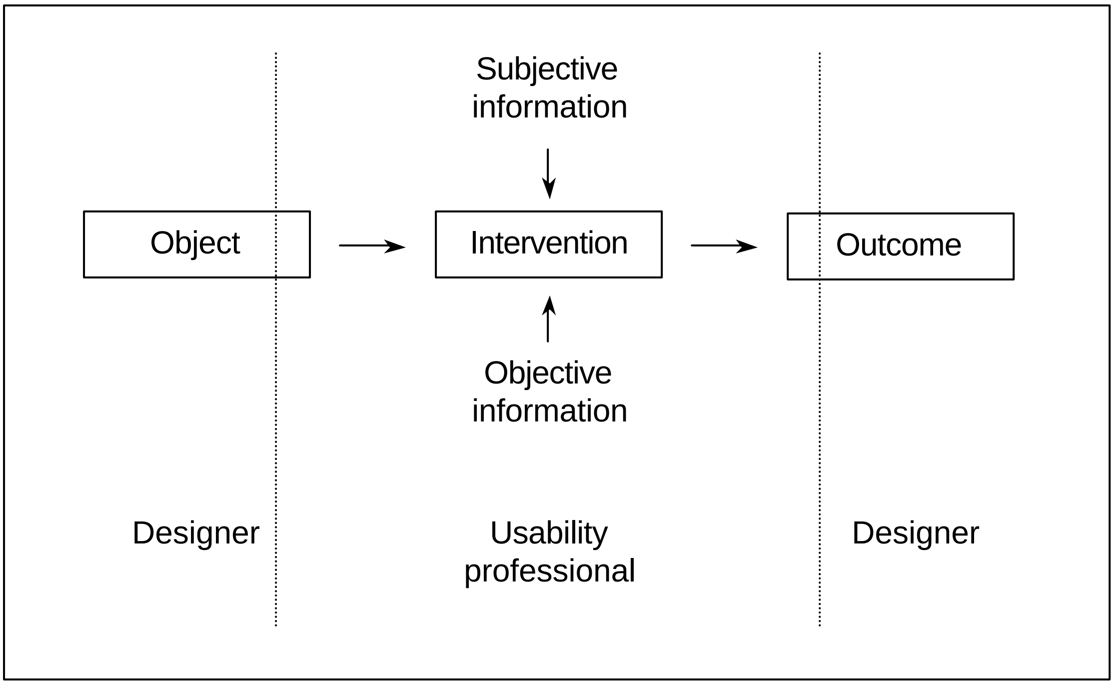

Figure 3. An overview of the user trial process (Kahmann and Henze 1999).

Kanis (1997a, 1998) presented a model of product functioning as negotiated by users, thus guiding the usability study protocols into looking more closely at human behaviour (Figure 4).

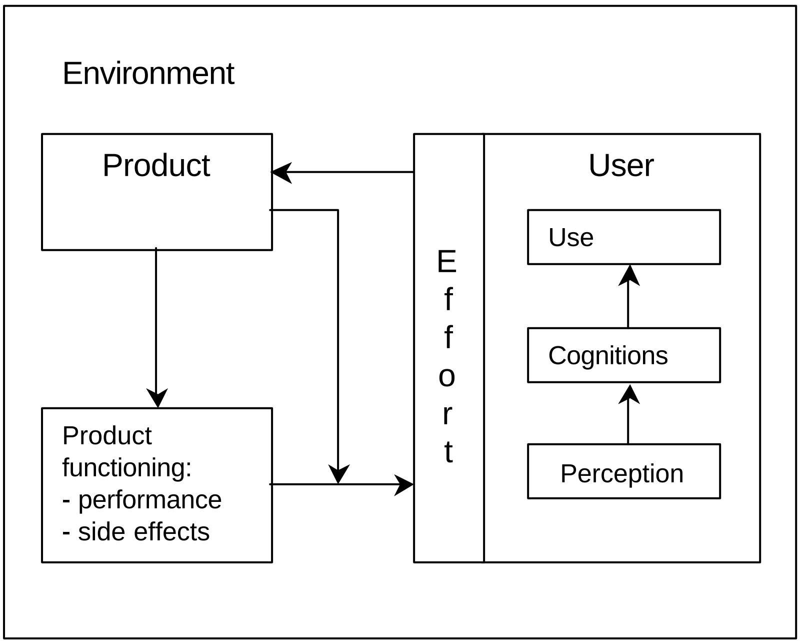

Figure 4. Product functioning as perceived by users (Kanis 1997a, 1998).

In consumer product evaluation it is important to collect the first information about a new product from a user trial to gather data about the experience of representative consumers (Butters and Dixon 1998). A user trial is a process to make abstract into concrete and thus should be used with caution in the early stages of a product development project as one should be generating ideas instead of criticising them (Green and Klein 1999).

For effectiveness, efficiency and satisfaction it is normally necessary to provide at least one measure of each. There is no general rule for how measures should be chosen or combined, because the relative importance of components of usability depends on the context of use and the purposes for which usability is being described. (SFS-EN ISO 9241-11)

Measures of usability should be based on data which reflect the results of users interacting with the product or work system. It is possible to gather data by objective means, such as the measurement of output or of speed of working. Alternatively, data may be collected from subjective feelings, beliefs, attitudes or preferences. Objective measures provide direct indications of effectiveness and efficiency, while subjective measures can be linked directly with satisfaction. It should be noted that it is possible to obtain data relating to each component of usability from objective and subjective measures. (SFS-EN ISO 9241-11)

If in some cases it is not possible to obtain objective measures of effectiveness and efficiency, subjective measures based on the user's perception can provide an indication of effectiveness and efficiency. Efficiency can be measured by relating the level of effectiveness achieved to the resources used. Similar calculations can be made with respect to efficiency in the use of mental or physical energy, materials or financial cost. (SFS-EN ISO 9241-11)

Satisfaction is a response of users to interaction with a product. It can be assessed by subjective or objective measures. Objective measures can be based on observation of the behaviour of the user, of for example body posture or body movement, or can be based on monitoring physiological responses of the user. (SFS-EN ISO 9241-11) According to Han et al (2000), so far evaluation of satisfaction has received little attention in usability studies.

There is a wide variety of methods which have been implemented in the user-centred design process. One possible approach to usability testing is to apply comparative testing procedures during which several models and brands of the same product are compared with one another. A typical situation is that evaluation methods vary from product to product and also between different assessments of the same product. (Butters and Dixon 1998)

Suri and Marsh (2000) proposed a scenario-building method to overcome the gap between analysis and synthesis, i.e. to permit the translation of human factors information into a form which stimulates well-conceived, user-centred design ideas.

Tools such as computer aided design (CAD), virtual reality (VR) simulation, mock-up or prototype assessment have been used in product evaluation (Dan 1997, Davies et al 1997, Grobelny 1997, Karwowski et al 1997, Säde et al 1998). Methods such as focus group (discussion group) interviews, observation techniques, protocol analysis, task-analysis and keeping of a convenience diary can be applied (Marinissen 1993, Ikeda 1997, Norris et al 1997, Trathen et al 1997, Popovic 1997, Rooden and Green 1997, Butters and Dixon 1998, Popovic 1999, Rooden 1999, Trathen et al 1999, Barrett and Kirk 2000). The use of mock-ups can be applied especially in settings where the usability of different environments is studied (Kirvesoja et al 2000). The testing procedure for mock-ups and other type of prototypes should be carefully designed as well as the test group involved (Rooden 1999, Trathen et al 1999).

The use of conjoint analysis, which is more typically a market research method, has successfully been used in usability testing of different products (Kirvesoja et al 1996, Kirvesoja and Väyrynen 2001). Conjoint analysis can be used to rate or rank products or product variants. Conjoint analysis is a set of techniques designed to measure the importance individual customers attach to various attributes of a product and consumers' degree of preferences for each level of each attribute. (Kirvesoja and Väyrynen 2001) Kirvesoja and Väyrynen (2001) have also applied Mitchell's method to the design and evaluation of multipurpose chairs. This method is based on paired comparisons in which the subject compares each given criteria with every other criterion by pairs. For usability testing a multi-criterion product evaluation has been created. The model includes combined evaluation by experts and users, paired comparison, calculation of weighting factors and a possibility to utilise user trials. The multi-criterion model helps to make optimal trade-offs in the context of user-centred design. (Väyrynen et al 1999/2000) Also an OPERA method has been used in usability studies. OPERA is an acronym for the five phases of the method: 1) own suggestions, 2) pairs' suggestions, 3) explanation, 4) ranking and 5) arranging (Mikkonen et al 2001).

2.4 Ergonomics and usability of hand tools

The design of a successful consumer product is dependent upon incorporation of information from a number of different knowledge domains as it must perform at a functional and at an aesthetic level and the product must also be manufacturable (Porter and Porter 1999). Hand tools represent one branch of widely used consumer products. One of the human beings' most distinctive characteristics is the ability to shape and mould the physical world around him. People create things which are essential to the development of culture and technology. All tools are extensions of the human body and help increase the speed, power and accuracy nature has given us. (Signo and Jackson 1999)

Hand tools can be considered to be an apparatus which compensate for human inadequacies and limitations while performing manual tasks. These limitations can be related to strength (pliers, wire cutters), penetrability (saws, files), bluntness (knives, scissors, drills), shortness (tongs), flexibility (hammer) or limited speed (hammer handle). (Cacha 1999) As hand tools are used daily, they have a strong effect on health, product quality, work performance, use of force, local muscular discomfort, biomechanical strain and professional pride in industrial work (Meagher 1987, Chaffin and Andersson 1991, Ulin et al 1995, Kardborn 1998).

By improving the ergonomics and usability of hand tools, work efficiency, productivity and quality as well as user comfort and safety can be improved (Meagher 1987, Buchholz et al 1992, Kadefors et al 1993a, Kilbom et al 1993a, Sperling et al 1993b, Tudor 1996, Kardborn 1998). Ergonomically well-designed hand tools used in work situations with balanced work content reduce the risk of occupational injuries of the hand, wrist and forearm (Sperling et al 1993b). Tichauer (1978) reported that improvement of hand tool design can lower the incidence of musculoskeletal disorders. However, it must be noted that Leamon and Dempsey (1995) were strongly critical of the reliability of Tichauers' report.

Kilbom et al (1993a) demonstrated that by improving the ergonomic quality of hand tools it is possible to increase the productivity of work. This is important also from the viewpoint of workers' health as they usually use tools with the highest productivity even at the cost of higher degree of a strain and fatigue (Kadefors et al 1993a, Kilbom et al 1993a).

Radwin and Haney (1996) proposed that hand tools should be selected by considering both physical process engineering requirements of the task being performed and ergonomics. When these aspects are considered together, the appropriate hand tool for a particular job should:

- maximise performance,
- enhance work quality,
- minimise physical load and
- prevent fatigue.

Hand tools still cause occupational disorders in many professions and are still involved in many industrial accidents (Cederquist and Lindberg 1993, Kadefors et al 1993a). Over the years much effort and research have been devoted to the explanation and understanding of the interrelationship between human performance and hand tool design with the aim to ensure that hand tools are used more effectively, accurately, comfortably and safely (Cederquist and Lindberg 1993, Mattila et al 1993, Rouvali and Mattila 1993, Kivistö-Rahnasto et al 1994, Kihlberg 1995, Ulin et al 1995, Tudor 1996, Vilkki et al 1996, Kallionpää 1997, Kallionpää et al 1997a, Kallionpää et al 1997b, Kallionpää 1998, Kardborn 1998, Nieminen et al 1999, Päivinen et al 2000, Nevala-Puranen and Lintula 2001, Niemelä and Päivinen 2001).

From the viewpoint of pathology and the physiology of the hand and arm, the disorders which can be due to the use of hand tools can be classified as follows:

- tendon disorders; such as tendinitis, tenosynovitis, stenosing tenosynovitis, ganglionic cyst, epicondylitis and rotator cuff tendinitis,
- nerve disorders; such as carpal tunnel syndrome,
- neurovascular disorders; such as thoracic outlet syndrome and
- instant trauma; such as fractures, dislocations, sprains and strains. (Cacha 1999)

Evaluation of hand tool ergonomics is a complex task, where not only functional properties, quality and reliability aspects are relevant, but also the user's subjective expectations and apprehensions concerning for example the professionality of the tool (Kadefors et al 1993a, Kardborn 1998). An interdisciplinary approach is necessary for hand tool evaluation, not only as regards the methodological set-up, but also as regards the actual evaluation process (Kadefors et al 1993a, Kardborn 1998). The methods used should be sensitive and specific as well as quantitative or qualitative in nature and they can be physical, physiological or psychophysical (Kadefors et al 1993, Wilson 2000). Quantification of usability takes the issues into a concrete domain that can be understood by others involved in the product creation process. Quantitative usability targets can also be written into the product specification. (Green and Jordan 1999)

Kadefors et al (1993a) concentrated on hand tool evaluation and published a list of factors which should be considered when one is assessing the ergonomics of hand tools. Kadefors et al (1993a) divided up the hand tool evaluation process to include characteristics of the tool and, on the other hand, effects on the user:

Tool characteristics:

- mechanical output of the tool (force, torque, acceleration),
- tool mass and centre of gravity,
- tool dimension and grip characteristics,
- possibility to use different grips or two-handed grip and
- grip surface characteristics.

Effects on the user:

- working posture,
- wrist flexion/deviation angles,
- muscular strain and fatigue,
- type of grip employed,
- local pressure on the hand and
- risk for injury in typical use of the tool.

3 Theoretical framework

The theoretical framework of this study is based on the relationship between the user-centred design process and the implementation of ergonomics and usability in the process (Figure 5). This study aims to find ways to integrate ergonomics and usability issues in user-centred development and process of designing consumer products. According to Marinissen (1993), ergonomics and usability data can be implemented into most phases of the design process.

The study covers four case studies with different approaches for implementing ergonomics and usability in the design process, starting from a theoretical, literature-based view on the application of the risk analysis method, and progressing through laboratory testing and concrete technical modification. The case studies 1 and 2 can be used as pre-screening methods and represent the implementation of ergonomics and usability in early parts of product development. Case studies 3 and 4 represent the methods which can be used in the evaluation of ergonomics and usability of prototype designs in the later parts of the design process.

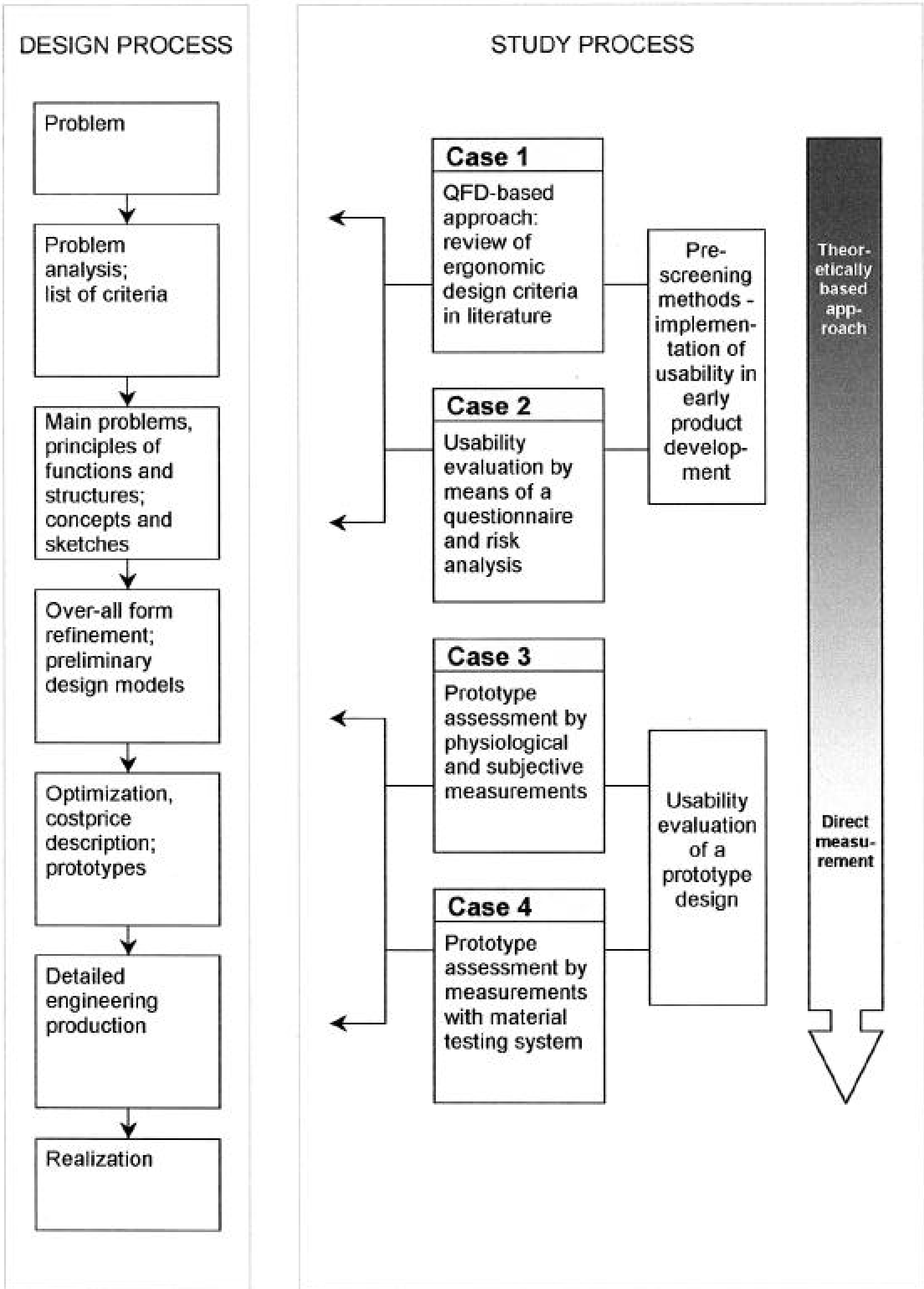

Figure 5. The framework of this study based on a user-centred design process (modified from Pahl and Beitz 1990 and Marinissen 1993).

4 Objectives of the study

The objective of this study was to describe and apply different approaches for the implementation of ergonomics and usability in the process of designing consumer products, especially hand tools. The purpose was to find ways to support the development and design process in order to be able to create more usable products and thus improve human well-being.

The objectives of the study were:

1. To find ergonomic design criteria in literature and classify them to be used as supportive material in hand tool design for example in conjunction with the Quality Function Deployment method (QFD).

2. To investigate if the usability and ergonomics of hand tools can be evaluated by means of a questionnaire and a risk analysis.

3. To assess the usability and ergonomics of hand tools during the design process by physiological and subjective measurements.

4. To investigate how different coating materials on hand tool blades affect force demands during simulated cutting.

5 Case study 1 - Ergonomic design criteria for pliers-like hand tools

5.1 Introduction

To integrate ergonomics and usability with efficient consumer product design, a structured methodology is needed. It is often not enough just to have knowledge and understanding of customer needs as this understanding is not as straightforward as might be assumed (Taylor et al 1999). Methods such as Kansei Engineering (Nagamachi 1997, Ishihara et al 1997, Jordan 1999c, Axelsson 2001) and the Sensorial Quality Assessment Method (SEQUAM) (Bonapace 1999) have been used to improve the ergonomics and usability of consumer products. Hsiang et al (1997) reported the use of Taguchi's method for the design of industrial knives. A design structure matrix presented by Eppinger (1991) could also be used in the incorporation of ergonomics and usability issues into design process. Also QFD has been used in the context of improvement of usability of products (Bergquist and Abeysekera 1996, Willén 1997). The QFD method has features similar to participatory ergonomics, with principles aimed at integrating the end-users into the design process.

The concept of QFD was introduced in Japan by Yoji Akao in 1966 (Dean 1998). QFD is a design method which can be used to identify user requirements and transform the requirements into product attributes necessary to satisfy and even delight the customer (Turunen 1991, Syan and Menon 1994, Dean 1996). QFD is defined as a system for translating consumer or customer requirements into appropriate company requirements at each stage, from research and product development to engineering and manufacturing as well as to marketing, sales and distribution (Reed and Jacobs 1993). A correlation matrix called "house of quality" (HOQ) can be used to adapt technology to people and to translate user requirements into engineering variables. The definition of QFD should be interpreted carefully as it:

- is not only for products, but also for processes and services,

- is not only a quality method, but also a planning method for enhancing existing products, processes and services as well as introducing new products, processes and services and
- is not to be used only by quality management departments, but it should be used at all levels of an organization as a planning tool. (Reed and Jacobs 1993)

In discussing the basics of the QFD approach, the term “product” will correspond to: assemblies, components, combination of “ingredients” or “materials”, non-physical products such as service and combination of services and processes. In QFD also, since the end user is not the only customer, the organization itself should also be treated as a customer to incorporate the organizations goals. (Reed and Jacobs 1993)

In consumer product design, customer requirements are usually expressed in vague qualitative terms such as easy to use or comfortable. Ergonomic design criteria should have specific formulations and general recommendations should be avoided (Wulff et al 1999). These requirements must be translated into a form that the organization can interpret and analyse. During the design requirements stage, those product characteristics that are of interest to the customer are identified. Industry has effectively used QFD for every level of product development from an entire automobile concept to the side view mirror for that vehicle. (Reed and Jacobs 1993)

In this case study principal design criteria for pliers-like hand tools, using garden pruners (pruning shears, secateurs) as an example are presented. Though studies in the area of hand tool ergonomics have been published, a detailed list of the factors applicable and complete enough for the design of new non-powered hand tools was not found. The criteria have been collected especially to be used with QFD. The main criteria are divided into subgroups. The implementation of the criteria in the QFD will not be discussed in this case study.

The aim of this case study was:

- to present a detailed list of the most important ergonomic design criteria for pliers-like hand tools, using garden pruners as an example.

5.2 Material and methods

The data for the design parameters was collected from literature by doing literature surveys using data bases and scientific publications. Data bases such as ABI/Inform: ProQuest Direct, Compendex, Elsevier: Science Direct, LEO, Risk Abstracts and Safety Science & Risk Abstracts were used.

5.3 Design parameters for pliers-like hand tools

A number of related but different hand tools can be regarded as belonging to the group of pliers-like hand tools. Pliers-like hand tools can be classified as consisting of jaws of various configurations on the head of the tool, a simple or complex joint, two handles and sometimes a returning mechanism such as a spring and a locking system. The tools belonging to this pliers-like group are typically used by one hand.

The following design parameters are grouped according to the part of the tool that they affect (Figure 6). The grouping was made to clarify different aspects in the design criteria. In the following text the most general definition will be “whole hand tool”. “Grasp surfaces” includes the design factors of “hand grips” and “locking mechanism”, as these are related to the interface between the hand and the tool. The other design criteria are grouped as follows: force transmission mechanism, return mechanism, blades and guide. All the design parameters included in this case study are listed in Table 1 and presented in more detail under the relevant subsection.

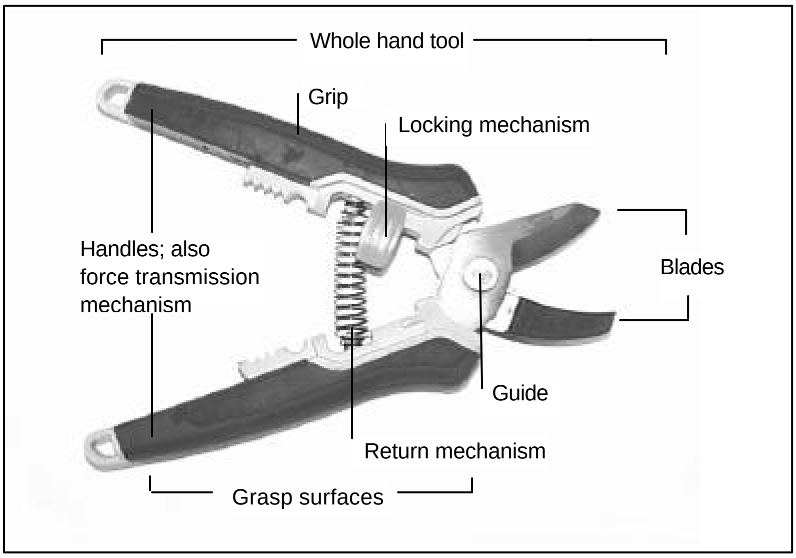

Figure 6. Parts classification used for design parameters.

Table 1. Design parameters and the related criteria collected from literature and presented in detail under the relevant subsections in this case study.

Design parameter	Criteria
Whole hand tool	- overall shape and the placement of structural elements - symmetry - balance - hand tool weight - stiffness - material selection - impacts, shocks and vibration - assembly and disassembly - suspender and wrist wrap - colour - environmental resistance - operating and service instructions
Grasp surfaces	- surface pressure - shear forces on skin - thermal insulation characteristics
Handles	- length of handles - grip span - arc of handle - grip guard - wrist position
Locking mechanism	- locking mechanism
Force transmission mechanism	- force
Returning mechanism	- returning mechanism
Blade	- type and shape of the blades - opening of blades - friction coefficient of blade material
Guide	- guide

5.3.1 Whole hand tool

Overall shape and the placement of structural elements

Tool design in general should aim to reduce any feeling of discomfort (Meagher 1987). The handle design should favour roundish or spherical shapes and fit the curves of the palm and fingers in order to avoid pressure on the palmar arc (Eastman Kodak Company 1983, Fransson-Hall and Kilbom 1993, Kadefors et al 1993a). The use of finger grooves is not recommended, as they can create high surface pressure on the fingers, are suitable only for one hand size and restrict the versatile use of the tool (Fransson-Hall and Kilbom 1993, Lewis and Narayan 1993). Tools should also be designed to eliminate any risk of injury to the fingers or hand as a result of being squeezed or pinched (Mital and Kilbom 1992). The use of a stopper and sufficient clearance between the handles of two-handled hand tools is also recommended (Eastman Kodak Company 1983).

The shape and placement of structural elements should be designed in such a way that the functioning of a tool is as efficient as possible. Parts such as the locking system should be easy to reach and operate. All parts should be dirt-resistant, and all materials should be easy to maintain and clean. (Kallionpää et al 1997b) This is especially important for elements requiring hygienic considerations, such as handles, return mechanisms, and force transmission mechanisms (Freivalds 1987, Kallionpää et al 1997b).

Symmetry

The shape of the handles is evaluated here in terms of shape and symmetry. Appropriate shape and symmetry of the handles are essential if one is to be able to change one's grip (Meagher 1987). Different grip postures should be possible in all hand tools (Sperling et al 1993a). This includes small changes in hand postures and the opportunity to use forward grips and reverse hand grips (Kilbom et al 1993a) or two-handed grips (Sperling et al 1993a). The possibility of using either the right or left hand is also desirable, as approximately every tenth person is left handed (Freivalds 1987).

Balance

When a hand tool is well balanced, it will automatically be directed to an optimal position (Tichauer and Gage 1977). Sperling et al (1993a) point out that a hand tool with poor balance can have an unfavourable influence on the wrist position. The balance of the tool also has an influence on the accuracy with which the hand tool can be brought into the correct working position and on muscular strain when one is using the tool in a static position (Kallionpää 1998). In order to reach the optimum balance and to avoid diversion from the neutral position, it is recommended that a hand tool's centre of gravity should be as close as possible to the centre point of the hand (Kadefors et al 1993a, Lee Yung-Hui and Cheng Son-Lin 1995). The correct placement of the centre of gravity will also prevent the user's grip from slipping (Tichauer and Gage 1977).

Hand tool weight

Hand tools should be designed so that they have as low a weight as possible. This is important as far as usability and the avoidance of fatigue are concerned (Meagher 1987, Sperling et al 1993, Ulin et al 1995). The weight and the centre of gravity of a hand tool affect muscular strain. Hand tools and the material handled increase the weight of the hand-arm system and thus the strain on hand, arm and back muscles (Sperling et al 1993a). The weight of a hand tool has a direct influence on the duration for which it can safely be used and on working accuracy (Eastman Kodak Company 1983). It is also important to note that light hand tools are easier to carry. (Lee Yung-Hui and Cheng Son-Lin 1995, Kallionpää et al 1997b)

Hand tools in general should not weigh more than 2.3 kg and those used for precision work not more than 0.4 kg unless counterbalanced (Eastman Kodak Company 1983). A hand tool for precision work should weigh as little as the function allows, but no more than 1.75 kg (Mital and Kilbom 1992).

Stiffness

The term "stiffness" is here used to describe inflexibility and rigidity in tools. The durability of materials used in handles, blades and other functional parts is a factor that influences the usability of a hand tool. Stiffness affects the actions and the use of the tool and also indicates reliability and durability. In pliers-like cutting hand tools the blades should not be too flexible sideways. (Kallionpää et al 1997b, Kallionpää 1998).

Material selection

Material selection is linked in many ways to ergonomics, e.g. through durability and friction characteristics of different parts of the tool. Materials as well as their quality and characteristics influence the whole tool, e.g. how professional the appearance of the tool is. The challenge remains of convincing the end users about new materials and their use. Environmental factors should also be considered when one is choosing the materials. The toxicity of materials and characteristics which can cause irritation or allergic reactions should also be considered. (Eastman Kodak Company 1983, Sperling et al 1993, Ulin et al 1995, Kallionpää 1998)

Impacts, shocks and vibration

The transition of impacts, shocks and vibration from the tool to the hand should be avoided, as they may lead to discomfort as well as harmful consequences. The principles that can be used to reduce vibration or shocks to the hand are presented in Draft Standard prEN 1030-1 (1993). The following guidelines are feasible for hand-held and hand-guided apparatus. The effects arising from exposure to hazardous vibration originating from machines through the hand tool can be reduced by:

1. Reducing the vibration magnitude at source.
2. Reducing the vibration transmission from the source to handles and other surfaces in contact with hands.
3. Minimising the transmission from the machine to the hand-arm system by ergonomic means (minimising the forces received or exerted by the operator's hand).
4. Minimising the exposure time by increasing the performance of the machine.
5. Thermal design to optimise hand temperature. (prEN 1030-1 1993)

Assembly and disassembly

Maintenance measures can not only increase effectiveness but also prevent injuries (Burger 1987). The possibility and ease of maintenance have an effect on the overall performance of the tool, thus affecting the cutting ability, user force demands and workload (Kallionpää 1998). Especially in the case of pliers-like cutting tools, it is easier to clean and maintain them, e.g. to sharpen the blades, if it is possible to disassemble the tool (Kallionpää et al 1997b). The wish of end users is that the blades should stay sharp as long as possible (Peltonen 1998). The returning mechanism, guide and blades should be demountable and available as spare parts (Peltonen 1998).

Suspender and wrist wrap

It is recommended that hand tools should be suspended so as to lighten the weight of the tool. This is especially important when the tool is used, for instance, in assembly tasks or corresponding situations. A possibility for suspension is also practical in order to keep workplaces orderly, as tools can be hung up. The use of a wrist wrap is recommended if the tool is used in situations where there is a risk of its dropping accidentally, such as during pruning of fruit trees (Kallionpää et al 1997b).

Colour

The colour of the product creates an image and acts as one of the marketing factors. Colours can have an influence on work safety (Giguère et al 1993) by signalling the possibly hazardous parts of the tool. Colours can also provide other signals; they can, for example, indicate the place appropriate for a particular function. The use of a certain colour on the surface of a grip can provide information on where and how to place the hand; thus the colour can make it easier to become familiar with the tool. A hand tool that contrasts with its surroundings (e.g. natural environment, toolbox) will be easier to identify and locate (Giguère et al 1993, Kallionpää et al 1997b, Kallionpää 1998).

Environmental resistance

It is important that all tool surfaces retain a good appearance and thus preserve the quality of the tool. Changes in materials, such as colour changes or rust on the blades, are to be avoided, as usually such changes affect the functioning of the tool and can also be taken as a sign of inferior quality. In addition to considering the deterioration of materials caused by exposure to the environment, one should also pay attention to design principles which improve corrosion resistance when one is designing a product (Tunturi 1988). The most basic principle is to ensure that the final product is easy to keep clean and dry (Tunturi 1988). Handles should be made from nonporous materials that do not absorb oil or other skin irritants. Furthermore, the material should not complicate the maintenance of hygiene. (Tichauer and Gage 1977)

Operating and service instructions

It is recommended that operating and service instructions should be provided with all tools, as they are of importance in guiding the users on how to use the tool correctly and to employ suitable work methods, thus keeping the workload as low as possible. Operating and service instructions influence the effectiveness of the work and the prevention of injuries (Burger 1987).

5.3.2 Grasp surfaces

Surface pressure

The sensitivity of the hand to pain-pressure was studied by Fransson-Hall and Kilbom (1993) and Hall (1997). The value of the pain-pressure threshold is affected by:

1. Gender (females are more sensitive but males are exposed to higher maximal pressures due to higher maximal force application).
2. The size of the object causing the pressure (small surface area creates higher surface pressure and is therefore to be avoided).
3. The material of the object causing the pressure (soft material is regarded as more pleasant).
4. The form of the object causing the pressure (rounded form is recommended over angular form).

5. The rate of increase of the pressure (a pronounced increase rate produces a higher pain-pressure threshold than a lower increase rate).
6. The exposure time of pressure (pain-pressure threshold decreases radically either with increasing number of repetitions or continuous pressure).
7. The area of the pain-pressure threshold measuring point on the hand.

The pain-pressure threshold is very dependent on the part of the hand (Fransson-Hall and Kilbom 1993), though there are conflicting data concerning sensitive areas. According to Tichauer and Gage (1977), the areas most sensitive to pressure are the palmar arc, the ulnar nerve, the area around the *os hamatum* and the middle palmar area, while less sensitive areas are found between the thumb and index finger. Fransson-Hall and Kilbom (1993) argue that according to their results there is a pressure-sensitive area around the *os pisiforme.* This is in line with Tichauer's findings. According to Fransson-Hall and Kilbom (1993) the most sensitive area of the hand is the thumb and thenar area, and the area of fingers II-V is the least sensitive area (Figure 7). However, this last study indicated that neither the mid-palm nor the fingers were markedly sensitive to externally applied surface pressure. It is recommended that most of the pressure created by hand tools should be directed to the hypothenar area of the palm (Fransson-Hall and Kilbom 1993).

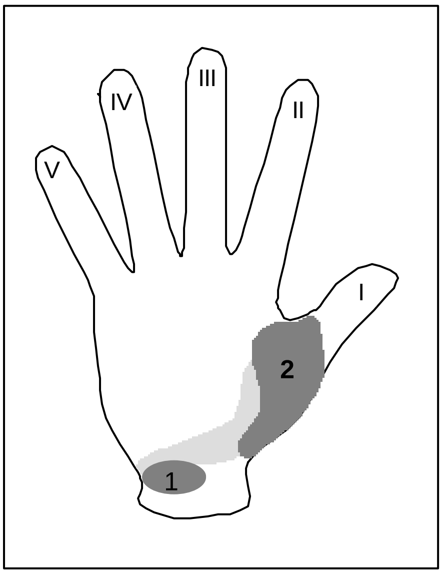

Figure 7. The most sensitive areas of the hand. Dark gray indicates pain-pressure threshold (PPT) of less than 80% of the average and light gray PPT of 81-100% of the average. Number 1 indicates the area around the os pisiforme, number 2 indicates the thenar area and numbers I-V finger numbering (modified from Fransson-Hall and Kilbom 1993).

The pain-pressure threshold has been found to be approximately 450-550 kPa for females and approximately 700-850 kPa for males. It seems that people tend to overestimate considerably the tolerable pain-pressure threshold for an 8-hour workshift: females by 3-4 times and males by about 10 times the value that would produce tissue damage. It should be noted, however, that the overestimation may be due to the limited time of the measurements. A 10 kPa load has been proved to cause tissue damage after one hour of exposure. (Fransson-Hall and Kilbom 1993)

The pressure on the hand in repetitive work should not exceed 1 kp/cm^2 (approx. 100 kPa) for females and 2-4 kp/cm^2 (approx. 200-400 kPa) for males (Grant and Habes 1995). Occasional maximums should not exceed 7 kp/cm^2 (approx. 700 kPa). Values for the amount of pressure that the human skin endures in cases of extended exposure, e.g. for a whole workshift, are not available (Fransson-Hall and Kilbom 1993). Fransson-Hall and Kilbom (1993) suggest that no numerical recommendations should be made until the subject has been studied more extensively. The recommendation is that the surface pressure should be as low as possible.

To minimise the surface pressure, the contact area should be as large as possible. The following are additional methods for reducing surface pressure:

1. Handles should be made sufficiently long (Fransson-Hall and Kilbom 1993). The contact area is thus increased and the end of a handle will not press on the hand.
2. The arc of the handle should not be too high, in order to avoid high local pressure on the palm.
3. Finger grooves and bosses should be avoided (Fransson-Hall and Kilbom 1993, Freivalds 1987).
4. All corners and edges should be rounded (Fransson-Hall and Kilbom 1993, Freivalds 1987) and the curvature radius should be as large as possible (Lewis and Narayan 1993).
5. High pressures should be directed to the less sensitive areas of the hand (Freivalds 1987).
6. The grasp surfaces should be of soft materials (Fransson-Hall and Kilbom 1993). However, materials should not be so soft that other parts, such as metal components, are able to penetrate them (Freivalds 1987).
7. The shape of the hand tool should follow the natural forms of the hand (Lewis and Narayan 1993).

Shear forces on skin

Shear forces acting on the skin of the hand are to be avoided, as they can cause injuries such as blisters. The friction coefficient between skin and handle is the source of the shear force. The friction characteristics of palm skin do not follow the classical laws of friction and differ from other materials in this respect; the friction is not directly proportional to the load. The friction coefficient is also dependent on the contact area of the skin. The contact area of the skin correlates positively with the friction coefficient on a clean surface, but negatively in the case of a contaminated surface. (Bobjer et al 1993) The friction coefficient varies according to the handle's surface material and texture, environmental temperature, skin texture and individual physiology (Meagher 1987), with some influence resulting from dirt and other substances (Bobjer et al 1993).

According to Bobjer et al (1993), there is no improvement in the friction coefficient if coarse surfaces and sharp edges are used. On the other hand, their study indicates that wide grooves improve the friction coefficient in a contaminated environment, although they increase the feeling of discomfort. Surprisingly, with few exceptions, the correlation between high friction coefficient and coarse surface is small, contrary to the usual assumption. The highest friction coefficient is achieved in a clean environment and on an even surface. On a contaminated surface, e.g. when there is a grease or oil layer on a surface, a coarse-patterned surface provides the best friction coefficient. According to the Eastman Kodak Company (1983), the best grip can be accomplished by using elastic handle material. Bobjer et al (1993) provides some guidelines for the design of handles:

1. For weak people, high friction may enable them to perform tasks which they normally could not do.
2. Low friction may be suitable for places where the hand constantly has to slide over a surface.
3. A large contact area increases the friction coefficient when the skin is clean. This reduces muscular strain and increases productivity.
4. A large contact area is also felt to be more comfortable.

Texture has considerable influence on the friction coefficient between hand and surface and on feelings of discomfort (Bobjer et al 1993). There are contradictory views regarding texturing. Tichauer and Gage (1977) recommend that the texture should be coarse enough to guarantee a good grip and to avoid slipping. On the other hand, Mital and Kilbom (1992) consider that a smooth surface is better. Meagher (1987) also states that too coarse a surface can lead to discomfort, skin irritation and diminished efficiency. Broad grooving of handles inhibits the transfer of maximum force and can produce discomfort because of the low surface area of skin contact (Meagher 1987). According to Bobjer et al (1993), a smooth surface is in general more comfortable than a patterned one. However, they also state that in unclean environments a patterned surface may be more beneficial because of its better friction characteristics. A coarse pattern is recommended in contaminated environments. For a clean environment there is no statistical evidence of difference between various patterns. On a non-patterned surface, perspiration and oil reduce the friction coefficient. High and low friction coefficients are extremely dependent on the environment. In the presence of perspiration, a high friction coefficient is produced by selecting a large contact area with the skin. In the case of oil or fat, a large contact area provides only a low friction coefficient. (Bobjer et al 1993)

Thermal insulation characteristics

The tool materials should be selected so as to minimise the heat loss from the hand of the user (prEN 1030-1 1993), as work in cold environments requires more time and is more demanding for muscles (Nieminen et al 1999). Thermally inert material is recommended for use in handles (Giguère et al 1993). Especially if the tool is to be used without gloves, the handle material should not conduct heat (Tichauer and Gage 1977). The following is recommended in prEN 1030-1 (1993): “If in use the handle is likely to be colder than the operator’s hand, the handle material should have a low thermal conductivity.”

5.3.3 Handles

Length of handles

Handles should be sufficiently long so that the end of the handle does not press on the sensitive areas of the hand (Fransson-Hall and Kilbom 1993). However, handles should not be too long, so as not to cause pressure on the wrist (Freivalds 1987). Several recommendations exist regarding the length of handles. The generally suggested minimum length is 100 mm. This recommendation is based on the breadth of the user's palm (Eastman Kodak Company 1983, Freivalds 1987). According to prEN 1005-2 (1995), handles should be at least 125 mm long, in order to make it possible to use the hand tool while wearing gloves. The Eastman Kodak Company (1983) recommends that for hand tools such as pliers, which need appreciable forces, the handles should be 130 mm long. To allow for the use of gloves with the latter, a length of 13 mm should be added (Eastman Kodak Company 1983).

An interesting proposal for the handle length of pliers-like hand tools has been made in a study by Lewis and Narayan (1993). They have assigned the handles three different sizes according to the size of users (5th, 50th and 95th percentile populations). According to Lewis and Narayan (1993), in pliers the upper handle should be 135-170 mm in length and the lower handle 95-120 mm. Table 2 lists recommendations for handle lengths for the three user groups.

Table 2. Proposal for the handle length of pliers-like hand tools (Lewis and Narayan 1993).

Size	Male (percentile)	Hand breadth in metacarpal	Female (percentile)	Hand breadth in metacarpal	Length, upper handle	Length, lower handle
Small			5th - 50th	69-76 mm	115 mm	95 mm
Medium	5th - 50th	79-86 mm	50th - 95th	76-86 mm	130 mm	105 mm
Large	50th - 95th	86-97 mm			140 mm	120 mm

Gloves should be chosen carefully, as they affect the use of hand tools by changing the grip. Gloves change both the shape and the size of the hand. Unsuitable gloves can also cause stress injuries when the user tries to improve the grip. (Tichauer and Gage 1977) It was also found that the use of gloves can increase fatigue when using a pliers-like hand tool (Fleming et al 1997). According to Freivalds (1987), gloves increase the size of the hand as follows: woollen or leather gloves increase the thickness of the hand by 5 mm and the breadth by 8 mm, and a heavy mitten can increase the corresponding measurements by 25-40 mm.

Grip span

The grip span of pliers-like tools influences the usability of the hand tool by defining how efficiently the tool can be handled and force transmitted. The distance between the outer surfaces of handles should be less than 90 mm when measured for the grip between the third finger, middle finger and bottom of the thumb (Eastman Kodak Company 1983). The grip force of pliers-like hand tools is at its highest when the grip span is 55-65 mm for males and 50-60 mm for females (Fransson and Winkel 1991). Force production decreases by 10% for each centimetre by which the grip span is enlarged (Fransson and Winkel 1991). When the force needed to cut a wooden stick of a certain diameter was studied, the maximum cutting force was found to occur when the cut had reached the middle of the branch or just a fraction further (Kallionpää et al 1997b). The grip span and the opening of the blades should be optimised in accordance with this information. When one is planning the grip span, the anthropometry of the user population should be taken into consideration, as well as the large variations between men and women as far as hand size is concerned. In general the female hand (length * breadth) is 84% of the estimated area for males (Hall 1997).

Arc of handle

Handles with too curved an arc can cause pressure to be concentrated on too small an area of the palm (Eastman Kodak Company 1983). The handles should also follow the natural form of the hand (Lewis and Narayan 1993). The height of the arc of a handle should be less than 13 mm over the whole handle length (Eastman Kodak Company 1983).

Grip guard

The purpose of a grip guard is to prevent the fingers from slipping into the cutting zone of the blades. An optimal grip guard is 15.2 mm in height (Cochran and Riley 1986). A height of 16 mm has also been recommended (Mital and Kilbom 1992).

Wrist position

The wrist position is the prime factor to be considered when one is attempting to reduce or eliminate load on the hand (Lewis and Narayan 1993). Correct wrist position can play a part in preventing ailments such as tendovaginitis and can affect tasks requiring precision (Armstrong et al 1982, Loslever and Ranaivosoa 1993, Sperling et al 1993a) and the efficiency with which force is produced (Duque et al 1995, Fransson and Winkel 1991). Duque et al (1995) have measured muscular activity in terms of maximal isometric voluntary contraction (MVC). In their study 30% MVC was attained in the case of all 11 wrist positions used in the study, but 70% MVC was achieved only when the wrist was in the neutral position. Force production was at its lowest when the wrist was in a bent position and at its highest when the wrist was either in a neutral position or in extension.

A hand tool should guide the wrist into a neutral position (Tichauer and Gage 1977). Sperling et al (1993a) suggest that an optimal position for the wrist involves 30° extension, 10° ulnar deviation and semipronation. To minimise exertion, Tichauer and Gage (1977) recommend avoiding ulnar deviation. A “handshake” position has also been proposed as an optimal position for the wrist (Mital and Kilbom 1992).

5.3.4 Locking mechanism

The location of the locking mechanism should be chosen in such a way that it is easy and quick to operate using one finger. The use of a locking mechanism should not require too much force. (Kallionpää et al 1997b) For a switch that is operated using one finger and can be moved in all directions, it is recommended that the maximum force requirement should be less than 6.9 N and the maximal torque less than 0.9 Nm (prEN 894-3 1992). The thumb is the strongest of all the fingers (Kinoshita et al 1996), and it is therefore recommended that the design should allow the thumb to be employed when the locking system is being used.

Pruners are commonly carried in pockets, and it is therefore necessary for a locking mechanism to be reliable (Kallionpää et al 1997b) to decrease the risk of the tool opening accidentally. A locking mechanism should be wide and rounded enough that it does not cause high local surface pressures on fingers (Kallionpää et al 1997b).

5.3.5 Force transmission mechanism

Force

Hand tools should be designed so that the force requirements imposed on the user are as low as possible, thus making the tool as easy to use as possible. High forces can cause discomfort, fatigue and musculoskeletal disorders and injuries. The maximum grip strength of a healthy young male using pliers-like hand tools is approximately 600 N; the figure is approximately 400 N for females. There is a reduction of 30% in maximum intermittent strength by the time that users reach the age of 60-65 (Freivalds 1987). Hall (1997) has reported that female hand strength amounts to 69% of the male strength. The smaller strength of females is partly due to the fact that on average the female hand is smaller, with less muscle mass (Fransson and Winkel 1991). For repeated and continuous work, 33-50% of the above-mentioned values is recommended. A two-handed grip improves force production by 60-70%. (Freivalds 1987)

Age, gender and repetition have a considerable influence on the ability to produce force (Meagher 1987, Sperling et al 1993b, Fleming et al 1997, Hall 1997). According to Chaffin and Andersson (1991), the occasional maximum force should be less than 90 N when the entire population is taken into consideration. In such cases the position of the wrist and arm should be optimal and exertion occasional. They add that grip force, position and frequency are very dependent on each other. Gloves reduce grip force by 15-20% (Chaffin and Andersson 1991). Grip force is also restricted by a feeling of inconvenience and pain (Fraser 1980, Freivalds 1987).

Maximum force requirements for the power grip of one hand on pliers-like hand tools are presented in prEN 1005-3 (1995). In an optimal situation the maximum force should not exceed 250 N for experienced professionals (85% of adults) and 100 N for domestic use (99% of adults). Adults are defined by prEN 1005-3 (1995) as being men and women aged 20-65 and capable of working. This maximal isometric force capacity (F_B) is influenced by fast, contradictive movements (m_v), the frequency (m_f) of repeated actions and the duration (m_d) of the work. Definitions of these variations are given in Table 3. Reduced force generating capacity (F_{Br}) is:

$$F_{Br} = F_B * m_v * m_f * m_d \qquad \textit{(Equation 1)}$$

Risk assessed force (F_r) can be calculated by using multiplier m_r. The risk assessed force is then

$$F_r = F_{Br} * m_r \qquad \textit{(Equation 2)}$$

Table 3. Values for multipliers in formulas according to prEN 1005-3 (1995).

Criteria	Value				Notes
Velocity (m_v)	1.0				-if action implies no or a very slow movement
	0.8				-if action implies an evident movement
Frequency (m_f)	(action time ≤ 0.05 min)			(action time > 0.05 min)	
	1.0, if	f ≤ 0.2	1/min	0.6	
	0.8, if	0.2 < f < 2	1/min	0.4	
	0.5, if	2.0 < f < 20	1/min	0.2	
	0.3, if	f > 20	1/min	does not apply	
Duration (m_d)	1.0				-if duration (working time) in similar actions < 1 h/day
	0.8				-if duration (working time) in similar actions 1-2 h/day
	0.5				-if duration (working time) in similar actions >2-8 h/day
Risk zone (m_r)	< 0.5,	recommended			
	0.5 – 0.7,	not recommended			
	> 0.7,	to be avoided			

Force requirements of 24 pruners were studied (Kallionpää et al 1997a, b, Kallionpää 1997). The force needed to cut a 13 mm thick, fresh branch was on the average 113 N, varying between 72 and 189 N. According to prEN 1005-3 (1995), in a situation where for example a professional worker cuts with 2-20 repetitions per minute and uses pruners for 8 hours per day, the following force-generating capacity would result: F_{Br} = 0.8 * 0.5 * 0.5 * 250 N = 50 N. The recommended limit would thus be 25 N.

For domestic use with 2-20 repetitions per hour and a working period of 1-2 hour per day the force-generating capacity would be F_{Br} = 0.8 * 0.5 * 0.8 * 100 N = 32 N. Thus, the recommendable limit would result in 16 N. When we observe these results, it seems that in the future minimising the force needed will be one of the most important tasks. The limit values for maximum force given that the prEN 1005-3 (1995) (250 N for professionals and 100 N for amateur use), should not be exceeded.

In the cube model presented by Sperling et al (1993a) and Kilbom et al (1993b), force requirements are presented as a percentage of MVC (% of MVC). A low force requirement is defined as being less than 10% of MVC, a medium force requirement as being 10-30% of MVC and a high force requirement as being over 30% of MVC (Sperling et al 1993a). Muscle activities during the use of different pruners were studied using EMG (Kallionpää 1997, Kallionpää et al 1997a). The results show that the average muscle forces in arm flexor muscles (m. flexor digitorum superficialis) were 15-22% of MVC and in arm extensor (m. extensor digitorum) muscles 9-15% of MVC. The maximum values were 63-84% of MVC and 37-58% of MVC respectively.

Disregarding the thumb, the middle finger is the strongest and the little finger the weakest (Fransson and Winkel 1991, Oh and Radwin 1993, Kinoshita et al 1996). According to Fransson and Winkel's (1991) recommendations, it is more relevant to consider fingers as intimately cooperative parts of the hand rather than as separate agents. Their argument is based on the fact that some forearm muscles, i.e. m. flexor digitorum profundus and m. flexor digitorum superficialis, contribute to flexion of several fingers, but are united in origin. The positions of other fingers affect the movements of a single finger (Fransson and Winkel 1991). Taking all the above information into consideration, it is reasonable to assume that the highest force production of the hand is achieved through the even use of all fingers.

5.3.6 Returning mechanism

Hand tools with two handles, such as pliers, should have a spring which returns the handles to the initial position (Eastman Kodak Company 1983). Kilbom et al (1993a) have reported an increase in working efficiency when a plate shears with a spring is used, as compared with the use of a plate shears without such a spring. The extra load created by the spring does not increase the required cutting force or the load on the user (Kilbom et al 1993b).

5.3.7 Blade

Type and shape of the blades

In some of the pliers-like hand tools, the jaws on the head are blades used for different cutting tasks. The type of blade influences the usability of a tool, for example, by determining how easy it is to see the object being cut. The blades of pliers-like hand tools used for cutting can be classified as bypass and anvil-types. These two types of blades have different characteristics and purposes. In the case of pruners, the anvil-type needs on average a little less cutting force than the bypass models. Rounding of the tips of the blades is a safety measure as it improves the safety of the tools, which are carried in the pocket. (Kallionpää et al 1997a)

Opening of blades

The opening angle of the blades defines the thickness of the material on which the tool can operate. It is advisable in the case of pliers-like cutting tools that the material being cut should be able to be inserted as deeply as possible between the blades, as cutting is then easier and the force requirement lower. In both a market survey by Peltonen (1998) and a “focus group” interview by Kallionpää et al (1997b), a large opening angle of the blades is quoted as being an important factor for pruners.

5.3.8 Guide

The guide is here defined as being the part of the system that holds the blades together. The purpose of the guide is to hold the blades in a correct operating position. The guide should allow smooth and efficient movement of the blades if the tool is equipped with a return spring. In tools without a spring, the guide can be used to adjust the tightness with which the blades operate. In pliers-like tools the guide is often a screw. According to a market survey conducted by Peltonen (1998), the users want the guide to be available as a spare part.

5.4 Discussion

5.4.1 Methodological aspects

The reliability of the study can be considered sufficient as the sample from the literature is based on a broad survey. The reliability of the literature survey is always based on the reliability of the used references and the completeness of the survey. The design criteria have been selected mainly from publications concentrating on ergonomics. Therefore the criteria reflect the results of this particular discipline. As not all the information concerning the ergonomics and usability of the product can be implemented in the design method, choices had to be made. Thus, any list of critical design factors cannot be complete. Depending on the choices made, the results of the collection of design criteria can vary. The data used for creating the design criteria have to be carefully evaluated for their reliability and care should be taken which references are used. An effort was made to use relevant standards, referee-evaluated scientific publications and commonly used and accepted hand books.

In this survey mostly literature in the English language was used. This may have resulted in missing some already existing information published in other languages. However, it must be noted that the authors of the used references represent various countries and several disciplines, thus improving the reliability.

5.4.2 Discussion of the design criteria

Designers need both conceptual and detailed design information to support ergonomics. There are a number of factors that make design for ergonomics difficult, one of them being the need of more knowledge on ergonomics. Also lack of research on topics of interest for design is a serious obstacle. It was also found that designers expect clear rules and want to find specific and pertinent information on how to accomplish ergonomic design. (Willén 1997)

The aim of this study was to present a detailed list of the most important ergonomic design criteria for pliers-like hand tools. Garden pruners were used as an example. The criteria was found and collected from literature and grouped so that it could be used as supportive material in hand tool design for example with the QFD method.

Design criteria for non-powered hand tools can be found in the literature but requires a broad literature survey. Also selection and grouping of the criteria was needed. As this method requires quite a lot of time and effort, its applicability for a very rapid design process can be problematic as it was found that designers in some companies spent very little time, even less than 1% of working time on ergonomics issues (Willén 1997). On the other hand, when the criteria have been found and collected, they can be applied in other cases as well.

The criteria presented in this case study 1 are the most important ergonomic criteria that should be integrated into the design process for non-powered hand tools. During the selection of the criteria special emphasis was on the design of pliers-like hand tools like garden pruners. When applying the data in a new design, care should be taken to ensure that for example the dimensions apply to the particular product and user population.

The criteria can also be modified to be used as e.g. a checklist when one is evaluating the ergonomics of hand tools. When selecting the design criteria, the restriction was made to concentrate firstly on non-powered hand tools and secondly on pliers-like one-hand operated tools. This may restrict the use of criteria in the design or evaluation of other types of hand tools. It should be noted that the factors presented here may be of varying importance for different tools. Some other factors not mentioned here can also be of importance in some cases. The main aim in design in the case of ergonomics and usability should be to decrease the effects of work load (Kattel et al 1996).

The criteria presented here are especially useful in a design process in which the QFD method is employed. Although it has been possible to find a number of recommended values for the criteria, some criteria still lack reliable recommended values or consensus on the several presented values, thus indicating the need for further research. For example, values for the amount of pressure that human skin safely endures in cases of extended exposure, e.g. for an 8-hour workshift, are not available. It is also possible that the recommendations for maximum hand tool weight should be reconsidered.

6 Case study 2 - Ergonomics and usability evaluation of electricians' work in cold climate using a questionnaire and risk analysis

6.1 Introduction

6.1.1 Risk analysis in consumer product evaluation

Safety is a relevant criterion for a usable product (Wilson and Whittington 1982, Norris and Wilson 1999). Consumer products should also be efficient, durable, serviceable and reasonably priced (Wilson and Whittington 1982). Designers and producers have to be convinced that evaluating for safety is a viable and cost effective process, which can be accommodated along with all other constraints on the product development process. The features of the product - person interaction which influence safety and which must be considered in any evaluation are: product, user, circumstances of use and environment. (Norris and Wilson 1999)

The three immediate influences on consumer safety are the product design, the behaviour of the consumer and the conditions in which the product is used (Norris and Wilson 1999). Ergonomics has an important role to play in consumer product safety by ensuring that this interaction is safe and by improving product design, the central influence on consumer safety (Norris and Wilson 1999). By improving e.g. machines and equipment, both productivity and safety could be improved (Salminen and Saari 1995). In some cases ergonomists can utilise human error assessment approaches and gain valuable insight into error reduction without having to quantify human error likelihoods or probabilities (Kirwan 1998).

In some cases, typically in professional use, consumer products can be understood as a part of a larger system. There are several strategies for improving system reliability and one of these is good design, i.e. the choice of design and proficient engineering are basic to high reliability (Harms-Ringdahl 1993). From the systems perspective a system consists of a number of elements that must interact for a desired result to be achieved. The main elements are:

1. Technical equipment and physical conditions.
2. Individuals within the company.
3. Organization.
4. System environment. (Harms-Ringdahl 1993)

The properties of the elements and the nature of the interaction between them determine the level of the accident risks. Consumer products typically belong to the category of technical equipment and are thus part of a system. The types of technical equipment that may be involved in accidents vary to a great extent, ranging from hand-tools to computer systems which control production plants. In the case of technical equipment, safety has traditionally been relatively well regulated by e.g. directives, norms and accepted good practice. (Harms-Ringdahl 1993) In the case of hand-tools there is still knowledge lacking on how usability issues are implemented efficiently in new products. Attempts to reduce risk by teating just one of the four elements generally lead to rather ineffective solutions (Harms-Ringdahl 1993).

6.1.2 Work safety analysis

Work safety analysis can be described as a systematic approach to the identification and evaluation of factors that may lead to accidents. It also includes the generation of proposals for increasing levels of safety. One goal is also to obtain an overall picture of hazards within a system. (Harms-Ringdahl 1993)

Work safety analysis is designed to analyse well-defined jobs in order to identify accident risks for people doing the tasks. The job is divided into tasks, hazards in the tasks are identified and suitable corrective measures are proposed. The method can be used both with tasks of an individual worker or a group working in a limited part of a production system. (Harms-Ringdahl 1987)

Work safety analysis can provide quantitative measures of certain types of risks. Numerical values are generated for the likelihood of certain events occurring, or calculations are made of possible consequences, or weighted measures are constructed, e.g. according to the principle of probability multiplied by consequence. (Harms-Ringdahl 1993) Work safety analysis has been evaluated as concentrating more on determining factors than on deviations (Suokas 1988).

When using work safety analysis, several different aspects must be included:

1. Gathering of information on the system provides the basis for the analysis and must be carried out systematically.
2. The entire system and the activities within it should be included in the analysis. The analysis needs to be designed systematically so that important elements are not overlooked. A main thread must be identified and followed.
3. A systematic methodology is required for the identification of hazards.
4. The risks to which these hazards give rise need to be assessed in a consistent manner.
5. A systematic approach is required even when safety proposals are to be generated and evaluated. (Harms-Ringdahl 1993)

If any one specific method is applied, it may mean that certain types of hazards will be observed, while others may not be detected. It is therefore recommended that for better coverage supplementary risk analysis methods are applied. (Harms-Ringdahl 1993)

6.1.3 Action error analysis

By analysing existing products, it is possible to identify difficulties that must be corrected in new products (Chapanis 1995). With the Action error analysis method it is possible to analyse procedures involved in the operation of technical systems. Its aim is to identify steps that are especially prone to human error and assess the consequences of such errors. The stages in the procedure are:

1. Making a list of the steps in the operational procedure. The list specifies the effect of different actions on the installation and it must be detailed.

2. Identification of possible errors for each step, using the checklist of errors.
3. Assessment of the consequences of the errors.
4. Investigation of conceivable causes of important errors.
5. Analysis of possible actions designed to gain control over the process. (Harms-Ringdahl 1993)

Various conceivable types of errors include: 1) actions not taken, 2) actions taken in the wrong order, 3) erroneous actions, 4) actions applied to the wrong object, 5) actions taken too late or too early, 6) too many or too few actions taken, 7) actions with an effect in the wrong direction, 8) actions with an effect of the wrong magnitude and 9) decisions failures in relation to the actions taken. (Harms-Ringdahl 1993)

In this case study 2, risks in work done by electricians working on telecommunications and electricity transmission masts in a cold climate were evaluated. As the electricians in telecommunications and electricity transmission systems companies work on different tasks and in different environments, the tasks to be analysed in this study had to be specified and chosen to represent the most typical ones. The study consists of two parts, namely a questionnaire and a risk assessment.

The aims of this case study were:

- to assess the risks and ergonomics and usability related to electricians' use of hand tools in cold and in a winter environment and
- to assess the overall risks of work done by electricians working on telecommunications and electricity transmission masts in a cold climate.

6.2 Materials and methods

6.2.1 Questionnaire

A questionnaire aimed to collect data on how electricians consider cold climate to affect their work safety, workload and performance was developed. The following categories were included: basic information, work safety, workload, the effects of coldness on the work performance and musculosceletal load, hand tools, protective clothing and other equipment and ideas for improvement measures. The division of the topics and the questions were formed after getting acquainted with the chosen work tasks and discussions with the electricians in the field. Most of the items were multiple choices, but some open questions were also included. The number of questions was 72, some of them including several subquestions.

The results of the questionnaire were used as one of the objectives when deciding the work tasks for risk assessment. In the questionnaire several topics were inquired about, but in this case study 2 only the parts concerning hand tools are included (Appendix 1). In the questionnaire it was inquired how often the hand tools are used and how usable the tools are according to their shape and handle material. It was not possible to include more detailed questions about the shape and material of the hand tools.

The questionnaire was distributed to 100 electricians working in telecommunication. A similar questionnaire was also distributed to 70 electricians working in an electricity transmission company. A total of 118 replies were obtained, thus yielding a response rate of 67% in telecommunications (67 replies) and 73% in electricity transmission (51 replies). All the electricians worked for either one telecommunications or one electricity transmission company in Finland. Both companies are the main suppliers in their fields and the questionnaire was given to all the electricians working in the tasks included in this study. All the electricians were male (Table 4).

Table 4. Subjects answering the questionnaire.

Characteristics		Telecommunications (n=67)	Electricity transmission (n=51)
Age (years)	mean	38	41
	range	20 - 54	21 - 55
Employed in current job (years)	mean	6	20
	range	1/3 - 25	1 - 33
Current status of health (%)	excellent	26	8
	good	64	73
	moderate	10	18
	poor	-	1
Handedness (%)	right	84	94
	left	15	6
	ambidextrous	1	-

The questionnaires were distributed to the electricians by the foremen of each company so that they could brief the electricians about the ongoing study. With the questionnaire a self addressed envelope (SAE) was included as the electricians were asked to mail the papers back directly to the researchers.

6.2.2 Risk analysis

The risks of the work were assessed by combining work safety analysis and action error analysis (Harms-Ringdahl 1993). The work safety was assessed in general, but also the special risks due to cold winter environment were taken into consideration.

The risk assessments were done in co-operation with the electricians by arranging a set of meetings between the electricians and researchers. During the meetings the risks of the work tasks were assessed. Before the analysis meetings the work was divided into tasks. This was done by the researchers after visiting three working sites of both companies and discussing with the electricians. For the risk assessment in telecommunications the work was divided into the following tasks: 1) mounting of new antennas on the masts, 2) maintenance of telecommunications masts between 83-90 metres high, including inspection of the structure of the masts and tightness adjustment of bolts and the backstays and 3) the work on the ground during these tasks (Figure 8). In electricity transmission systems the tasks evaluated were related to the construction of new 110 kV and 400 kV electricity lines (Figure 8).

The electricians together with the researchers considered what risks were related to the tasks. After that, the cause for the risk as well as the consequences and their probabilities were recognized (Equation 3). Later the present safety measures were evaluated and proposals for improvements created. The subjects in telecommunications were three males with whom one risk analysis session was held. In the electricity transmission company the subjects were three males with whom two separate meetings were held. All electricians were experienced in their work.

Figure 8. Electricians working on the maintenance of telecommunication mast (left) and on the assembly of an electricity transmission mast (right).

Five categories were used for the rating of the probability (P) of an accident and the seriousness of the consequence (C) (Table 5). The risk (R) was obtained using equation 3:

$$R = P * C \quad \text{(Equation 3)}$$

Table 5. The rating of probability and consequences used in the risk assessment.

Rating	Probability	Consequence
1	Very unlike / once over 10 years	Not serious / scratches
2	Unlike / once every 1-10 years	Minor consequences / possibly needing medical care
3	Possible / yearly	Serious / needing sickleave of 1-3 days
4	Probable / monthly	Very serious / needing sickleave over 3 days
5	Very probable / weekly	Extremely serious / very serious injury, death

6.3 Results

6.3.1 Risks in telecommunications

In the questionnaire, 9% of the studied electricians claimed to have had an accident or injury related to the use of hand tools during the past five years. The rate of hand tool use was also inquired about and there were several tools which over half of the electricians used daily: socket wrench (89% using daily), side-cutting pliers (89%), open-end wrench (87%), monkey wrench (77%), carpenter's knife (76%) and screwdriver (67%) (Figure 9).

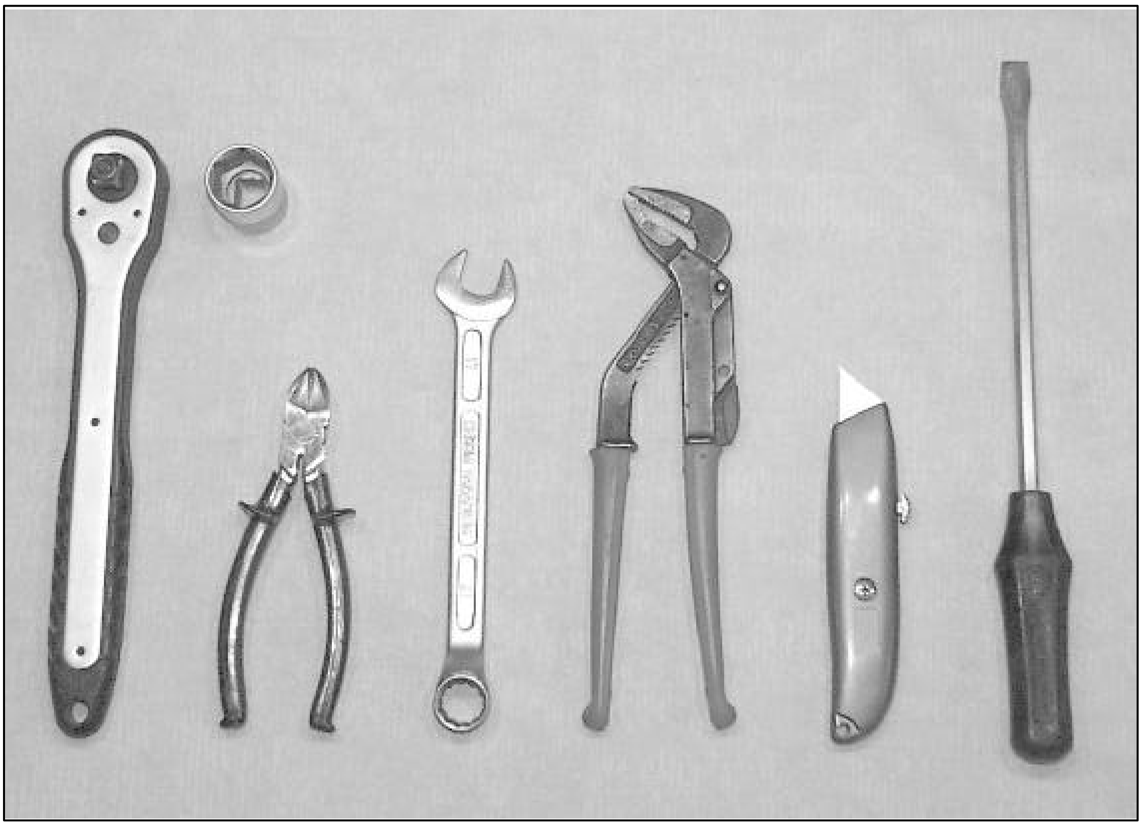

Figure 9. The hand tool types the telecommunications electricians most often used. From left: socket wrench and socket, side-cutting pliers, open-end wrench, monkey wrench, carpenter's knife and screwdriver.

The electricians were also asked to rank the usability of the used hand tools in outdoor conditions according to the shape of the tool. The answer options were: good, satisfactory, poor and not in use. The side-cutting pliers, screwdriver and socket wrench were considered good or satisfactory by over 98% of the electricians. The least usable were the adjustable wrench, which 30% of the electricians considered poor and the carpenter's knife, which was considered poor in 15% of the answers.

It was also inquired about how usable the hand tools are in outdoor conditions according to the handle material. The best tools were the side-cutting pliers and the socket wrench, which over 94% of the electricians considered good or satisfactory and both of which had a plastic or rubber handle. The worst ones were considered to be the adjustable wrench (31% considered as poor) and the carpenter's knife (18% considered as poor).

The risks were ranked according to the risk ratio obtained by estimating the probability and consequence of the risk (Equation 3) (Table 6).

Table 6. The greatest risks in telecommunication work with the risk ratio over 10.

Rank	Risk definition	Probability * Consequence
1	Things falling from the mast (tools, ice, etc.)	4 * 5 = 20
2	Injuries from manual materials handling and lifting of heavy equipment	5 * 4 = 20
3	Tools falling from the carrier bag during climbing	3 * 5 = 15
4	Falling of ladders when checking the backstays as the ground can be very uneven	3 * 4 = 12
5	Working on rooftops, walls and old masts as usually it is not possible to use the safety equipment in the best possible way	2 * 5 = 10
6	Electromagnetic radiation on the masts with other companies' antennas	5 * 2 = 10

6.3.2 Risks of electricity transmission

According to the questionnaire, 6% of the studied electricians working in electricity transmission have had an accident related to the use of hand tools during the past five years. In electricity transmission the most often used hand tools are lineman's pliers, which 53% use daily and 41% weekly, the open-end wrench (38% daily, 48% weekly), the socket wrench (31% daily, 53% weekly) and the smith's hammer (24% daily, 49% weekly) (Figure 10).

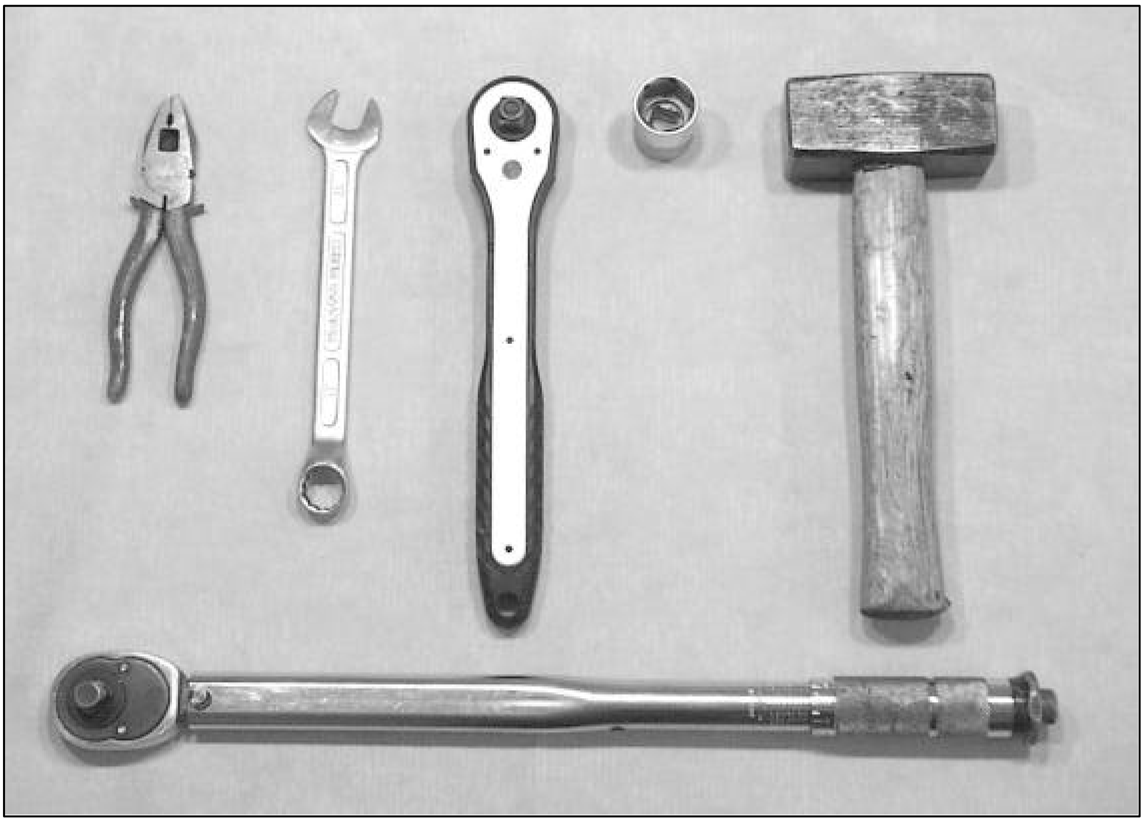

Figure 10. The hand tool types the electricity transmission electricians most often used. From left: lineman's pliers, open-end wrench, socket wrench and socket, smith's hammer and torque wrench.

The hand tools were rated as how usable they are according to the shape of the tool. The most satisfactory was the lineman's pliers and the open-end wrench, which over 90% of the electricians rated as good or satisfactory. The worst scores were given to punch (35% rated as poor), the smith's hammer (31% rated as poor) and the torque wrench (16% rated as poor).

The best hand tools for outdoor use according to the handle material were the lineman's pliers and the open-end wrench, which were rated as good or satisfactory in over 90% of the answers. The most unsatisfactory tools were the torque wrench (25% rated as poor) and the socket wrench (16% rated as poor).

In the risk analysis the risk ratio is obtained by estimating the probability and consequence of the risk (Equation 3) (Table 7).

Table 7. The greatest risks in electricity transmission work with the risk ratio over 10.

Rank	Risk definition	Probability * Consequence
1	Things falling from the masts (tools, bolts, ice etc.)	4 * 5 = 20
2	Injuries from lifting of heavy equipment, structural elements etc.	5 * 4 = 20
3	Sicknesses from sitting on cold metal structures	4 * 4 = 16
4	Fingers getting squeezed between the structures during building of new masts	4 * 4 = 16
5	Traffic accidents in the work sites that are near roads	3 * 5 = 15
6	Accidents when pulling the cables from mast to mast as there is a possibility that the cable breaks or gets loosened from the pulling vehicle and thus can be catapulted nearby with a great force	3 * 5 = 15
7	Communication problems and misunderstandings between electricians and the driver of a mobile crane when erecting masts built on the ground	3 * 5 = 15
8	Sudden and unpredictable explosions of insulation parts made of glass if safety glasses are not used. If used, as required by the working instructions, the risk was	3 * 5 = 15 3 * 2 = 6

6.4 Discussion

6.4.1 Methodological aspects

The benefit of a questionnaire is that it is a quick and easily available method. The disadvantage is that it is superficial and general in nature and also dependent on the subjects' self expression abilities. When a questionnaire is used, the repeatability of the study is affected by the fact that not all significant questions are included and the asked questions themselves can guide the answers. By using multiple choice and open questions it was attempted to decrease this effect. The problem with multiple choices is that the answers are already given, while with open questions there are problems regarding the interpretation and classification of the answers. It is also possible that the questions or the terms used are not understood or they are misunderstood. Due to the fact that the themes in the questions reported in this study were a part of a larger questionnaire, it was not possible to include several differently modified questions on the same subject. This could have improved the repeatability of the questionnaire.

As the questionnaire was used for basic information on the electricians' use of hand tools, the reliability of the answers can be considered sufficient. The response rate can be considered to be satisfactory. However, it must be noted that the results may be somewhat biased, as usually only motivated subjects reply to a questionnaire.

The choice of the risk analysis method was based on the nature of the study. Risk analysis was done in co-operation with the electricians and is based on their opinions. When a group interview is used, there is always a possibility that researchers may lead the conversation too much. This was avoided by getting acquainted with the work tasks beforehand and then ensuring that all subjects had equal opportunity to express themselves. In this way the conversation stayed on relevant tasks and proceeded systematically. It is possible that participants find the expressing of dissimilar opinions difficult, and thus some knowledge is missed. Special emphasis was paid to creating an easy and friendly environment in which discussion was easy.

Before the risk analysis meetings the work was divided into tasks. The definitions were made by the researchers after getting acquainted with the work and were then approved by the electricians. There is a possibility that with these kinds of artificial divisions data is overlooked as the work in reality is continuous.

As it was not possible to evaluate the risks with all electricians from the companies, the results present only some electricians opinions and skill in analysing the work. On the other hand, all participating electricians were experienced in their work and the risk analysis method and the terms used were carefully explained to them.

6.4.2 Discussion of electrician's work in cold climate

The results of the questionnaire indicated where more emphasis needs to be put when selecting tools for electricians or designers where there is a need for improvements. More relevant in this case was that with the risk assessment methods the problems related to the use of hand tools were emphasised. Secondly it was found out that falling of tools with other equipment created the greatest risk for the electricians. When evaluating the results of the risk analysis it should be noted that the electricians did not regard the probability of themselves falling as being high. The electricians explained that they rely on the safety equipment and thus falling was not included in the list of main risks in the work.

Working in cold, slippery and dark conditions creates special requirements for electricians' work. More effort is needed to overcome the resistance of snow, heavy equipment and coldness. Even though the emphasis of this study was on the evaluation of work done in cold environments, most of the risks are present also in a warmer climate. High masts are also very untypical working environments, creating special needs for the equipment used.

In the assembly of telecommunications and electricity transmission systems where hand tools are an essential part of the work, they were also regarded as one of the main risks in the work. The risk is even more relevant according to the results of the questionnaire where cooling of fingers and hands were mentioned as causing most inconvenience and disadvantage for most electricians (Päivinen et al 2000).

Both in telecommunications and electricity transmission, things such as tools, ice and equipment falling from a mast were regarded as the greatest risk (Päivinen et al 2000). If something falls from a mast, it can be extremely dangerous for the colleagues working on a lower level of the mast or on the ground. For example, during mast maintenance the risk of a torque wrench slipping and falling is relevant as the work postures are difficult and a lot of force is required for the task and as there are several men working on the same mast at different heights. The electricians use a variety of hand tools. Most of them are common consumer products, which are available for all users.

Most of the hand tools did not seem to have thermal insulation on the handles. Many of the tools are slippery and cold in wintertime, thus requiring more forceful gripping. The electricians mentioned in their answers the need for a more usable grip which would improve the thermal insulation and allow a more secure grip. Attention should be paid to the thickness and size of the handle. It was also mentioned that the sockets could easily get loosened from the socket wrench.

The electricians in telecommunications reported that they had modified the hand tools to make them more suitable for their use. They used ropes to prevent the tool dropping from a mast and they had welded the sockets to the socket wrench to secure the sockets into the tool. Also an open-end wrench was shortened, made slimmer on the head of the tool and the angle between the tool head and the handle had been altered. The electricians in electricity transmission reported that especially the socket wrenches break too easily. The electricians in that company too had done modifications to the hand tools, for example by narrowing and shortening the tools and altering the working angles, and some tools had been combined together.

The prevention of tools, equipment and ice falling from masts is very important. The risks created by ice can be reduced with proper working instructions which restrict working on icy masts. In both companies there were safety instructions for environmental conditions. There still are emergency situations during which work on icy masts has to be done.

The electricians reported the usability of hand tools as not suitable for working in cold climates. An idea of applying a yo-yo-like apparatus to personal fall protection equipment or overalls and to which tools could be attached came from the electricians. The possibilities to improve the handles of tools to make them more suitable for different environmental conditions should be noted as the tools should in no way be slippery in any conditions. And if possible the tool handle should support the worker in applying force to the work target. Keeping hands warm is also important as the sensations and the ability to create force weaken in cold (Nieminen et al 1999). The suggestions for improvement to hand tools can be summarised as follows:

- the prevention of hand tools and equipment from dropping; the idea of a yo-yo-like apparatus was produced,
- improvement of handle materials in order to provide more secure grip in slippery conditions and to provide better thermal insulation and
- more secure fixing of sockets in socket wrenches should be provided.

The electricians recognised the risks and had also made modifications to some of the hand tools they used. Usually questionnaires and risk analysis are used as evaluation tools for overall improvement of work conditions. From this kind of studies, valuable knowledge for consumer product and in this case hand tool development, can be gained. With the risk analysis methods it was possible to identify problems typically related to ergonomic situations. The problem is that the knowledge is difficult to transmit to tool manufacturers and thus does not readily lead to improvements. Often good connections and co-operation between researchers and manufacturers are needed.

7 Case study 3 - Ergonomics and usability evaluation of garden pruners during design process

7.1 Introduction

7.1.1 Electromyography

Some consumer products, e.g. hand tools, are used for such tasks that require muscular effort from the user. One aspect of ergonomics and usability is to study the user's level of muscular force needed when using a product. To be able to evaluate hand-intensive work, a variety of methods is needed. Specific methods for the measurement of force, pressure distribution and angles are available. For the estimation of internal exposure, electromyography (EMG) is the only non-invasive method giving on-line readings. (Hägg 2001) EMG means continuous recording of the electrical activity of a muscle (Lamb and Hobbard 1992). With this method for example the relative strain of the muscle can be determined. EMG can be used for example as an aid in the improvement of human-machine interface (Figure 11).

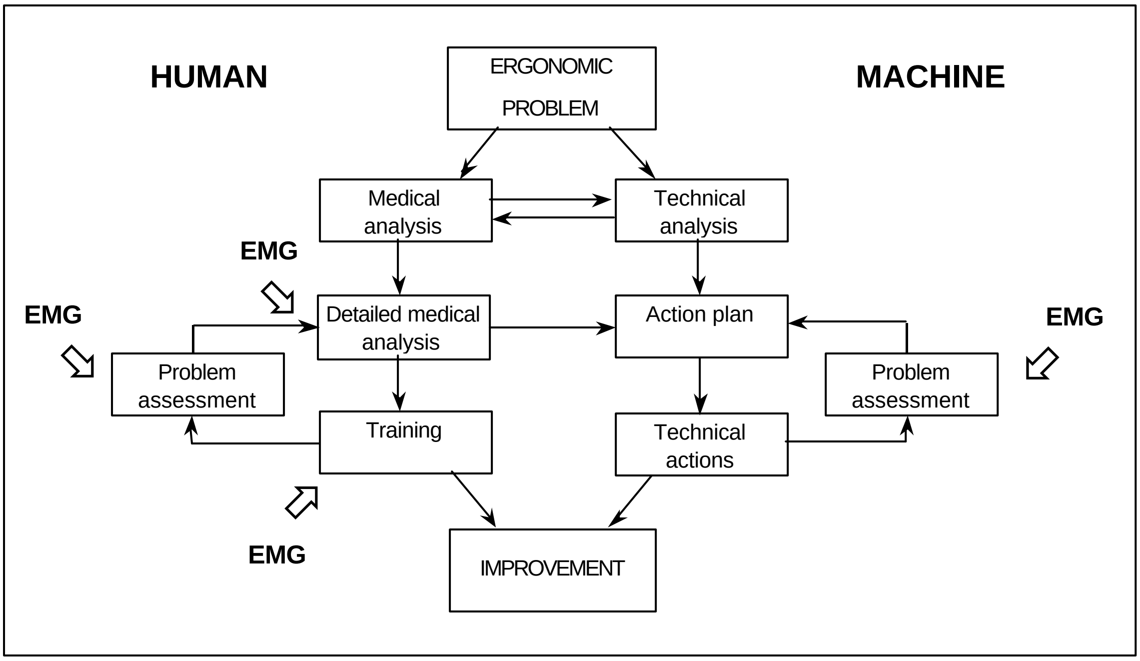

Figure 11. The process for ergonomic improvements with the aid of EMG (Jonsson 1994).

The electrical activity of the muscles depends on the level of muscle contraction (Jonsson 1982, Leskinen 1993, Jonsson 1994). The relationship between EMG and muscle force is dependent on factors such as muscle length, velocity, cross talk between electrodes and cocontractions of both synergistic and antagonistic muscles. Some confusion exists regarding the relationship between processed EMG and muscle force. In controlled, isometric contractions, the relationship between EMG and muscle force has been reported as both linear and curvilinear (Redfern 1992, Jonsson 1994). Models of curvilinear relationships have included second-order polynomials and exponentials. The kinematics of the movement, processing methods used and the acquisition procedure all have an effect on the muscle force-EMG relationship. (Redfern 1992) As the muscle fatigue increases, typical changes, i.e. increased amplitude and decreased frequency values, can be interpreted from the EMG (Redfern 1992, Jonsson 1994).

It is important to evaluate the output of force when using hand tools as their ergonomic characteristics are evaluated. EMG has been used in the evaluation of local strain of arm muscles as well as ergonomic evaluation of hand tools (Fellows and Freivalds 1991, Cederquist and Lindberg 1993, Freivalds and Eklund 1993, Kadefors et al 1993a, Kadefors et al 1993b, Kihlberg et al 1993, Kilbom et al 1993a, Lewis and Narayan 1993, Kihlberg 1995, Martin et al 1996, Attebrand et al 1997, Bruder 1997, Lee et al 1997, Oh and Radwin 1997).

For the EMG measurements focusing on the evaluation of hand tools, muscles located in the arm region and acting in the movements of hand and fingers are typically chosen for the measurements. For example the following muscles have often been studied: m. flexor digitorum, m. extensor digitorum communis, m. flexor carpi ulnaris and m. extensor carpi radialis (Fellows and Freivalds 1991, Kadefors et al 1993a, Kadefors et al 1993b, Kilbom et al 1993a, Kihlberg 1995, Lee et al 1997, Rempel et al 1997, Oh and Radwin 1997, Freund et al 2000).

Several muscles with different functions are closely located in the forearm. A certain amount of EMG overlapping is likely to occur within the extensor and flexor muscle groups (Hägg et al 1997). Wrist extensors as the prime movers in extension act also as stabilizers of the wrist during gripping. EMG results indicate that gripping is more fatiguing for the extensors than the flexors. (Hägg et al 1997)

There are several factors which should be recognised when interpreting EMG results. Gerleman and Cook (1992) and Aarås et al (1996) have collected factors influencing EMG amplitude:

- type of electrode,
- electrode placement,
- electrode contact area,
- preparation of electrode site,
- tissue distance between electrodes and muscle,
- direction of the movement of the extremity,
- muscle length,
- muscle temperature,
- type and velocity of muscle contraction,
- orientation of electrodes relative to the axis of the muscle fibres,
- number of muscle fibres within the pickup area of the electrode,
- number of motor units within the pickup area of the electrode and
- source and amplifier input impedance.

As some of the before-mentioned factors depend on the experimental set up, they can be controlled. Some vary from experiment to experiment but are fixed in one session, for example subject-related factors such as the thickness of tissue between the electrodes and muscle. Some of the factors are subject to continuing changes (e.g. electrode impedance, skin temperature) or to random fluctuations such as EMG interference pattern. (Aarås et al 1996)

The normalization process of EMG measurements allows comparisons between subjects and through which the EMG amplitude is related to exerted force. A normalization can be performed giving the workload as % of MVC (maximal isometric voluntary contraction) (Westgaard 1988, Louhevaara et al 1990, Németh et al 1990, LeVeau and Andersson 1992, Soderberg 1992b, Aarås et al 1996, Lamotte et al 1996, Malchaire et al 1997, Rempel et al 1997, Freund et al 2000). Aarås et al (1996, 1997) stated that normalized EMG measurements are repeatable and comparable.

When measuring MVC, it has to be noted that the ability to generate muscle contractions is an individual quality which is affected by muscular fitness, skill and motivation (Grandjean 1980, Tulppo and Mäkitalo 1993, Nieminen 1994). Due to the instinct of self preservation and other protective mechanisms, the measurement of MVC always remains somewhat inaccurate (Chaffin and Andersson 1991, Lamotte et al 1996).

Even though the MVC varies qualitatively and quantitatively, it is considered an acceptable normalization method when the influence of external effects is minimised (Jonsson 1982, 1994, LeVeau and Andersson 1992, Tulppo and Mäkitalo 1993, Aarås et al 1996). For a more accurate normalization, a method in which muscle activity is measured from a series of (e.g. 5%, 10%, 15%, 29%, 30%, 40%, 50% and 70% of MVC) submaximal muscle contractions has been proposed (Jonsson 1982, 1994, LeVeau and Andersson 1992). Louhevaara et al (1990) have used a method in which the levels 10%, 20%, 35% and 50% of MVC are defined. In same cases it is possible that with a high work load the EMG results are overestimated (Jonsson 1982).

Based on studies of muscular endurance during static and dynamic work, the following limit values for local strain have been suggested for constrained work with a duration of one hour or more up to an 8-hour work shift. The static strain level should not exceed 2-5% of MVC. The mean intermittent strain level should not exceed 10-14% of MVC. Also the peak dynamic strain should not exceed 50-70% of MVC. Jonsson (1978, 1982)

Sperling et al (1993b) have classified preliminary limits for hand tool handling. The demand is low if the grip strain is lower than 10% of MVC and can be maintained for continuous or repetitive work for less than 30 minutes. The force demand is moderate if the required mean grip strain corresponds to 10-30% of MVC. If the required grip strain corresponds to more than 30% of MVC the demand is high and that level can be maintained for only a few minutes. Also Byström and Fransson-Hall (1994) have stated that the continuous isometric contraction is not acceptable if the mean strain is 10% of MVC or higher.

When using surface EMG, only the strain of the muscles can be monitored, not e.g. the strain on joints or tendons. It can be assumed though that in tasks requiring high muscular strain also other body structures are under a high strain. (Hämäläinen and Vanharanta 1992)

During EMG measurements it is possible that electrical equipment located e.g. in the same room may disturb the EMG signals. These can be avoided or lowered by careful grounding of the test person. Also movements of the cables can affect the results. This can be avoided by fixing the cables to the skin or by placing the amplifier near to the electrodes. Disturbances can also be due to improper attachment of the electrodes to the skin. (Jonsson 1994)

As surface electrodes are used in occupational settings it is of importance to place the electrodes as accurately as possible on the appropriate muscles. It is possible that the EMG signal might vary according to the position of the electrodes for a fixed position of the arms and additionally with the sliding of the skin on the muscles as e.g. the forearm rotates. (Malchaire et al 1997). By using Ag/AgCl (silver/silver chloride) electrodes, the disturbances due to the electrodes can be decreased (Ko 1988).

7.1.2 Local muscular discomfort

The relative strain on muscles, tendons, ligaments, joints and bones can be evaluated by assessing the discomfort perceived by the worker (Delleman and Dul 1998). One technique for measuring discomfort is the Localised Muscular Discomfort (LMD) method in which a worker is asked to rate his or her discomfort in different body regions on a diagram of the body (van der Grinten 1991). The LMD method provides reliable results for comparison of work situations. (van der Grinten 1991, Delleman and Dul 1998) Modified LMD questionnaires, e.g. visual analogue scale (VAS), have been used e.g. in work place and hand tool evaluations (Bruder 1997, Haslegrave 1990, Delleman and Dul 1990, Nevala-Puranen 2001, Nevala-Puranen and Lintula 2001).

7.1.3 Questionnaire

Questionnaires have been used in ergonomics as a basis for more directed research or in epidemiological studies. For example Spielholz et al (1999) presented a self-report questionnaire for the evaluation of upper extremity musculoskeletal disorder risk factors. Also a Nordic questionnaire has been used to evaluate upper extremity musculosceletal complaints (Lusted et al 1996, Malchaire et al 2001). Questionnaires have also been used in product design (Bruder 1997, Ikeda 1997, Butters and Dixon 1998). In consumer product usability evaluation numerical rating scales have been used (Ikeda 1997, Butters and Dixon 1998, Freund et al 2000). Usually a five-point scale is adopted (Ikeda 1997, Butters and Dixon 1998). Subjects can also be encouraged to comment freely and list any particularly positive or negative features. (Butters and Dixon 1998)

A systematic approach in which first the current situation and the user's expectations were evaluated for example by a questionnaire has been used in the evaluation of hand tool ergonomics. In the next phases hand tool prototypes were developed and analysed by several methods. (Sperling et al 1993b, Lee et al 1997)

7.1.4 Focus group interview

A focus group interview helps to test the projected use of the product or system and is usually run in conjunction with other methods (Butters and Dixon 1998, Popovic 1999). The most common approach is that users are asked to discuss issues related to the usability of the proposed product designs or to generate ideas for designing in general (Popovic 1999, Barrett and Kirk 2000, Bruseberg and McDonagh-Philp 2002). The method is useful by helping to decide which aspects of the product should be concentrated on and to identify the issues that are important for the users (Butters and Dixon 1998, Barrett and Kirk 2000, Bruseberg and McDonagh-Philp 2002).

The focus group consists of leaders and a number of participants. The meetings are not rigidly structured in order to allow the participants an opportunity to voice their opinions. The leaders may have some questions ready in order to give prompts if necessary. The advantage of this method is that it can be applied at any stage of the design process. The main disadvantage is that it relies on the interpretation of data. (Popovic 1999) Focus group interview needs careful handling by the moderator to get most out of it and to ensure that all opinions are represented (Butters and Dixon 1998, Barrett and Kirk 2000).

In this case study 3 a new model of garden pruners (pruners, pruning shears, secateurs) was to be designed and ergonomics and usability were to be integrated into the design process. Integration of ergonomics and usability was based on hand tool evaluation and comparison. Prototype pruners were compared with pruners already in the market.

The aims of this case study were:

- to integrate ergonomics and usability into the design process of a garden pruner and
- to evaluate the ergonomics and usability of prototype garden pruners by comparing them with pruners already on the market.

7.2 Material and methods

7.2.1 Study design

An anvil and by-pass prototype pruners were produced by Fiskars plc and a comprehensive group of pruners was chosen from the market representing the brands and models which are known and intended for professional and active amateur use.
The study was done in two parts in order to obtain ergonomic information on the prototypes and to ensure that the final product fulfils the set criteria (Figure 12).

Between the first and second part of the study the by-pass Prototype 1 was chosen for further development as this type of pruner is used more often than the anvil-type. The anvil prototype was left to be developed later.

In the first part of the study the pruners were evaluated with a focus group interview, EMG measurements, rating of hand tool characteristics and mapping of LMD. Also force measurements were done, but the results are reported in an other connection.

In the second part of the study EMG and LMD were used. In this part of the study one of the pruners was the model developed from the by-pass type prototype (from here on called Prototype 2) and five were chosen according to the results of the first part of the study, and another three new ones were also included. It was possible to use five pairs of each tool except for the prototype of which there was only one by-pass type pair.

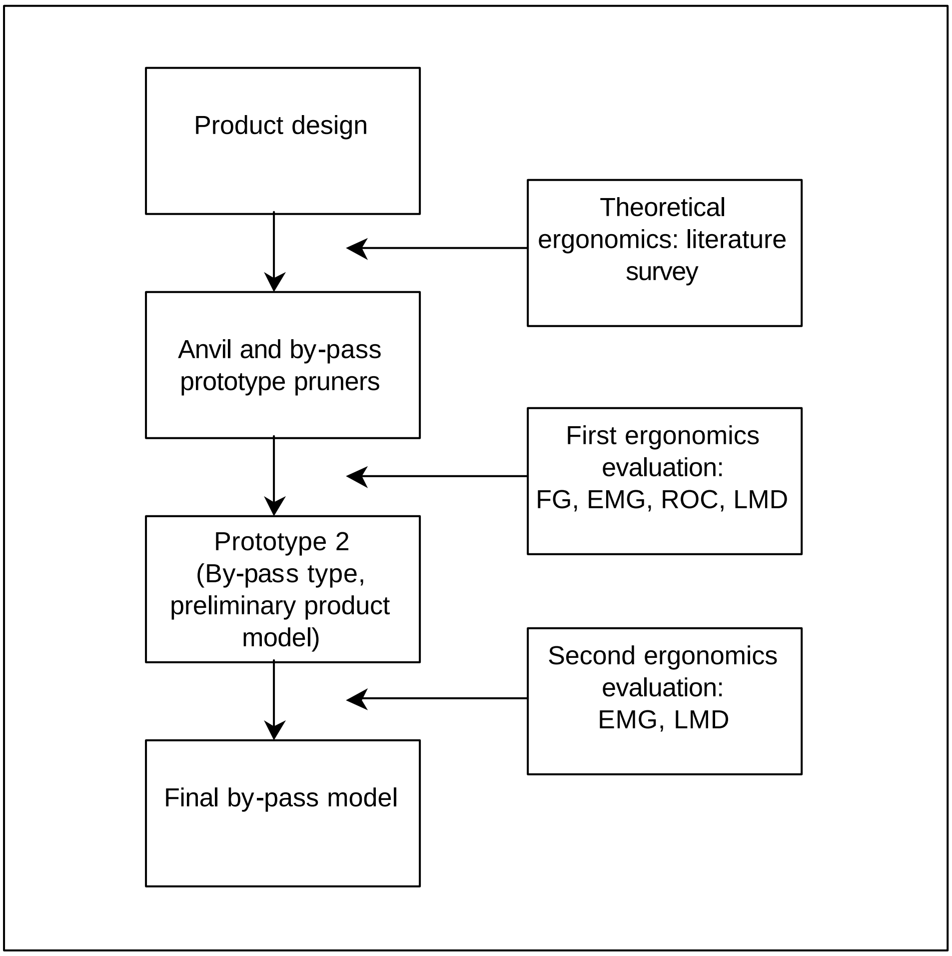

Figure 12. Integration of ergonomics into the design process.
FG =focus group interview, EMG = electromyography, ROC = rating of hand tool characteristics, LMD = mapping of localised muscular discomfort.

7.2.2 Subjects

In the focus group interview there were six participants (two females and four males). Two of the participating gardeners were working in executive positions, two as teachers in a polytechnic and two were active leisuretime gardeners. The aim was to have a heterogeneous group consisting of both professionals and amateurs.

Six (3 males and 3 females) gardeners volunteered to participate in the first part EMG measurements (Table 8). Two of them were professional and four active leisure time gardeners. They all signed an informed consent document and none had musculosceletal disorders or health problems, which could affect the measurements. All subjects were right handed. The subjects in any part of the study did not know that among the tested pruners there were prototype pruners as well and they were informed that the aim of the study was to compare different pruners. Subjects were not paid except for travelling expenses.

Table 8. The mean age, height and weight of the subjects in the first part of the study (range in parentheses).

Gender	Age (years)	Height (cm)	Weight (kg)
Female (n=3)	27 (24-33)	167 (164-172)	68 (60-80)
Male (n=3)	45 (33-59)	177 (175-180)	84 (77-93)

Eleven subjects (5 males and 6 females) participated in the second part of the study. They were all right handed and leisure time gardeners (Table 9).

Table 9. The mean age, height and weight of the subjects in the second part of the study (range in parenthesis).

Gender	Age (years)	Height (cm)	Weight (kg)
Female (n=6)	27 (22-32)	166 (158-175)	60 (50-69)
Male (n=5)	29 (28-35)	184 (174-195)	88 (65-110)

7.2.3 Pruners

The number of pruners varied in different parts of the study from 28 pairs in the focus group interview to eleven pairs in the second part of the EMG studies. In the first part of the study, both anvil and by-pass Prototype 1 pruners were tested (Table 10). The pruners for the EMG studies were chosen among the best pruners in the force measurements (not reported here) and according to the opinions expressed in the focus group interview.

In the second part of the study, all pruners were professional models (Table 10). Between the first and the second part the by-pass Prototype 1 was developed into a preliminary product model called Prototype 2. A special feature in the by-pass Prototype 1 and Prototype 2 was that their lower handle rotates as the handles are pressed together, thus allowing the handles to move parallel to each other instead of the traditional way in which the handles are fixed to each other at one point.

All pruners were sharpened and oiled before measurements and freshly cut alder wood was used. In the first part of the study the wood diameter was 11-13 mm and in the second part 12-15 mm.

Table 10. The evaluated pruners in the first and second part of the study.

Model	Blade type	First part		Second part
		FG*	EMG* ROC* LMD*	EMG* LMD*
Bando BD 334-1	by-pass	X	X	X
Bando BD 2013	anvil	X		
Felco 7	by-pass	X	X	X
Felco 11	by-pass	X	X	X
Felco 30	anvil	X	X	
Fiskars anvil prototype	anvil	X	X	
Fiskars by-pass Prototype 1	by-pass	X	X	
Fiskars by-pass Prototype 2	by-pass			X
Fiskars Classic, white	by-pass	X	X	
Fiskars Classic, grey	by-pass	X		
Fiskars Classic, white	anvil	X	X	
Fiskars Clippers 9613	anvil	X	X	
Fiskars Clippers 9614	by-pass	X		X
Fiskars 7923	by-pass	X		
Fiskars 7927	by-pass	X		
Fiskars 210243	by-pass			X
Freund 2000	by-pass	X		X
Freund 2020	by-pass	X	X	
Gardena 343	by-pass	X		X
Gardena 601	by-pass	X	X	
Gardena 603	by-pass	X		
Sandvik P2-20	by-pass	X	X	X
Sandvik P38-20	anvil	X		
Sandvik P126-22	by-pass	X	X	X
Wolf RR19	by-pass	X		
Wolf RS19	anvil	X		
Wolf RR26	by-pass			X
non-brand pruners	by-pass	X		
non-brand pruners	by-pass	X		
non-brand pruners	anvil	X		
non-brand pruners	anvil	X		

*FG = focus group interview
EMG = electromyography
ROC = rating of hand tool characteristics
LMD = mapping of localised muscular discomfort

7.2.4 Electromyography

The EMG data was collected with a portable Mega Electronics ME3000P device (Kuopio, Finland). Two sets of bipolar Ag-AgCl surface electrodes (Medicotest M-OO-S) were used. The EMG was recorded on average mode with the averaging period of 0.1 s and the sampling frequency of 1000 Hz. The data was stored on an external 1 MB memory card and transferred to a PC for later analysis with Mega Electronics ME3000P software.

The electrodes were applied to the right arm over the flexor (m. flexor digitorum superficialis) and extensor (m. extensor digitorum) muscles according to recommendations of Zipp (1982). Each pair of the electrodes was placed over the centre of the belly of the muscle, parallel to the muscle fibres. The muscles were selected based on function and accessibility.

The MVC of both flexor and extensor muscles was recorded before the pruner tests. The MVC of the m. flexor digitorum superficialis was measured by Jamar Hand Dynamometer. The maximal EMG response for the m. extensor digitorum was measured as the subject sat in front of a table. The subjects' arm was on a 90° angle on the side of the body with the lower arm at the table. Then the subject was asked to raise her or his hand as the researcher opposed the movement (Staubesand 1989). The subjects had three attempts, lasting for 2-3 seconds and the highest recorded value (μV) was used in analysis. Jonsson (1994) recommended that the test contraction should last less than 5 seconds.

Each subject performed three sets of fifteen cuts with each pruner. The pruners were given to the subjects in random order. A set of fifteen cuts was completed with all pruners before the second and third rounds. Between each set of fifteen cuts was a rest period of at least one minute, and between each of the three test periods there was a rest period of approximately 30 minutes. The EMG measurements were designed so that no former experience of the work was needed. It is thought possible that professional experience strengthens arm muscles, improves dexterity and manual skill (Kilbom et al 1993a).

7.2.5 Focus group interview, rating of hand tool characteristics and local muscular discomfort

The study process was begun with a focus group interview in which six subjects' opinions and experience of the ergonomics and usability of pruners were collected. During the interview the participants were supplied with the pruners and had an opportunity to test them. A selection of 28 pairs of pruners were provided for each pair of participants. The atmosphere of the situation was easy and informal and the interview was videotaped for later analysis.

After completing the EMG measurements in the first part of the study, the subjects were asked to evaluate the following properties of the pruners: shape of the handles, material of the handles, cutting efficiency (blades), appearance, reliability and general usability. A five-point scale (5= good, pleasant, 1=poor, unpleasant) was used for the rating and the subjects were also encouraged to express their other opinions.

During the EMG measurements a mapping of LMD was used to evaluate the body areas where discomfort was experienced. Body maps of the arm and hand region were provided. The subjects were asked to mark the areas of discomfort on the maps after having completed fifteen cuts with each pruner. This was repeated in all three sets of cuts with each pruner.

7.2.6 Statistical methods

In this study descriptive statistical methods such as average was used. A Kruskal-Wallis test was used as the data was not normally distributed. A Kruskal-Wallis test is also called a *H*-test. The Kruskal-Wallis test suitable for the comparison of several samples. (Miller and Freund 1985, Milton and Arnold 1990, Ranta et al 1997)

7.3 Results

7.3.1 Muscle strains during cutting task

The average muscle strain according to % of MVC was lower when cutting with anvil-type pruners than cutting with by-pass pruners (Figure 13). The % of MVC levels when cutting with the by-pass Prototype 1 were the lowest for the by-pass pruners in the first part. In the first part the % of MVC levels, when cutting with the anvil prototype, were the second-lowest compared with other anvil-type pruners.

The average % of MVC levels with anvil-type pruners were 17% of MVC (SD 2) for the flexor muscles (m. flexor digitorum) and 11% of MVC (SD 1) for the extensor muscles (m. extensor digitorum superficialis), while with the by-pass pruners the level was 19% of MVC (SD 2) and 13% of MVC (SD 2), respectively.

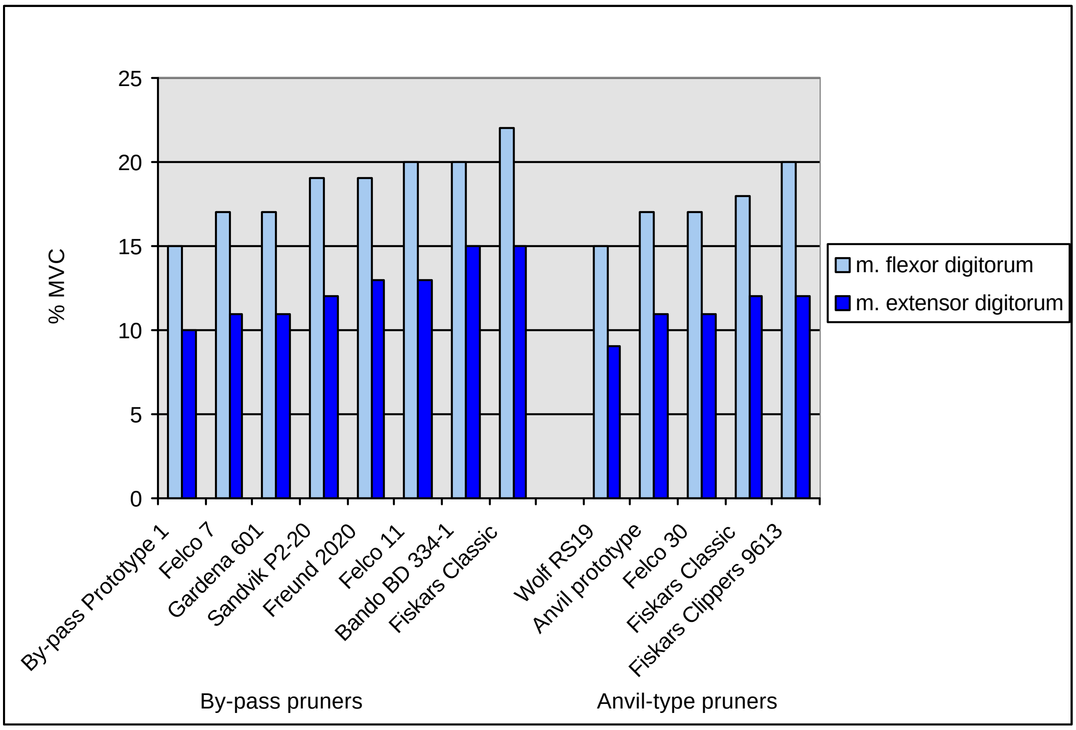

Figure 13. The mean % of MVC levels in the first part of the study when cutting fresh 11-13 mm diameter wood (n=6).

In the second part of the study the % of MVC levels of flexor muscle were in average 16% of MVC (SD 1) and that of the extensor muscle 18% of MVC (SD 2), respectively (Figure 14).

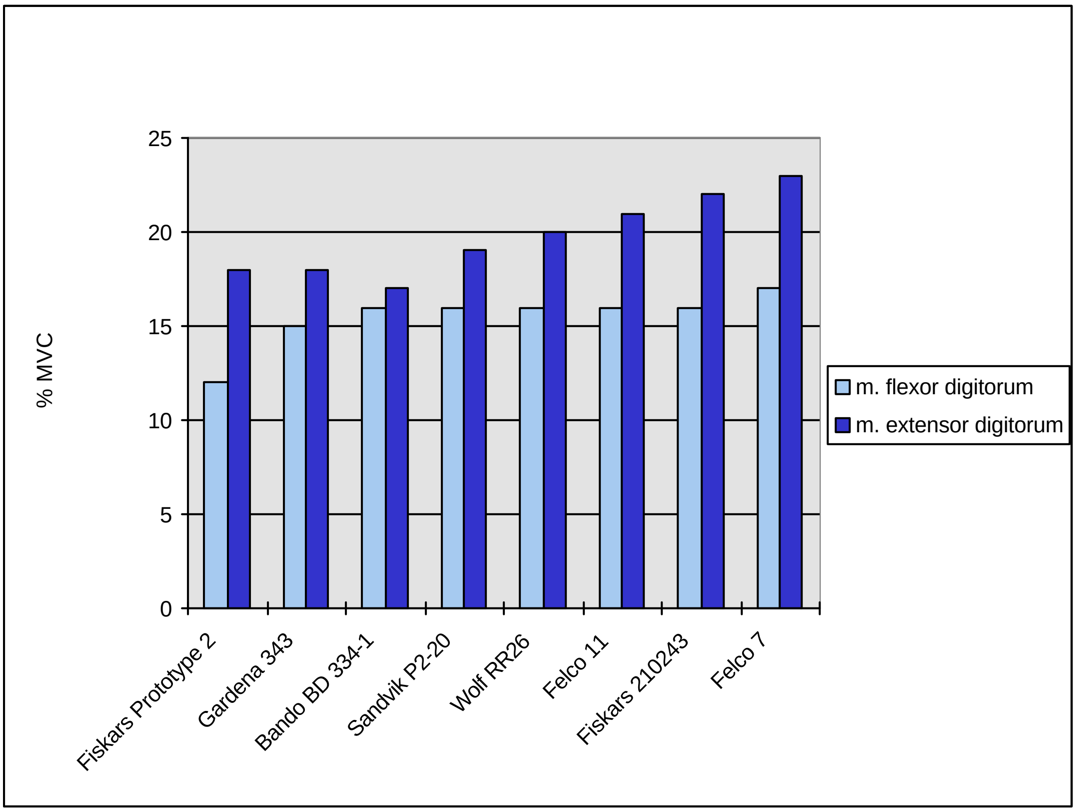

Figure 14. The mean % of MVC levels in the second part of the study when cutting fresh 12-15 mm diameter wood (n=11).

The mean % of MVC of the flexor muscle was the lowest in both parts of the study when working with the by-pass Prototype 1 and Prototype 2. The average % of MVC of the extensor was the second-lowest of the by-pass pruners. The results are also presented for how the prototypes compared with the other evaluated tools (Table 11). A statistical analysis with Kruskal-Wallis test was performed for the EMG results. No statistically significant differences between pruners were found.

Table 11. The average values of the % of MVC in the first and second part (n=6 in the first part and n=11 in the second part).

	Type of pruner	% of MVC	
		m. flexor digitorum	m. extensor digitorum
Part one	*By-pass Prototype 1*	15	10
	By-pass, other (range)	17-22	11-15
	Anvil prototype	17	11
	Anvil, other (range)	15-20	9-12
Part two	*By-pass Prototype 2*	12	18
	By-pass, other (range)	15-17	17-23

7.3.2 Results of the focus group interview

The following main arguments arose from the focus group interview:

1. The handle material should be durable and warm and the friction should support use in different environments. Thus, handles should not be slippery or too rubbery.
2. The shape of the handles should fit the hand, handles and the blade opening angle should not be too wide, but the blade opening angle should be sufficiently wide.
3. The handles should not have sharp edges or abrading texts or logos. The locking mechanism should be located so that it is reliable, easy to use and can be used by one hand.
4. The blades should be sharp and not too flexible sideways and they should have rounded points as sharp points can harm the plants and as the pruners are often carried in the pocket.
5. The importance of easy maintainability was emphasised.
6. Other comments that came up were the type of the coil spring used, shock absorption characteristics, the possibility to use a wrist wrap if needed, maintainability, availability of spare parts, a colour which contrasts with the environment and is pleasant and soft feeling when working with the tool.

7.3.3 Rating of hand tool characteristics

After completing the EMG measurement in the first part of the study, the subjects were asked to rate several pruner characteristics on a five-point scale. Twelve of the pruners got 18-20 points and only one type 14 points, thus indicating no big differences regarding the preferability of the pruners.

7.3.4 The areas of local muscular discomfort

The areas of local muscular discomfort were located on the palmar side of the hand, localising in the palmar side of fingers, the thenar and the area between thumb and index finger. None of the subjects reported discomfort in the arm. Three of the tools caused a feeling of stretching on the palmar side of the hand in some subjects. With two pairs of pruners no discomfort was reported - these models were the by-pass Prototype 1 and Felco 7.

In the second part of the study, working with the Bando BD334-1 pruner caused the most claims of discomfort. The most comfortable pruner was the Fiskars 210243. Discomfort in the thenar region was reported for all pruners, except for the by-pass Prototype 2, which has a rotating handle.

7.4 Discussion

7.4.1 Methodological aspects

The study was done in laboratory conditions so further studies are needed to be able to generalise the results for the real working situation. On the other hand, the aim was to compare different pruners and to find factors affecting their usability. By doing the measurements in laboratory conditions, the test situation could more easily be controlled and kept constant for each subject.

The focus group method was used to collect data on user opinions regarding the garden pruners. This data was used to design the list of items for the rating of hand tool characteristics. In focus group meetings there is the possibility that not all opinions get to be expressed or the terms used are misunderstood or used to define different phenomena. Special care was taken to create an easy atmosphere in which it would be easy to express ones' opinions and to ensure equal opportunities for all participants to express themselves. Also the terms were defined to the participants and when necessary clarifying questions were asked.

The repeatability of EMG measurements can be considered sufficient as many of the factors influencing the results can be controlled. The EMG measurements were influenced by the study protocol, the subjects and their number, the measurement device and the researcher. The study protocol was designed so that the measurement of muscle strain was done on the same day for one subject. Thus, the setting of the electrodes was the same for each pair of pruners. Also the same type of electrodes was used for each subject. The placement of the electrodes was done carefully by palpating the muscles and following the recommendations of Zipp (1982). With this procedure the possibility for systematic and random errors was minimised.

The subjects were professional and amateur gardeners. Some of the amateur gardeners were not very used to using pruners. By describing the procedure carefully to the subjects, an effort was made to ensure that all subjects used the pruners correctly and in the same manner. It is likely that the subjects' skill in performing the task was improved during the measurements.

The subjects' anthropometry affected the EMG results as some of the subjects experienced difficulties when operating some of the pruners. Also the way in which subjects cut the wood could have influenced the results. Every measurement session was begun by carefully explaining the study protocol to the subjects. The subjects' were also provided with a written specification of the measurement protocol and after reading it were asked to confirm voluntary participation by signing the document. Despite the instructions to cut the wood in a relaxed and normal way, some subjects were enthusiastic and did the cutting rapidly, and thus the standard deviations of the results increased (Appendix 2 and 3). During the measurements the pruners were given to the subjects in random order.

It must be noted that all subjects were right handed and some of the pruners were designed only for right-hand use including the prototypes. Thus, the results would have been different if left-handed users had taken part in the study.

The EMG results are affected by muscle fatigue (Jonsson 1994). This was minimised by designing the study protocol so that there was sufficient time for recovery. The significance of sufficient breaks was emphasised and the subjects were told that they could rest as long as they liked but at the minimum 1-2 minutes between every set of 15 cuts. Between the three sets of trials there was a break of half an hour. The fatigue level was inspected by analysing the changes in the % of MVC between the three sets of trials. The EMG amplitude increases and the frequency decreases as the muscles become fatigued (Jonsson 1994). The highest average change (1% of the MVC) was discovered in the first and second set of cuts in the first part measurements.

A compromise to use freshly cut wood was made, despite the fact that it was more likely to create inaccuracies in the results than the use of dried wood. The use of freshly cut wood is more in line with the real working situation. It was attempted to minimise the inaccuracies by collecting all wood from the same location and by storing it outside as short a time as possible.

The number of cuts was defined as three times 15 with each pruner. By increasing the number of the cuts, the accuracy of the results could be improved, but on the other hand this could result in increasing the subjects' fatigue and decreasing motivation. The results are also affected by the accuracy of the MVC measurements. The accuracy of the results would be improved if the measurement of MVC could be done in a similar setting as the recording of EMG. MVC can be regarded as an acceptable normalization method (Aarås et al 1996, 1997).

The mapping of LMD was done by providing pictures of hand and arm to the subjects (van der Grinten 1991). The method was carefully explained to the subjects and after every set of fifteen cuts they were asked if they had perceived discomfort in any part of the body, especially in the upper extremity, and were encouraged to mark the areas in the maps. The method yielded some responses. As the occurrence of discomfort is not located in an exact area, the results give an indication as to where discomfort was sensed. As the cutting time was short, it is possible that the results underestimate the discomfort compared with a real gardening situation.

The ROC was used to evaluate the pruner characteristics. The rating form was explained to the subjects before EMG measurements. The form was present for them during the EMG measurements and the subjects had the possibility to look at the questions after they had finished the set of fifteen cuts. They had the possibility to make comments on the form even before all three sets of cutting with each pruner were finished. The final rating was done after the three sets of cuts. Through this protocol the subjects had an opportunity to become familiar with all the tools. A five-point scale was used. Only minor differences in the final results were observed. This could indicate the wrong choice of questions or misunderstanding in the terms. As the questions and the terms were explained, it is more likely that small differences are due to the difficulties in finding differences between quite similar products during the relatively short period of trial.

7.4.2 Discussion of ergonomics and usability of garden pruners during design process

The structure of this study follows the main principles of usability testing that Kahmann and Henze (1999) have proposed and was carried out as a comparison which Butters and Etchell (1997) proposed as one possible approach for usability testing. Hall (1999) demonstrated that using mockups with a small (n=6-10) number of subjects early in the design process can be used to easily gather useful design information which can be used as a sound basis for redesign. Also Green and Klein (1999) showed that a user trial can be used for quick scanning and evaluation of possible solutions. The evaluation of hand tools is an interdisciplinary task and several methods should be applied in the evaluation process (Kadefors et al 1993a, Butters and Dixon 1998).

The first aim of the study was to integrate ergonomics and usability in the design process of a garden pruner in order to ensure that these characteristics are as good as possible in the end product. The second aim was to evaluate the ergonomics and usability of prototype garden pruners by comparing them with pruners already on the market. With the aid of versatile ergonomics evaluation it was possible to compare different products and prototypes. In this kind of development process the use of several methods ensures that different aspects of the developed tool are observed. With the focus group method it was possible to create the basis for the experiment by collecting users' opinions on the developed tool. It is very valuable knowledge, which should be utilized as much as possible in the design process. By the EMG method it was possible to evaluate the physiological demands on users. The final value of the rating of hand tool characteristics in this study remained low. It may be due to the questions used or the difficultness for people to evaluate separate design factors. In some cases trained subjects could be used in usability assessments because untrained users find consistent assessment difficult (Butters and Dixon 1998).

The evaluation of results of the EMG measurements is based on the % of MVC. A high % of MVC indicates high muscle strain. In both parts of the study the muscle strain can be regarded high during working with garden pruners. According to the recommendations (Jonsson 1982, 1994, Kilbom et al 1993b, Sperling et al 1993a, Byström and Fransson-Hall 1994, Malchaire et al 1997), muscle strain when working with hand tools should in long-term tasks be lower than 17% of MVC and preferably lower than 10% of MVC. The muscle strain of the arm flexor and extensor muscles exceed 10% of the MVC and in many cases were close to the highest acceptable limit of 17% of MVC.

In the first part of the study, average flexor strain with by-pass pruners was 15-22% of MVC and with the anvil pruners 15-20% of MVC. The extensor strain when working with by-pass pruners was 10-15% of MVC and with anvil pruners 9-12% of MVC. In the second part of the study, when working with the by-pass pruners, the arm flexor strain level was 12-17% of MVC and the extensor strain level 17-23% of MVC. Hägg et al (1997) reported that the gripping work can be more fatiguing to extensors than the flexors. This could explain the higher extensor strain in the second part as thicker wood was used and thus, fingers had to be more extended during the cutting. It is possible that if goniometric measurements were used in addition to the other evaluations, more information could have been gathered.

In the second part some female subjects experienced difficulties in cutting with some pruners and were not able to complete the test series (see Appendix 3). The results are presented only for those pruners by which at least eight of the eleven subjects were able to complete the test protocol. The test protocol was considered incomplete if the subject failed to do at least twelve cuttings and this was repeated at least in two sets of fifteen cuts. Thus, the pruners Fiskars Clippers 9614, Freund 2000 and Sandvik P126-22 were excluded from the final results. According to the pruner manufacturers, these kinds of tools are meant for cutting approximately 20 mm wood. In the tests fresh wood with the diameter of 12-15 mm was used. In the test situation it was observed that in some tools the blades' opening angle was so small that the cutting had to be done with the tips of the blades and was thus being more demanding for the users. Also in some pruners the handles' opening angle was so large that when the wood was between the blades, the handles were so widely apart that cutting with one hand became impossible.

Wakula and Landau (2001) have compared the stress-strain situation of pruning grapevines in vineyards while using different pruners. In field conditions no differences were observed in the total strain caused by the various types of non-powered pruners. In the present study the evaluations were made in the laboratory, which creates an artificial situation, but every effort was made to maximise realism.

It can be assumed that in long-term work with high local strain the probability of cumulative trauma disorders could increase (Radwin et al 1987, Silverstein et al 1986, 1987, Hagberg et al 1992, Bishu et al 1993, Loslever and Ranaivosoa 1993, Marras and Schoenmarklin 1993, Roman-Liu et al 1996, Malchaire et al 1997). The diameter of wood varied from 10-13 mm in the first part to 12-15 mm in the second part. Most of the pruner manufacturers claim that the pruners are recommendable for a wood diameter of 15-20 mm. Cutting of 15 mm diameter wood was very difficult, and in some cases even impossible for some female subjects. According to the results, it can be recommended that pruners should be used only for relatively light cutting work and that loppers or pruning saws should be used for more demanding work. The manufacturers should provide working instructions in which this has been noted. At present the instructions seem to give too positive an image.

The EMG results describe the strain of arm m. flexor digitorum and m. extensor digitorum superficialis in the laboratory situation. In a real work setting the arm and body postures vary, and thus further measurements should be done to define the work load in real work.

The level of statistically significant differences was low. This may be due to the rather small sample size or the number of repetitions. However it can be assumed that the practical differences in the physical strain of the pruners are relevant for the users in the long run. As the strain was high in relation to the recommendations, it can be assumed that even minor differences in % of MVC are important for the users.

8 Case study 4 - The effects of different hand tool blade coatings on force demands

8.1 Introduction

Application of an existing technical solution in consumer product design can be a way to improve the ergonomics and usability. A technical solution for the improvement of hand tools can for example be the use of different materials such as polytetrafluoroethylene for coating of wood cutting blades. In case of garden loppers and axes the cut material is of natural origin, typically different types of wood.

Wood has a typical unhomogeneous and fibrous structure which depends on the wood type. Its mechanical and shear properties depend on the force applied and the cutting direction with reference to the direction of wood fibres. An actual physical model of the cutting process is extremely complicated. (Hlebanja 1990, Beer et al 1999)

It has been reported that the force needed to cut wood corresponds linearly to the density of the wood type. The effects of wood humidity on cutting force are more complicated. For example, when working on birch wood the maximum cutting force is needed when the wood humidity is 10%. The force decreases as the humidity decreases to 0% or increases to 50%. (Kuusisto 1987)

During the construction of a tribological system the tribological strain and interactions between the materials should be recognized. The basic surface, the facing surface, the intermediate substances and the environment are included in the structure of a tribotechnical system. The physical, chemical and other technical properties define the real nature of the tribological incident as well as the friction and the nature of wear. (Kivioja et al 1998)

Some antiabrasive coatings like TiN, (Ti, Zr)N and ZrN in contact with metals decrease the friction coefficient, but increase its value when put in contact with wood.

This may be explained in terms of the specific physical and chemical structure of wood (Beer et al 1999).

Polytetrafluoroethylene (PTFE) is characterized by one of the lowest friction coefficient values of all known materials, including thermoplastic polymers (Ziemanski et al 1993). PTFE coatings reduce build-up on cutting tools, especially where moisture content may be elevated or the material has plant resins present in large quantities (Effner 1998).

PTFE differs from other plastics as the shear strain strength of its surface (4 N/mm^2) is considerably lower than the shear strain strength of the interior parts (20 N/mm^2). Also the humidification angle of PTFE is very large, 126°, as on other plastics (e.g. Perspex and Nylon) it is almost 0°. Large humidification angle indicates that the surface energy does not decrease when it is covered with water, meaning that the adhesion energy of water and PTFE is low. Due to this the friction coefficient is very low with most materials. As temperature rises, the friction coefficient stays low as far as the softening point (~320°C). In temperatures lower than 0°C the friction coefficient slightly rises. (Kivioja et al 1998)

Wood corresponds to composite materials in its' structure. The transformation in the shape of wood is strongly reminiscent of viscoelastic behaviour of plastics. The friction coefficient depends somewhat on the normal force and the geometry. Wood usually includes water, and if the proportion of water is under 40%, wood is considered dry and if it is over 60% wood is considered wet. The friction coefficient between wood and steel is approximately 0.5, and with wood against PTFE the value is 0.1. For dry wood the friction coefficient is higher as in friction water functions as a lubricant. (Kivioja et al 1998, Beer 1999) In comparison, the friction coefficient of high-speed tool steel (HSS) with oak wood is 0.68, with beech 0.70 and with poplar 0.60. The friction coefficient with titanium nitride-coated steel is 0.91 for oak, 0.79 for beech and 0.87 for poplar (Beer et al 1999). By optimising the blade characteristics the force demands can be lowered and thus the ergonomics and usability of the tool can be improved.

In this case study 4 the effects on force demands when cutting using differently coated hand tool blades were studied. The force demands in cutting wood with chromium-coated steel, lacquered steel and PTFE-coated hand tool blades were measured with a materials testing system (MTS). One type of lopper blade with two different coatings and three types of axe blades with two different coatings were compared.

The aim of this case study was:

- to measure the force demands when cutting wood with a chromium-coated, lacquered and PTFE-coated hand tool blades.

8.2 Materials and methods

8.2.1 Lopper blades

The force required to cut wood with different lopper blades and axe blades was measured with Instron MTS 810 and Instron 8810 material testing systems, respectively. Both were applied with a force cell. The lopper and axe blades were pressed down on wood with a constant velocity of 50 mm/s. During the lopper blade measurements the data was collected with the rate of 200 Hz and during the axe blade measurements with the rate of 100 Hz. The measurement distance, i.e. the depth of the cut, defined the number of collected data points.

In the case of the loppers there were six similar blades, three of which had a chromium-coated surface and three a PTFE-coated surface (Figure 15). A Cr-Mo-V-steel is used as the basic material for the blades. The blades were new and in the same condition as they are supplied in the final tools. All blades were from the same manufacturer. With the lopper blades, six measurements with each blade were made, totalling 18 measurements with both chromium-coated and PTFE-coated blade types.

Figure 15. The chromium-coated steel (upper) and PTFE-coated (lower) lopper blade. Excluding the coating material, the blades are identical.

8.2.2 Axe blades

Three different axe blades, two of each with the same shape but with different coatings, were also compared (Figure 16). Three of the blades were PTFE-coated and the others were lacquered. The blades are made of C-55 steel. Pigment particles are added to the PTFE. For the lacquer coating, acrylic powder lacquer is used with electrostatic spraying and a heating process.

The axe blades were in the condition in which they are supplied to the end users in the final tools. All axe blades were from the same manufacturer. With the axe blades eight measurements were done with each blade. To minimize the effects of quality differences of natural wood, the measurements were organized so that during each cutting wood from the same tree was used for all axe blades.

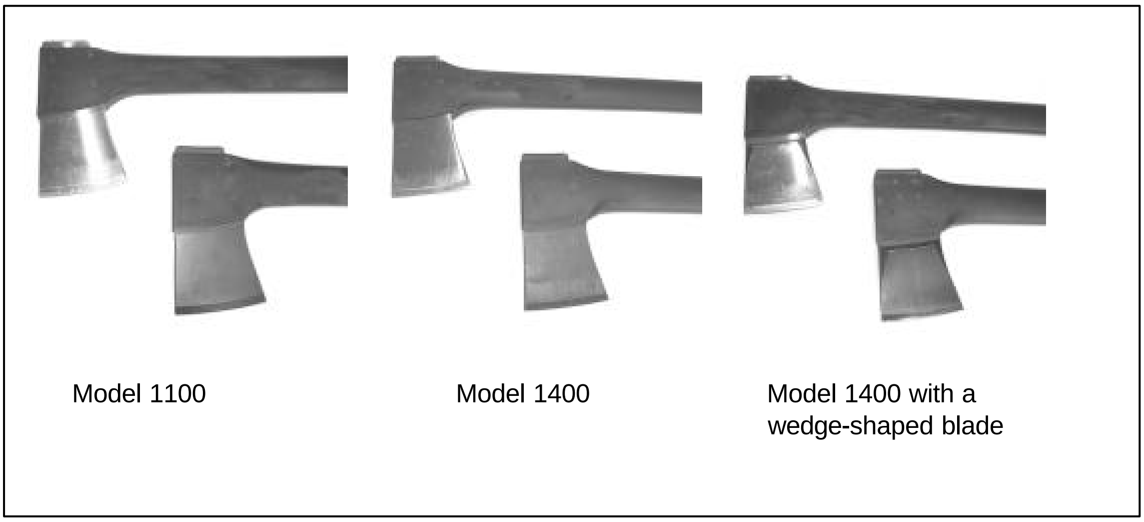

Figure 16. The different models of axe blades. The lacquered steel blade of each model is presented on top and PTFE-coated blade of each model underneath.

With the lopper blades 21 mm x 26 mm fresh alder (Alnus) wood was cut (Figure 17). The size of the wood was maximised according to the size of the blades. With the axe blades 51 mm x 102 mm (2” x 4”) spruce (Picea abies) wood was cut (Figure 17). The wood had been cut to 120 mm long pieces to enable easier handling. In both cases the cuttings were done transverse to the fibres of the wood as otherwise the wood would have split.

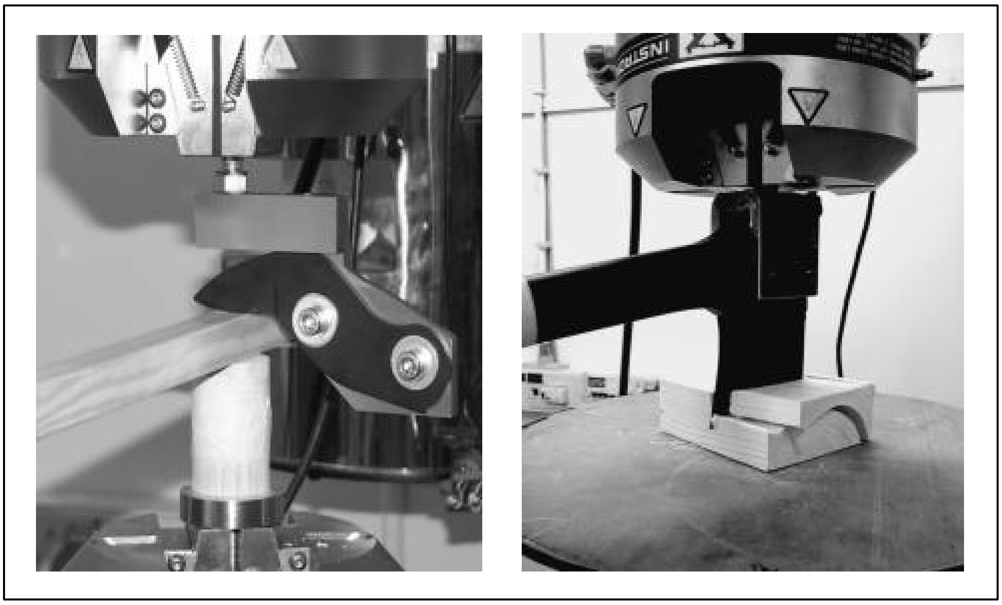

Figure 17. The testing system for the lopper blades (left) and the axe blades (right) with the materials testing system. Specially designed holders for the blades can also be seen.

8.2.3 Statistical methods

In this study descriptive statistical methods such as average were used. The Kruskal-Wallis and Mann-Whitney tests were used as the data was not normally distributed. A Mann-Whitney test is also called a *U*-test. The Kruskal-Wallis test is suitable for the comparison of several samples. The Mann-Whitney test is suitable for the comparison of two samples. It is one of the most efficient tests and does not depend on the distribution of the data. (Miller and Freund 1985, Milton and Arnold 1990, Ranta et al 1997)

8.3 Results

8.3.1 The force demands of lopper blades

The results were analysed as the average force (kN) needed for the cutting and as the maximum values obtained during the measurements (Table 12, Figure 18).

Table 12. The average and maximum force results for the lopper blades (kN) (n=6).

Blade no.	Chromium-coated steel blade (kN)		PTFE-coated blade (kN)	
	average	maximum	average	maximum
1	2.3	3.2	1.7	2.3
2	1.9	2.6	1.4	1.9
3	2.3	3.3	1.9	2.5
Average (n=18)	2.2	3.0	1.7	2.2

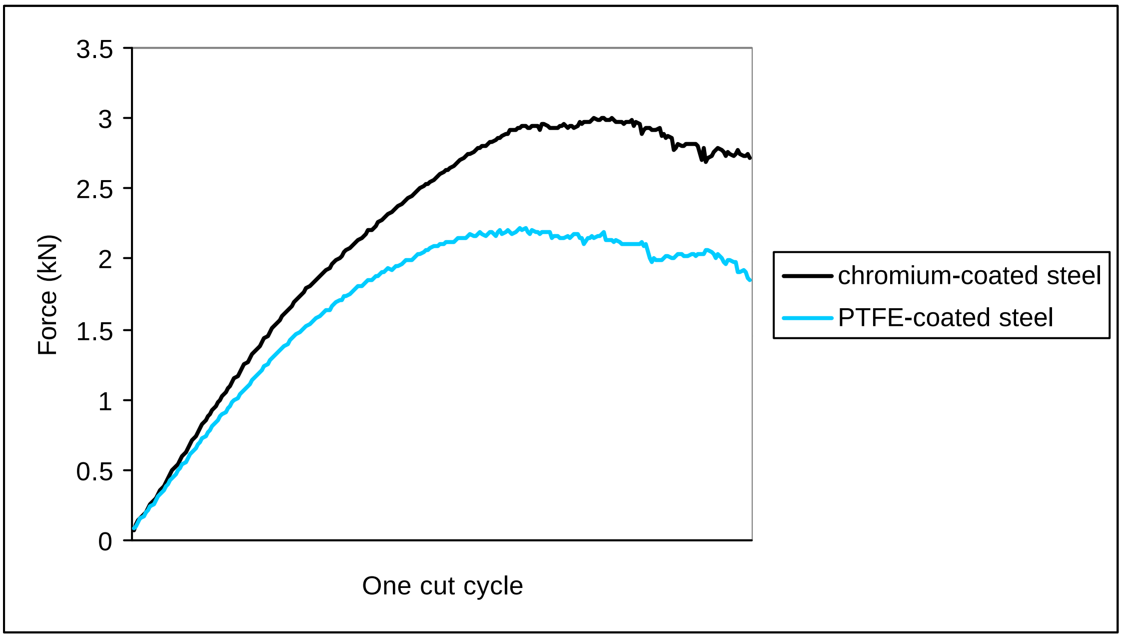

Figure 18. The average force demand curves for chromium-coated steel and PTFE-coated lopper blades (kN). One cut cycle stands for one measurement and is used instead of measuring point (n»250) to clarify the phenomena.

The PTFE-coated blade resulted in 22% lower average force and 26% lower maximum force than the steel-surfaced blades. The difference between the force demands of PTFE-coated and chromium-coated steel blades was significant ($p<0.001$). A Mann-Whitney test was used as the data was not normally distributed.

8.3.2 The force demands of axe blades

The results were analysed as the average force (kN) needed for the cutting and as the maximum values obtained in the measurements (Table 13, Figure 19).

Table 13. Forces when pressing the axe blades into the wood (kN) (n=8).

Blade type	Average force (kN)	Maximum force (kN)
1100 lacquered	11.9	19.0
1100 PTFE	11.1	17.7
1400 lacquered	13.4	20.6
1400 PTFE	12.0	18.2
1400 lacquered, wedge-shaped	13.6	20.6
1400 PTFE, wedge-shaped	11.6	17.6

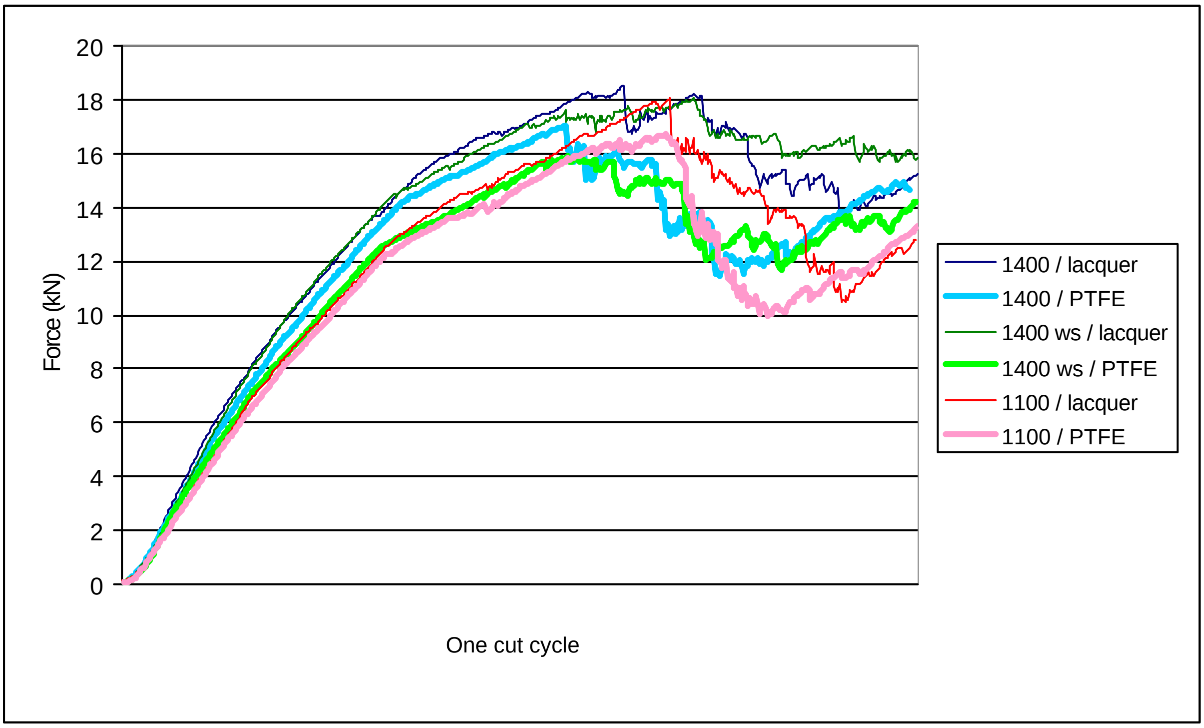

Figure 19. The average force demand curves for differently coated axe blades (ws=wedge-shaped) (kN). One cut cycle stands for one measurement and is used instead of measuring points (n»600) to clarify the phenomena.

According to the results, the PTFE coating on different axe blades seems to lower the average force demand by 10% and the maximum force by 11%. There was a significant difference ($p<0.001$) between the force demands of PTFE-coated and lacquered steel blades. A Mann-Whitney test was used to evaluate differences statistically as the data was not normally distributed.

8.4 Discussion

8.4.1 Methodological aspects

It can be argued whether or not the used method of this case study was correct for usability evaluation. The choice of the method was made on the basis of the aims. As there is a lack of a standardised method for this kind of evaluation, a new system was constructed. The materials testing system is a commonly used and accepted method e.g. for force measurements in materials science. In this test arrangement the systems capability to measure forces was used. It was presumed that if force demands in a simulated cut could be decreased with blade coating material, at least some of this effect would result in decreased force demands during the actual use of hand tools. Thus, the evaluation of ergonomics and usability was done indirectly.

The repeatability of the tests was improved by using several repetitions. Also the compared blades were of the same shape. The results correspond to the relative differences of the studied products. The results do not give the actual force demand values when instead of the studied tools a whole tool is used in a real setting.

The use of natural wood has an effect on the results as the cut material is not homogenous. The effects of this were minimised by using wood from the same trees for each blade and by having several repetitions.

The average results of the chromium-coated steel lopper blades differed significantly ($p<0.001$) from each other (blade no.2 required less force than the other two). This was also so in the case of PTFE-coated blades. This may be due to differences between the sharpness of the blades or more likely to the use of real wood as the cut material. By testing more blades or by doing more repetitions, the repeatability of the study could have been improved.

8.4.2 Discussion of effect of different hand tool blade coatings on force demands

According to the results, it seems that PTFE coating lowers the force demands if compared with chromium-coated or lacquered steel blades when wood is cut. Statistically significant differences between the force demands of PTFE-coated and chromium-coated or lacquered steel blades were found.

In the design of hand tools, especially if considering cutting hand tools, blade optimisation has an important role in the tool usability (Niemelä and Päivinen 2001). It is reasonable to assume that in this case the lower cutting force results in lower demands on the hand tool user. On the other hand, better blade efficiency may also result in higher quality of the work.

It is important to note that the force demands in this study do not represent the force demands in normal user situations. The blades were pressed into the wood transverse to the wood fibres, which represents the cutting situation with garden loppers but not with axes, which are typically used for splitting wood. This procedure was chosen due to the measurement arrangements to prevent the wood from splitting.

In the future it would be important to study how the lower force demand affects the force required of the user. It can be assumed that at least in cases with such differences in the studied products measurements by a MTS method can be used.

9 General discussion

9.1 Implementation of the present results

The short cycle of product development has resulted in product testing being dominated by time limits. This situation requires methods which combine pragmatic and scientific principles. (Kahmann and Henze 1999) By applying ergonomics principles during the design process, it is possible to lower the demands on the users and thus lower the risk of work-related disorders and improve the usability of tools. There are several ways to assess and improve usability of consumer products. Depending on the needs of the manufacturer, different approaches can be chosen. In this study four different approaches were presented.

The main theoretical and practical value of the present study is based on finding ways to support the integration of ergonomics and usability into the consumer product design process. A broad perspective on these issues through hand tool related case studies was adopted with the aim that the methods and results would be implementable in other contexts as well. In all case studies different methods were used. These case studies concentrate on non-powered hand tools and thus the cases do not cover the whole issue and care should be taken when generalising these results. The topics presented in this study should therefore be carefully evaluated if applied to the process of developing other products.

9.2 Collection of design criteria

The main theoretical and practical value of the case study 1 lies most probably in the literature survey and the collection of design criteria for hand tool development. In some consumer product related design cases it is practical to use already existing information and to modify it to fit one's own needs. If for example a design method like QFD is applied, it creates a need for thorough background information which is classified into design criteria. In the case of hand tool design, literature on the ergonomics of the tools can be found but there is a lack of a comprehensive information bank of design factors and recommended values. When this kind of data has once been collected, it can be applied to design processes of other similar types of cases with some restrictions.

To fulfil the aim of evaluating whether it is possible to find ergonomic design criteria in the literature to be used with the QFD method in the case of hand tool design, a literature survey was carried out. By means of a broad literature review, data on hand tool usability was found. The process was very time consuming and thus may not be the ideal solution for designers with great time pressures. On the other hand, once the information has been collected, it can be used in other connections with some modifications. On the basis of case study 1 it can be recommended that ergonomics and usability information should be collected and brought together in an easily implementable form for designers of different consumer products. The literature review for the design criteria showed that the data is very scattered in many references not easily obtainable for designers.

9.3 Risk analysis

Risk assessment methods are typically aimed at assessing selected systems and their components. In case study 2 risk analysis methods were used to evaluate electricians' work done in cold conditions on high masts, which is a very demanding working environment. Hand tools are an important part of this working system and risks related to them were also found to be one of the main risks in the work. With the risk assessment and a questionnaire related to it, information on the usability and ergonomics of hand tools was gained.

Case study 2 demonstrated that working in extreme conditions or even just outdoors creates special risks and requirements regarding the equipment used. In the case of hand tools the electricians used mostly basic tools which are also meant for ordinary use. It is recommended that special care should be taken when choosing equipment and tools for work done on masts and in cold weather. The people responsible for providing the equipment for the electricians should have enough information on safety and ergonomics and also the economical possibilities to choose the best possible equipment. It is recommended that if possible the workers should be able to test the equipment beforehand and take part in selecting the products. It is also recommended that there should be the possibility to choose some equipment according to one's own preferences. There is a need to study what kind of handle materials would ensure a secure grip in most weather conditions. Also, it is necessary to find ways to prevent hand tools from dropping.

9.4 Usability evaluation of garden pruners during design process

By the application of ergonomics principles to the design process it is possible to lower the demands on the users and improve the usability of the tool and thus lower the risk of work-related disorders. Implementation of ergonomics and usability in the process of designing a consumer product is important in ensuring that the end product has as high an ergonomic quality as possible. The process requires firm co-operation between the researchers and the designers.

With the aid of versatile ergonomics evaluation it was possible to compare different products and prototypes. Ergonomics can be implemented in the design process by using physiological measurements and subjective evaluations. With this kind of development process the use of several methods ensures that different aspects of the developed product are taken into account. With physiological evaluations, different products or modifications of products can be compared. On the other hand, if physiological evaluations are used as the only evaluation method data for users' preferences, images and attitudes are missed. In the future the challenge for ergonomics is to look not only at but also beyond usability. Thus, it has been emphasised that in addition to usability also the people-product relationship is affected by issues such as the look and the feel of the product (Green and Jordan 1999). It is therefore recommended that subjective evaluations should also be used together with physiological methods to ensure as complete a picture of the studied product as possible. Methods should be chosen so that they support the delicate design and development process and do not restrict designers' creativity.

With the use of subjective and objective methods, a diverse overview of different products can be gained. By using the EMG method, information on consumer products and their prototypes was gained.

On the basis of case study 3 it is possible to give some recommendations. Pruning work even in laboratory conditions seems to create high muscular strain and therefore special care should be taken when choosing the tools for pruning work, especially in occupational settings. It has been found that workers tend to choose tools with which the productivity is the highest, even if the work strain is higher (Kadefors et al 1993a, Kilbom et al 1993a).

As the muscular load and strain was high in the first and second part of the study, it is be recommended that the manufacturers should still try to design pruners which could be used with less force. On the other hand, the muscular strain can be decreased in the case of current tools as well if they are used for cutting thinner wood and other tools such as saws are used for thicker wood. It is recommended that there should be an opportunity for consumers to test hand tools before choosing to work with them, especially when selecting hand tools for long-lasting tasks.

The results of case study 3 were used in consumer product design and thus improved hand tools could be supplied to the market (Figure 20).

Figure 20. The final model of the Prototype pruner 2 (see case study 3) is presented in this stamp (lower right-hand side) published in Finland 8.10.1999 for the celebration of modern Finnish design.

9.5 PTFE as a blade coating material in cutting hand tools

Sometimes the usability of the product can be improved with the application of an already existing technical solution which is implemented in a new system. Different measurements can be used to ensure that the required effect is gained or to evaluate the direction and magnitude of the modification made. In case study 4 a materials testing system was used as an indirect method for ergonomics and usability assessment. It was found that by using a PTFE coating on cutting hand tool blades, the force demands compared with chromium-coated or lacquered blades could be reduced markedly. It is likely that as the change in the force demand was significant, also some of this positive effect is translated through the final product to the users, thus improving the usability characteristics of certain consumer products. It is also reasonable to assume that the safety, quality, productivity and comfort of the work are also improved due to the decreased force demand. It is possible that reduced force demands could also have a positive effect in prevention of musculosceletal disorders, at least in long-lasting work tasks.

The results of case study 4 demonstrated that it is possible to improve one critical part of a cutting hand tool by choosing a blade coating with less friction. With such carefully directed modifications it might be possible to improve other hand tools as well.

9.6 Future needs in research

Hand tools are used in very heterogeneous conditions. There is a need to find handle materials which are also suitable for use in cold, wet and icy conditions. There is also a need to find ways with which falling of hand tools is prevented in work in high places.

It was found that simulated pruning work in laboratory conditions creates high muscular strain. It would be important to study the strain in real working tasks and according to the results give recommendations on the safe use of pruners and their selection. It would also be necessary to study the effects of hand size and the opening angle of the pruner handles for the workload.

PTFE was found to decrease force demands in simulated wood cutting tasks compared with chromium-coated or lacquered hand tool blades. In the future it would be important to study how different coatings affect the usability during the real use of the hand tools and how fast PTFE coating wears off these kinds of products.

10 General conclusions

In the future it is likely that ergonomics and usability will come to play a more important role in competition in the market as just delivering functional and well-performing devices does not ensure competitive success. To use this trend successfully, it is important that designers as well as manufacturers, marketing and consumers have sufficient information on ergonomics and usability issues.

If user-centred design is to be successfully performed, ergonomics and usability data should be easily available for the designers. The data should be presented in a way that the information is easily modified to be used by itself or with different design methods.

The case studies in the present study represent four different ways to support the design of consumer products in the area of ergonomics and usability. Case studies 1 and 2 were mainly aimed at the early steps of the design process and the other two at the later parts of the design process. According to the main aims introduced in the chapter “Objectives of the study”, the following conclusions can be drawn:

1. Ergonomic design criteria for pliers-like hand tools was found and collected in the literature. The data is presented as a detailed list and classified to be used as supportive material for hand tool design for example in conjunction with the QFD method. Garden pruners were used as an example tool. The procedure made it possible to gain considerable insight into the subject but was time consuming.

2. It was possible to investigate the ergonomics and usability of hand tools using a questionnaire and a risk analysis. The falling of hand tools and other equipment was ranked as the main risk when electricians were working on telecommunications and electricity transmission masts in cold conditions.

3. Physiological and subjective methods were used to assess the usability and ergonomics of garden pruners during the design process of a new tool. By performing the measurements in two parts and comparing different tools and prototypes, it was possible to integrate ergonomics and usability issues into the design process.

4. The force demands while performing simulated cutting with differently coated hand tool blades were compared. PTFE-coated blades were found to create the lowest force demands compared with chromium-coated and lacquered blades.

Various approaches can be used to integrate ergonomics and usability into a user-centred design process. The approach is dependent on the needs of the designer and the product designed. The integration can be done in diverse phases of the design process.

The main benefits from these different approaches are that they provide information which can be applied in different settings in further design cases as well as direct results applicable to a current product design. As a result of the present research more ergonomic and usable consumer products were supplied to the market.

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APPENDIX 1

The questionnaire for the evaluation of telecommunications electricians use of hand tools

1. How often do You use the following hand tools in your work?
    1 Daily
    2 Weekly
    3 Seldom
    4 Never

Open-end wrench	1	2	3	4
Socket wrench	1	2	3	4
Monkey wrench	1	2	3	4
Carpenter’s knife	1	2	3	4
Adjustable wrench	1	2	3	4
Screwdriver	1	2	3	4
Other, what?	1	2	3	4

2. Assess the usability of the hand tools that You use according to the shape of the tool.
    1 Good
    2 Moderate
    3 Poor
    4 I do not use the tool

Open-end wrench	1	2	3	4
Socket wrench	1	2	3	4
Monkey wrench	1	2	3	4
Carpenter’s knife	1	2	3	4
Adjustable wrench	1	2	3	4
Screwdriver	1	2	3	4
Other, what?	1	2	3	4

3. How the hand tools which You evaluated as poor could be developed?

4. Assess the usability of the hand tools that You use according to the handle material of the tool for outside work.
    1 Good
    2 Moderate
    3 Poor
    4 I do not use the tool

Open-end wrench	1	2	3	4
Socket wrench	1	2	3	4
Monkey wrench	1	2	3	4

Carpenter’s knife	1	2	3	4
Adjustable wrench	1	2	3	4
Screwdriver	1	2	3	4
Other, what?	1	2	3	4

5. Are the handles of the hand tools which You use thermally insulated (i.e. made of rubber, plastic or wood)?
   1 All
   2 Some
   3 No, which?

6. Do You use gloves when working with hand tools?
   1 Often
   2 Sometimes
   3 Seldom
   4 Never

7. If You observe a fault or a defect in a hand tool do You change it immediately?
   1 Always
   2 Usually
   3 Never

8. Is it easy to obtain a new hand tool to replace a broken one?
   1 Yes
   2 No, why?

9. Has the hand tools You use been modified? Which tools and how?

10. How do You carry the hand tools and other equipment to the mast?

Ergonomics and usability evaluation of garden pruners during design process: the muscle strains and the standard deviations in the first part of the study

Table 1. The muscle strain (% of MVC) and standard deviations of the m. flexor digitorum measurements in the first part of the study.

	Male 1		Male 2		Male 3		Female 4		Female 5		Female 6	
	% of MVC	STD	% of MVC	STD	% of MVC	STD	% of MVC	STD	% of MVC	STD	% of MVC	STD
By-pass pruners												
Bando BD 334-1	5	0.7	27	11.8	15	2.3	21	2.9	18	1.8	33	8.3
Felco 7	6	1.4	24	6.7	14	1.1	20	2.1	13	1.7	26	3.5
Felco 11	9	3.4	27	13.4	15	0.8	24	1.2	16	1.2	29	2.4
Fiskars Classic	7	1.8	23	13.5	17	0.4	26	1.3	20	2.7	37	4.6
Fiskars by-pass prototype 1	4	0.5	21	3.0	13	0.9	18	2.3	11	0.8	26	2.1
Freund 2020	6	0.7	21	3.5	14	1.1	26	1.6	20	2.2	29	3.5
Gardena 601	5	0.7	20	10.6	13	0.9	22	0.3	13	1.2	28	4.2
Sandvik P2-20	5	0.3	27	12.7	16	0.5	20	1.0	15	0.5	29	2.4
Anvil pruners												
Felco 30	6	0.7	18	5.8	13	0.3	23	3.4	16	1.6	27	1.7
Fiskars anvil prototype	4	0.7	23	10.9	13	1.8	21	1.3	12	1.8	26	4.6
Fiskars Classic	5	0.5	22	10.2	15	1.4	22	2.6	17	2.2	27	2.7
Fiskars Clippers 9613	6	0.6	23	9.8	17	1.6	25	1.6	18	0.8	30	3.3
Wolf RS19	4	0.3	19	8.6	12	1.1	19	2.8	11	0.2	24	2.7

Table 2. The muscle strain (% of MVC) and standard deviations of the m. extensor digitorum superficialis measurements in the first part of the study.

	Male 1		Male 2		Male 3		Female 4		Female 5		Female 6	
	% of MVC	STD	% of MVC	STD	% of MVC	STD	% of MVC	STD	% of MVC	STD	% of MVC	STD
By-pass pruners												
Bando BD 334-1	8	0.5	10	2.4	13	2.5	15	2.1	19	1.0	25	4.5
Felco 7	7	1.4	8	1.8	12	2.5	10	0.7	14	0.3	16	1.3
Felco 11	9	0.8	8	2.2	14	2.4	14	0.4	15	1.0	20	1.8
Fiskars Classic	8	1.4	8	3.8	13	1.2	15	0.5	16	1.3	27	6.4
Fiskars by-pass prototype 1	5	0.1	8	0.4	11	0.2	9	0.9	12	1.0	15	0.6
Freund 2020	9	1.3	7	1.3	12	1.4	16	1.3	17	1.4	20	2.8
Gardena 601	6	0.6	7	1.8	11	1.5	14	0.4	13	2.1	18	3.7
Sandvik P2-20	7	0.9	9	3.8	12	0.6	11	0.9	15	0.9	20	2.4
Anvil pruners												
Felco 30	6	0.5	7	2.0	10	0.9	14	1.5	13	0.9	18	2.1
Fiskars anvil prototype	6	0.9	7	2.3	11	0.2	11	1.6	13	1.7	17	3.2
Fiskars Classic	6	0.6	9	1.3	10	1.2	13	1.0	13	1.4	19	1.2
Fiskars Clippers 9613	7	0.4	9	2.7	11	0.7	14	1.5	14	1.3	19	0.3
Wolf RS19	5	0.5	6	1.5	8	0.6	11	1.2	11	0.9	15	0.9

APPENDIX 3

Ergonomics and usability evaluation of garden pruners during design process: the muscle strains and the standard deviations in the second part of the study

Table 1. The muscle strain (% of MVC) and standard deviations of the m. flexor digitorum measurements in the second part of the study.

	Male 7		Male 8		Male 9		Male 10		Male 11		Female 12		Female 13		Female 14		Female 15		Female 16		Female 17	
	% of MVC	STD	% of MVC	STD	% of MVC	STD	% of MVC	STD	% of MVC	STD	% of MVC	STD	% of MVC	STD	% of MVC	STD	% of MVC	STD	% of MVC	STD	% of MVC	STD
Bando BD 334-1	17	0.5	4	0.3	10	0.2	12	3.4	11	0.6	18	1.2	29	1.9	-	-	-	-	10	1.5	31	0.9
Felco 7	16	2.3	3	0.5	11	1.8	13	0.7	10	0.6	20	0.8	26	1.9	18	2.9	23	1.8	13	1.3	32	3.7
Felco 11	16	0.6	4	0.6	10	1.7	14	2.2	11	2.5	21	1.4	-	-	15	1.8	20	0.5	13	1.8	31	1.0
Fiskars 210243	15	2.1	4	0.8	8	2.0	11	1.5	9	1.2	22	0.9	24	2.5	20	1.8	19	2.6	12	0.9	30	1.1
Fiskars 9614	18	3.4	5	1.2	9	0.7	11	1.9	11	1.6	19	1.5	27	0.6	-	-	-	-	-	-	-	-
Fiskars prototype 2	12	1.5	3	0.4	5	0.8	8	0.9	8	1.7	16	0.9	25	2.0	14	2.2	14	0.5	8	1.4	17	1.1
Freund 2000	19	1.6	6	0.9	12	2.2	13	1.9	12	3.1	-	-	-	-	18	0.5	-	-	15	0.9	29	0.4
Gardena 343	17	1.9	4	0.4	8	0.9	12	2.1	11	2.6	20	2.5	25	1.4	19	1.2	-	-	13	1.5	23	2.4
Sandvik P2-20	22	2.3	4	0.2	8	0.6	12	1.1	10	0.7	-	-	26	1.3	18	1.3	-	-	14	0.5	30	1.7
Sandvik P126-22	17	1.5	4	0.9	10	2.0	12	1.6	11	1.4	20	1.1	-	-	-	-	-	-	-	-	26	4.1
Wolf RR26	17	1.2	4	0.6	8	0.4	9	0.4	9	0.9	21	0.9	23	0.3	-	-	20	1.8	16	5.5	31	2.4

- = The subject was not able to complete the test series

Table 2. The muscle strain (% of MVC) and standard deviations of the m. extensor digitorum superficialis measurements in the second part of the study.

	Male 7		Male 8		Male 9		Male 10		Male 11		Female 12		Female 13		Female 14		Female 15		Female 16		Female 17	
	% of MVC	STD	% of MVC	STD	% of MVC	STD	% of MVC	STD	% of MVC	STD	% of MVC	STD	% of MVC	STD	% of MVC	STD	% of MVC	STD	% of MVC	STD	% of MVC	STD
Bando BD 334-1	11	1.0	5	0.5	11	0.1	20	3.5	15	1.1	22	0.8	33	4.7	-	-	-	-	10	1.0	30	2.0
Felco 7	12	0.7	4	0.7	12	1.7	18	1.6	14	1.2	25	0.2	28	5.4	38	4.8	59	3.8	10	1.0	29	4.9
Felco 11	12	1.5	5	0.0	10	2.3	21	4.1	15	2.5	24	2.0	-	-	36	4.0	52	3.6	11	1.1	28	2.9
Fiskars 210243	9	0.8	5	0.4	7	1.3	18	3.7	15	1.2	26	1.9	26	4.7	42	1.4	54	0.9	9	0.7	26	0.8
Fiskars 9614	10	0.9	6	1.8	9	0.4	20	2.8	15	1.8	20	1.8	30	3.5	-	-	-	-	-	-	-	-
Fiskars prototype 2	10	1.4	4	0.1	6	0.8	14	0.0	11	1.4	23	2.8	26	3.3	30	5.4	50	10.1	6	1.0	17	2.7
Freund 2000	14	0.7	6	0.4	11	2.0	20	2.9	18	2.9	-	-	-	-	40	1.8	-	-	13	1.4	27	2.5
Gardena 343	11	1.4	5	0.4	8	0.9	18	1.6	17	1.3	23	3.6	26	3.7	42	0.8	-	-	11	0.5	21	4.3
Sandvik P2-20	15	1.7	5	0.4	9	1.3	19	0.9	17	1.8	-	-	27	3.7	41	4.5	-	-	11	1.8	29	1.7
Sandvik P126-22	12	0.3	6	1.3	11	1.7	21	3.9	18	2.7	24	2.8	-	-	-	-	-	-	-	-	24	4.4
Wolf RR26	10	1.5	4	0.3	7	1.0	16	0.7	14	0.2	25	0.6	27	2.9	-	-	49	7.8	14	5.4	29	5.5

- = The subject was not able to complete the test series

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