Friction and discomfort in the design and use of hand tools

Exposure to textures at different loads and velocities with reference to contamination

by

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Abstract

The skin of the palm of the hand has no friction. It is only when in contact with other objects that frictional forces appear. This friction does not, however, conform to the classic laws of friction. The thesis shows that static skin friction is lower than dynamic friction, and that increased velocity increases the coefficient of friction, but increasing load reduces it. Consequently, references to coefficient of friction where palm skin is one of the friction partners require velocity, surface pressure and skin conditions to be specified in addition to contaminants in the friction interface, before reliable conclusions can be drawn.

Eleven textured and one non-textured samples all made from the same material were investigated using eighteen male subjects. They were exposed to five contaminants, three skin conditions, three levels of load and velocities in the range 2-128 mm/s.
It was concluded that velocity in the friction interface is the most dominant factor contributing to palm friction. Only small, non-significant, differences in friction were found between different types of textures under non-contaminated conditions, but major, and significant differences were observed under contaminated conditions. Coarse textures increased discomfort.

For static- and dynamic friction the type of texture, coarse or fine, will affect friction in different ways depending on the skin conditions being "clean" or "contaminated." Experiments show that coarse textures generate <u>less</u> friction than fine under the <u>clean</u> conditions. Under <u>contaminated</u> conditions however coarse textures generate <u>more</u> friction than fine. The highest coefficient of friction μ=2.22 (SD=1.12) was recorded under dynamic conditions for a clean hand on a non-textured surface when the surface pressure was low - 6.3 kPa (SD 2.1). The lowest coefficient of friction μ=0.05 (SD=0.03) was found under static conditions, with lard present on a non-textured surface when the surface pressure was high - 81.4 kPa (SD=31.0). Two regression models were developed. Regression coefficients are presented for surface topography variables as well as skin condition and contamination, velocity surface pressure and discomfort. Two new surface topography representations explain the generation of friction forces. The uppermost 5% of the volume of texture peaks provided significant information for transfer of friction forces.

<u>Key words</u>: hand, skin, palm, glabrous, texture, handle, discomfort, slip, accident, injury

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Section A. Problem definition

Chapter 1. Introduction

1.1 Introduction

This chapter introduces the importance of carefully choosing textures in the design of objects used and manipulated with human hands. Both industrial designers and ergonomists are in a position to make recommendations on such matters. This chapter introduces a task-user-environmental approach and explains how these variables may affect friction in the hand-handle interface. Attention is drawn to the scarcity of relevant design data in the literature. The objectives of the research are presented together with the structure of the sections and chapters of the thesis.

1.2 The relevance of friction and comfort in design and use of hand tools

A hand tool is an extension of our arms and hands and is the most important link in influencing the environment. This has always been the case but, in a modern technological society, there is an additional demand for fast and very accurate adjustments, tuning and control of processes and machines. This in turn places considerable design demands on control actuators and hand tools. They must be designed to enable prompt and accurate actions and provide feedback of delicate information to the human operator. Friction (i.e. the forces acting in the interface between the hand and the tool) has a major influence on performance, safety, health, efficiency and quality of the work produced. This friction is influenced by many factors, including textures, the respective surface coating treatments, and any eventual contaminant.

The hand is unique. It is through the hand that tactile information about our environment is gained. Heat, vibration, surface load and texture can be detected. The hand can detect its position on a handle, or on a control actuator or on a tool and perform a tremendous number of tasks, from manipulation of tiny pieces and instruments, both slowly and rapidly, to handling heavy loads. When coping with the environment is difficult, e.g. in the presence of glare, noise, and vibration, or when work needs to be performed in the dark, or under cold conditions, or with gloves (maybe under stressful situations), then the shape and size of handles becomes critical. Their immediate contact with the hands through the intrinsic qualities of the material, including minor textures or larger grooves and ridges (natural or man made) will affect performance. With training and education, learning to cope with many difficult situations may be possible, but it is easier to perform the task if the controls and handles are designed to fit the characteristics, abilities and limitations of the hand. Users of hand tools often want the handle to have such a texture so as to gain a steady grip without it unintentionally sliding out of the hand and that they can also control the tool without too much muscle involvement. Too coarse a texture is not desirable as it can result in discomfort and soreness in the hand, particularly when the tools are used repetitively.

Palm skin itself has no friction. It is only when it (or any material) touches something that friction occurs. Amonton (1699) found that when two surfaces are in contact with each other, the relationship between the forces acting in the direction perpendicular to them, (the normal force) F_n, and the force that is needed to introduce a displacement between these surfaces, (the friction force), F_f, is constant. Amonton *ibid* introduced a factor, μ, and the "coefficient of friction" to express the relationship. The coefficient of friction was calculated thus: $\mu = F_f / F_n$, or expressed alternatively, $F_f = \mu * F_n$, (Figure 1.1).

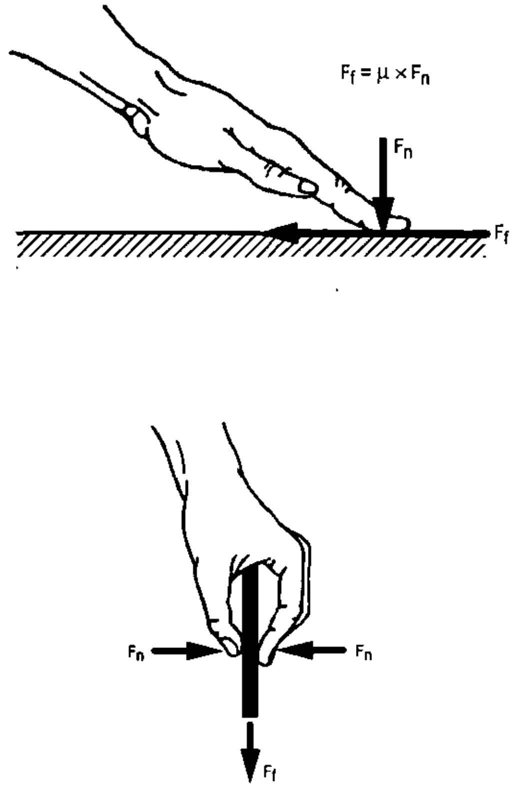


Figure 1.1 Friction and normal forces acting in the hand object interface.

The hand is exposed to a wide range of frictional forces both when we are handling tools and controls at the workplace, or in the home. A high friction interface means that we can perform the work task with lower grip force and with only a minor risk of the object slipping out of the hands.

The higher the friction, the more frequently the palm contact occurs, and the higher the forces, a blister or a callus may develop in the exposed area (Akers 1985). In such cases, it might be better if the friction between the palm and the friction partner is lower. Although friction is the most common mechanical condition the hand is exposed to, very little is known about how it can be affected by tasks, individual differences, or environmental conditions.

In the domestic environment a safe and comfortable grip is required, for example, when removing the lids off jars, bottles and containers. The user population is likely to include people with both well-used hands and soft palm skin. Designers of shampoo or shower gel bottles and caps need considerable expertise to recommend materials and textures to meet demands when using wet and soaked hands (Figure 1.2).

Figure 1.2 **Example of objects with potential to be designed to provide high friction without causing discomfort**

A mechanic may increase the risk of an injury and lose precision when using hand tools that have low friction as a result of exposure to oil or grease. Too much friction may reduce the flexible manipulation of tools such as pencils, computer mice and many precision tools used in laboratory work and in, for example, the assembly of miniature mechatronics.

Very few objects that are handled are held static. Frequently there is an element of manipulation. Although some hand tools, such as scissors, are basically operated with a static hand / handle interface, others like handles on spades or brooms are used dynamically.

The right material with an appropriate texture is therefore likely to act in favour of safety and comfort, and reduce the risk for musculoskeletal injury. To the average hand tool user, the matter of friction can be an issue of comfort or risk management. For a disabled user, the use of appropriate textures and friction may mean the difference between being able to use the tool, or not. Attempts to open containers of medicine often illustrate this situation and highlight the importance of proper design and material selection. An optimal coefficient of friction is not always the same as maximum friction. Handles on pliers may need high or low friction at different locations on the handles as they are held both steadily or manoeuvred with great flexibility in the hands. For example, it might be questioned as to what range of textures are appropriate for handles on a crutch or a walking stick? It is easy to claim the need is for high friction, but is it possible to combine that with comfort in the hand/handle interaction?

The use of protective gloves is good practice in many instances when the hand is in contact with sharp, hot or contaminated conditions. Several researchers have, however, shown that the use of many types of protective gloves reduces a person's capacity to generate high forces in grip force exercises because of reduced tactile[1] feedback and pressure on the interdigital nerves. More intense muscle engagement and an increase in fatigue responses when gloves were used were recorded with the use of EMG methods (Fleming et al, 1997, Riley et al, 1985, and Sudhakar et al, 1988). When the subjects' hands were anaesthetised in order to eliminate tactile feedback, it was shown that they used, on average, five times as much grip force to perform a given task compared to a normal situation (Johansson et al, 1992). Johansson *ibid* showed that with two digits anaesthetised the subjects failed to adopt appropriate gripping forces. Moreover, the subjects did not respond by adjusting the grip force as rapidly. However, there was pronounced inter-individual variation. With only one digit anaesthetised (thumb) the handicap was less severe. Grip force regulation was impaired under conditions of digital anaesthesia, and it was shown in pinch grip studies that afferent input from both the index finger and the thumb was required for the adequate grip force regulation.

[1] Tactile sense is the sense of touch, not to be confused with haptics which describe the perceptual system that uses several cutaneous and kinesthetic inputs to derive information about objects, their properties (including thermal), and their layout (MacKenzie and Iberall 1994).

Lederman (1978).report improved perception of surface textures when a thin cotton sheath was applied between a surface and the palm skin as it traversed across a surface. Lederman *ibid* also report that the use of thin cotton or silk gloves to exaggerate the perceived roughness was reported to be well known amongst coachwork inspectors at Aston Martin Sports cars and by German craftsmen. Lederman *ibid* suggested that when a lateral force (i.e. friction force) is applied to the skin, a sideways bias might be added to the receptors of texture in the palm skin. When such shear is decreased, i.e. by using the thin glove, the sideways bias is reduced and the nervous information concerning the textures only may be given a higher priority.

Thus properties of surfaces, which we know as friction, will affect the amount of force we will require to perform most tasks but also the eventual discomfort under static to dynamic conditions. By selecting textures to be held and handled by hands, performance, health, efficiency and quality of the work produced may be improved.

One reflexion is that friction in the hand object interface play an important role for safe manual handling of tools and objects. Good control of handles means efficient work and less errors and flaws which affect the quality of the work performed.

1.3 The need for friction data in industrial design

The provision of friction and discomfort data, to guide designers in their choice of materials and textures when designing objects such as hand tools, equipment and controls, is the prime concern of the present research. In designing for the human operator, ergonomists and industrial designers traditionally consider the task(s), the user(s), and the environment(s) in which objects are handled. Task analysis may show what forces are applied, their frequency and duration, the postures that are adopted and the part and area of the hand that is in contact with the object. Users may differ in age and sex but also in regard to hand usage and the condition of the palm skin (as hands develop physiological attributes as a result of exposure). Anthropometric differences and strength will affect the pressure at the hand/handle interface. Working environments vary from cold, dry arctic climates, to hot tropical climate or involve a wide range of indoor climates. Gloves may be needed to protect hands from hypothermia, excessive heat or mechanical injuries. In many cases, however, the provision of an appropriate choice of textures and materials for hand held objects will probably reduce the need for gloves and improve the quality of feedback and precision.

Worldwide there is a growing interest in designing to fulfil the needs of the human operator. This is primarily due to two factors. Firstly, there is increasing concern with safety at the workplace, particularly as regards the frequent involvement of both repetitive motions and high force in many industrial tasks. These are also often combined with poor hand / arm posture, caused by the inappropriate design of hand tools. Secondly, this interest reflects the recognition of the importance of quality as well as high output volumes in many industrial tasks and the need for tools which will exploit both user capability and wishes and which also provide high performance qualities.

Many industries world-wide have experienced an increasing frequency and cost of insurance claims. Additionally, threats of legal action from national occupational safety and health agencies have sometimes arisen. These typically occur if action has not been taken to reduce risks for cumulative trauma disorders amongst the work force. Ergonomists and health and safety experts from many countries have cited the results of a number of research projects at the Occupational Safety and Health Agency (OSHA) hearings at the United States Congress (March-June 2000) to demonstrate this point.

Since the introduction of industrial production, the design of hand held objects has been technology driven rather than operator oriented. Thus, more attention was paid to engineering solutions. The reason probably being that the quality of the output from operator-handle activity was rarely discussed, or specified in criteria, thus omitting hand / handle interface issues. By introducing industrial designers and ergonomists in to the design process in the 1930's, interest was shifted towards operator demands (i.e. the shape, size, textures and materials used for the object that the user is controlling with the hands).

1.3.1 Textures and materials for use in handles

Unfortunately designers, engineers and even producers of materials for use in handles and control actuators, lack detailed information on the frictional properties of materials which come in contact with the human hand and how they are affected by the properties of textures. While they can find friction data from engineering textbooks, which describes the friction between engineering friction partners, such data will probably be inappropriate in the search for friction when the skin of the palm is one of the friction partners.

When designing machine tools for injection moulding of plastic products, the industrial designer often selects a particular pattern or texture as a result of a touch sensation or by visual inspection.

1.3.2 Handle design guidelines

A number of publications have stressed the importance of well-designed handles for hand tools, power tools and controls (see Chapter 4. "Design recommendations for handles in the literature"). Such authors frequently stress the need for appropriate friction. Unfortunately, information regarding the friction properties of various textures and materials is rarely given. In particular, data on friction under contaminated conditions being static or dynamic are particularly rare.

1.3.3 Friction partners

When the hand comes in to contact with an object the two become friction partners. At such times a number of mechanical, chemical and perceptual processes take place concurrently or sequentially. These depend on factors in the friction interface, many of which can be affected by industrial design and engineering activities. Thus, when a screwdriver is used to turn a screw, the torque is both a function of the diameter of the handle and the friction force acting in the hand-handle friction interface in the direction of the torque. As soon as the hand touches the handle surface, a pressure is applied. Due to different size of the contact areas the pressure may vary from the finger side to the thumb side of the contact. The friction gained is a function of qualities of the two friction partners. With one, the skin, there may be the individual skin qualities such as whether the skin is dry or moist. With the other, the tool or object held, it may be the particular texture or intrinsic material properties. In addition, the eventual contaminant on the friction interface between the friction partners will also affect the friction. A slip may occur generating a sliding motion at low or high velocity. A slip may affect the coefficient of friction, but also discomfort. Too high a friction may eventually cause a blister, calluses or an open sore. High friction may also restrict the flexible manipulation of objects as the material may stick to the skin. The literature is unclear whether coarse textures increase or reduce friction.

The typical screwdriver case is illustrated in Figure 1.3. In the hand / handle friction interface, the normal force, F_n, is used along with information of the coefficient of friction to calculate the friction forces F_f, which provides the torque F_t or the push F_p, along the blade.

The grip forces provided by the hand are transmitted through the biomechanical link system of the upper limbs including muscles, tendons, bones and joints.

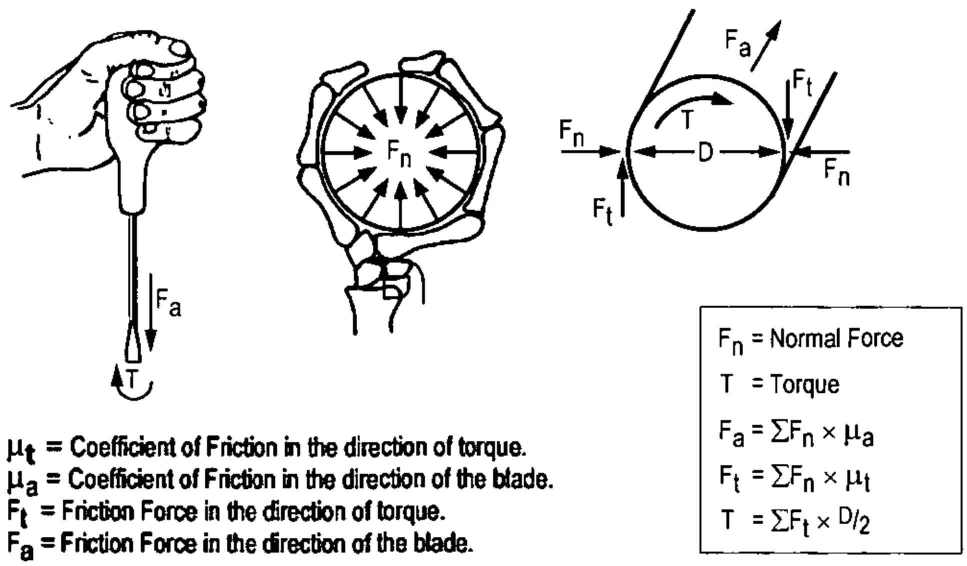


Figure 1.3 **Example of forces acting in the hand handle interface.** **Fn = Normal force; Fft = Friction force in direction of torque; Ffa = Friction force in the axial direction; μt = Coefficient of friction in direction of torque; μa = Coefficient of friction in the axial direction. (Modified from Pheasant 1994)**

Thus there is published awareness of the need to design hand tools and other objects which we touch with our hands, such that the risk for injury is minimal, and to improve the tactile and haptic feedback. Industrial designers are one among several professionals in the position to influence the selection of such textures. When friction exists there is always surface partnership and an interface condition. The designer may influence the choice of the engineering side of this partnership but as to skin conditions and contaminants the information to the user on behaviour and routines are essential.

1.4 Aims and objectives of the research

The aim of this research was to provide designers with data on what friction and discomfort can be expected and perceived when textures are touched and used by the volar side of the fingers (digit pulp) under different task and environmental demands. Examples of tasks involving such factors are the use of forceful grips, or grips used in light precision work both under static or dynamic conditions. In addition environmental factors such as sweaty, dry and hydrated (very wet) hands, as well as oil and grease on the friction interface are of relevance.

The objective of the research was:

- To conduct a literature review to catalogue what is currently known, and to identify gaps in our knowledge about palm friction and discomfort.
- To investigate hand tool related accidents and injuries focusing on incidences with palm slip involvement.
- To collect empirical data to further our knowledge of topographic aspects of textures, skin conditions and contaminants as well as pressure, velocity in the friction interface, and their influence on the coefficient of friction and discomfort.
- To disseminate design relevant tasks, user and environment data and suggest guidelines for the application of the findings.

1.5 Structure of the thesis

This thesis is divided into two main sections and thirteen chapters.

- Section A is concerned with the problem definition and identification of the scientific standpoint and the identification of gaps in the understanding of palm friction and discomfort (Chapters 1 to 7).
- Section B describes the experimental work in which textures were evaluated for friction and discomfort under static and dynamic conditions against a range of environmental and hand conditions (Chapters 8 to 11). Chapter 12 contains a general discussion and suggests applications of the findings. The individual chapters are summarized as follows:

Chapter 1 Introduction

The introduction to this thesis explains the relevance of friction and comfort in design and use of hand tools and other implements that are used at work or at home. It introduces the concepts of friction, friction partners, and some related basic formula, which date back to the eighteenth century. The aim and objectives of the research and the structure of the thesis are presented. The role and the responsibility of the author are described, as is the contribution of others to this thesis.

Chapter 2 The hand in friction partnership

This chapter refers to some basic hand anatomical, physiological and neurological principles and presents details for palm tissue and the organs that give tactile (touch) feed back. Some fundamentals regarding sweating are also reported.

The chapter describes how hand forces are generated, and gives a classification of different types of force and precision grips. Palm pressures when common hand tools are in use are described. Biological responses to surface pressure on skin and palm are described both as a consequence of use, over-use and misuse. The effect of skin moisture on palm friction is reported and mechanically induced injuries to the skin through the use of hand tools are described.

Chapter 3 Friction safety and performance in hand object interaction

This chapter covers health and safety aspects of hand tools, both as to the type of tools and industries that are involved in accidents and the industries where they occur. This chapter also contain results from a specific analysis of accidents and injuries where slip from hands using hand tools has been reported.

Chapter 4 Design recommendations for handles in the literature

This chapter is a review of design recommendations that have been published in the scientific literature.

Chapter 5 Friction in hand-object interaction

This chapter identifies and evaluates the literature in the area of skin friction and particularly palm-skin friction measurement. Results of palm friction research are presented along with details of the dependent, independent, and controlled variables. Different ways to increase and decrease friction by modifying conditions of the skin is reported, and in particular, the effect of moist skin, water, oil and grease are described. Finally, this chapter identifies the limitations of previous research and specifies the required parameters to be included in the present series of research.

Chapter 6 Traditional equipment for skin friction research

This chapter reports the equipment and methods used in earlier skin-friction research. Based on findings in the literature investigation they are scrutinised and the research criteria are set for the series experiments which follows in Section B.

Chapter 7 Laboratory equipment and instruments

This chapter presents the equipment that was developed for the three experiments and the methods for calibration and data management. The actual procedures used in the experiment are described.

Chapter 8 Aspects of hand friction considered in this series of research studies

This chapter presents arguments for conducting three separate experiments based on the identification of the gaps in the understanding of palm friction and discomfort. Each dependent and independent variable is presented and their allocation to these experiments are shown. An additional four experiments relating to hand friction has been performed by the author. They are briefly presented. The experimental approach is presented and issues concerning the variables (three dependent, eight independent and seven other variables) in the three experiments are reported.

Chapter 9 Experiment 1

This chapter reports the first of the series of three experiments of this thesis: "Dynamic friction and perceived discomfort for textured and non-textured surfaces in palm contact under clean and contaminated conditions".

Chapter 10 Experiment 2

This chapter reports the second of the series of three experiments of this thesis: "Static friction and perceived discomfort for textured and non-textured surfaces in palm contact under clean and contaminated conditions".

Chapter 11 Experiment 3

This chapter reports the third of the series of three experiments of this thesis: "Friction in fine and coarse textures. Special attention to skin moisture and contamination".

Chapter 12 General discussion and application of findings

This chapter identifies and reflects on key issues for the generation of friction and discomfort based on factors identified in this thesis. Application issues of the findings are presented. Future research is suggested.

Literature references

Appendices

Appendix 1. Tables

Appendix 2. Surface topography

Appendix 3. Regression analysis

Appendix 4. User participation in hand tool design

Appendix 4. Related palm friction studies by the author

Chapter 2. The hand as a friction partner

2.1 Introduction

This chapter places the development of human hands in a historical perspective and describes the basic anatomy of the hand. It shows how prehensile forces are generated and controlled by the nervous system.

Hands can adopt a variety of positions in which forces can be used. Several of these positions are grouped to established different types of grip. Such classification systems are reported together with how different positions of the hand affect the generation of forces.

This thesis also covers the perceptual aspects of textures in friction contact with the palm. Much of our perception of the environment is gained through tactile feedback from our hands. The nervous organs involved and responsible for these sensations are vital to safe use of hand tools and provide us with a safety margin against injury or loss of this vital extremity. The chapter describes how texture information is transmitted through the skin and how nerve endings and mechanoreceptors very close to the skin surface receive this information. The function of some of the receptors responsible for tactile perception are described and the sensitivity of palm skin to externally applied forces is reported along with data showing the level at which skin, in the post mortem state, ruptures. Friction is a function of the forces acting on the skin. Heavily used hands build up calluses after such exposure, but too much mechanical energy will create a blister or other skin trauma. Common pressures to which palm skin is exposed while hand tools are used over a typical work cycle are reported together with the medical and financial consequences to individual's employers and insurance companies of friction injuries to skin.

2.2 Evolution of hand tasks

When designing objects to be touched and operated with our hands, we need to consider the demands that nature has put on the hand during human evolution. The history of mankind dates back 3 – 4 million years (Wilson 1998). The human species, Australopithecus Afarensis, which is regarded the ancestor of present day humans, lived 3.9 – 2.9 million years ago and was assumed to have an erect posture, a habitual bipedal gait and the ability to flex the fingers to generate a precision grip, in addition to the power grip their ancestors already had (Figure 2.1).

The first hand tool design appeared in that period in the form of hammer-heads, created and used by homo sapiens in West Africa (De Heinzelin et al, 1999). Stones, fashioned into tools and specifically shaped, were made to fit well into the human hand. Anthropologists believe these tools to be a major key to the development of humans (Asfaw et al1999). They were probably used for carving meat from the bones of dead animals, but also to crush bones (large amounts of crushed animal bones were found in caves, next to "hammer-like" tools made of stone). The majority of these bones were of a type that carries large quantities of marrow, rich in proteins – which have had a developmental effect on human brain capacity.

The first 1 – 3 million years were hard for mankind with hunting and fishing, using very basic tools, as important means for survival. Agricultural work and farming started approximately one million years ago and has been a basic pre-occupation ever since, with the exception of the last few generations. The demands on human hands were high during the agricultural and farming period, when tools were held in awkward postures for long periods with considerable force applied. Research by Armstrong (1986a) and Silverstein et al, (1987) showed that such working situations are risk factors for Cumulative Trauma Disorders (CTD), and that they still exist today.

2.3 The hand in prehension

The hand is a complex and versatile mechanism, which is operated by a total of 42 muscles (Pheasant, 1994) The large muscles contributing to the major hand forces are located in the forearm and transmit the forces by tendons to the fingers, while the small intrinsic hand muscles provides us with the ability to perform precision work. When the hands are in a neutral position and at rest, the fingers adopt a slightly flexed position and are partly spread (Figure 2.1).

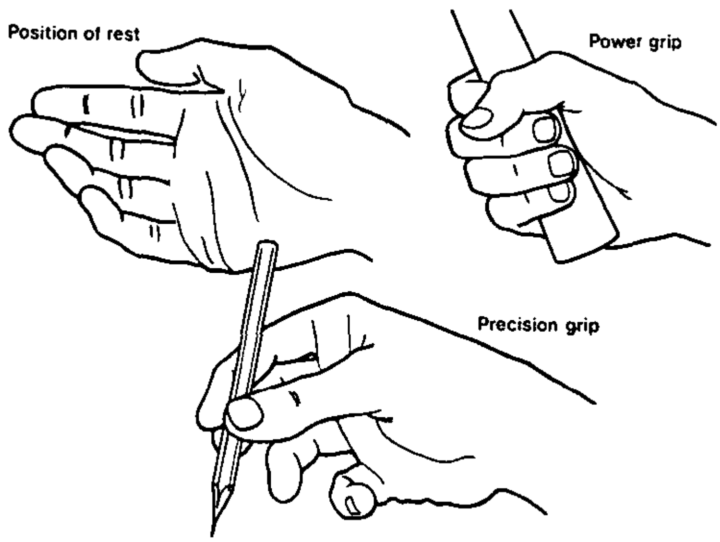


Figure 2.1 **Position of rest and examples of a power grip (sled hammer), and precision grip (pen grip),(according to Pheasant 1994)**

The little fingers are usually the most flexed and the index fingers the least flexed. The position of rest is determined by the passive tendons in the opposing muscle groups (particularly the long flexors and extensors in the forearm). Thus, if the wrist is passively extended, the fingers will flex further and vice versa.

2.3.1 Classification of grip

Napier (1956) presented "A scientific terminology for describing the movements and functions of the hand as a whole". His classification was both a functional and anatomical description of the human hand prehension. He stressed, however, that the most important influence on the chosen posture is the goal of the task; i.e., the intended activity. Napier's *ibid* classification included the power and precision grasp and a type called a coal hammer grip. Cutkosky and Howe (1990) extended Napier's (1956) power / precision classification. They classified various grip modes based on observations of single-handed operations by machinists working with hand tools. They used a set of attributes e.g. sphere, disk, cane to illustrate nine power grasps and seven precision grasps (Figure 2.2). In power grasps, the emphasis is on stability, the ability to resist external forces and gain security without slipping. In precision grasp, the emphasis is on dexterity, which is defined as how accurately fingers can impart larger motions or forces, and sensitivity, or how accurately fingers can sense small changes in force and position. According to their classification, multiple finger prehensions can be divided into two major categories: "circular" and "prismatic" grips. In a circular grip, the thumb and fingers are placed radially around a spherical object. The prismatic grip includes all grips in which the thumb and the fingers oppose each other in grasping flat objects. Both types of grip are relevant to hand tool use and show that the fingers and digit pulp interact with hand held objects in most type of power and precision grips. In applying these types of grips both the contact area in the hand handle interface and the surface pressure will vary. No research has been found to explain the extent to which these variations in grip types affect the contact area. Some recorded surface pressures are however reported (Hall 1995) presented in Table 2.4, page 52

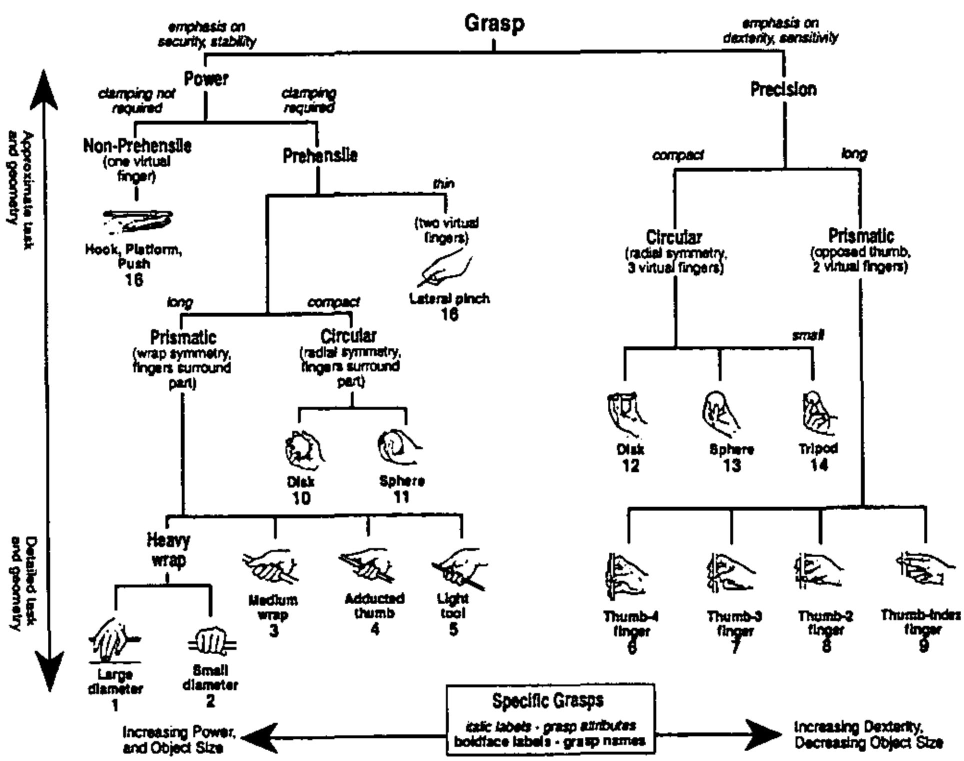


Figure 2.2 **Cutkosky and Howe's classification (1990)** Note: On the left are power grasps, and on the right, precision grasp. The level of task and geometry is indicated on the ordinate

2.3.2 Power and precision grips

A power grip, illustrated as numbers 1 and 2 at the lower left in Figures 2.2, is when the fingers flex around the object and hold it against the palm compared to the precision grip, illustrated to the right in Figures 2.2, in which the object is held between the tips (pads or sites) of the thumb and one or more fingers. Where greater control is required (with less force) the thumb moves to a position along the shaft of e.g. a tool handle, as in using a small hammer, see number 4 in Figure 2.2. As the need for precision increases the index finger may also move along the shaft of the handle, thus providing the possibility of either power gripping or precision manipulation as the occasion demands. Precision grips may employ the tip of the thumb and the fingers; see number 9 in Figure 2.2, or the pad of the thumb opposing the sides of the index finger (as in turning a key). A more complex form of precision grip is used for writing and involves the pads of the index finger, a thumb and the side of the middle finger. Traditional forms of power and precision grips are used when tools are operated in many skilled tasks.

2.4 The control of forces in prehension

Hand function is controlled by the brain and spinal reactions which, through the nervous systems, send precisely coordinated messages to the muscles controlling the functions of the hand. The coordination between grip force and other forces engaged in control of the hand is dependent on several signals acting quickly, accurately, automatically and unconsciously (Johansson and Westling 1984a). The control of muscle activity is partly based on earlier experiences (memorised exposures) of palm contact, and the commands appear to be programmed into sensomotor memories (motor programmes which are trigged within milliseconds to initiate appropriate signals) and other signals from receptors in the palm and hand (sensory feedback) (Johansson and Westling 1984b). When an object comes into contact with the skin, the tissues are moved over many receptors and are translated as a feeling of pressure that includes intensity and shape of the texture. The tissues conduct discrete impulses to the central nervous system for identification and (Montagna and Parakkal 1974). If the programmed commands used do not fit, i.e not enough prehensile forces are directed to avoid a slip, then, more muscle engagement is called for.

Whilst Napier's (1956) view to base the classification on task analysis is vital it was considered to be too coarse for further research purposes. The classification by Cutkosky and Howe (1990) was, however, more useful to identify postures and areas of palm skin in contact with hand held objects. Control mechanisms in the central nervous system will send an alarm signal and some aspects of the program would then be modified. Thus, the relative activity of the muscles involved, and the duration of the contraction, will be adapted to the physical properties of the object to be touched or held (e.g. inertia, external forces acting on the object, coefficient of friction) and, of course, to the major macro relationship of the object to the hand. The mechano-receptors in palm skin that are directly receiving information on activities in the area of contact between the palm and the manipulated object have an extraordinarily important role to play. This can be illustrated by the fact that patients with reduced fingertip sensation (as the dominant symptom) show disturbed hand / motor activity. They drop objects more easily and have difficulty in fastening a button, knitting, etc

(Johansson 1992). The same types of symptoms are noticed when low temperatures disturb these sensations. Moreover, vibrations in a hand tool can create both reduced tactile sensations and reductions in the signal transfer. Vibrations will disturb the force co-ordination of the hand to adjust to different frictions (Johansson *ibid*). Using other control systems, primarily vision, will however partially compensate for the loss of motor function when tactile information is disturbed. However, this demands an increased mental awareness, which itself might be a risk factor in the use of hand tools. Johansson and Westling (1987) has shown that mechano-receptors in the glabrous skin of the palm and fingers signal to the central nervous system to adjust the grip force so that a safe grip is adopted to avoid dropping. Johansson *ibid* found that when the tissue starts to slip, or only a fraction of the contact area starts to slip, the central nervous system autonomously adjusts the normal force within 60 - 70 ms, as if it was a reflex action to avoid a slip. It appears that the frictional characteristics of the material and previous experience with the materials affect the grip force. Thus when a "new" material, such as Teflon®, was tested, much lower safety margins against a slip were found.

2.4.1 Grip forces

The grip force is highly relevant to palm friction as the forces acting in the normal direction in relation to the skin, F_n, together with data on the coefficient of friction μ, in the hand handle interface, comprises the major parameters in the calculation of the friction forces that can be achieved with our hands, i.e. $F_n \times \mu = F_f$.

The ability to apply forces when holding and using tools and equipment are, among other things, dependent on wrist posture. As the angle of the joint increases or decreases beyond its midpoint (neutral position), there is a proportional decrease in effective strength. The forces primarily acting in the direction of the tendons will also generate lateral forces in the direction of the tendon sheaths and surrounding structures in the carpal tunnel increases (Armstrong and Chaffin, 1979a). The postures also determine how long a worker can perform a job without adverse health effects such as fatigue and Cumulative Trauma Disorders (CTD). In bent hand positions more exertion is required to do a task than is required to do the same task in the neutral position. A number of wrist and finger postures have been identified as particularly stressful according to Putz-Anderson (1988). The general terminology for hand and wrist postures are listed below and illustrated in Figure 2.3.

- Ulnar deviation – bending the wrist toward the little finger.
- Radial deviation - bending the wrist toward the thumb.
- Extension - bending the wrist up and back.
- Flexion - bending the wrist down towards the palm.
- Pinching – flexor surface of thumb is opposed to index finger.

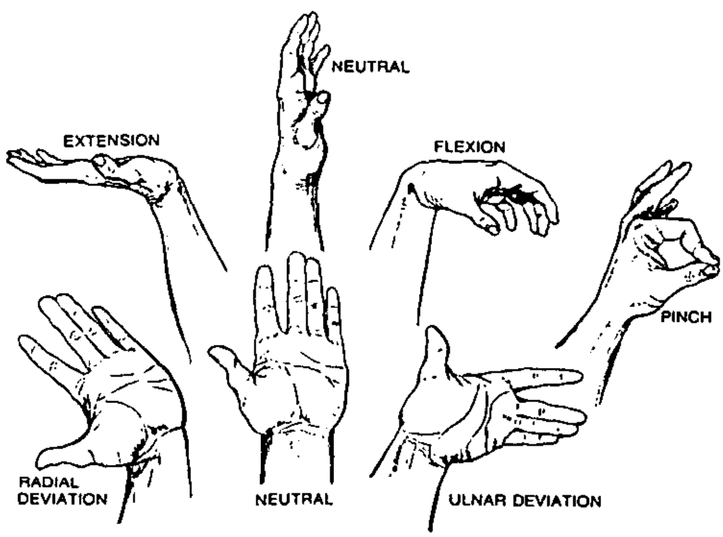


Figure 2.3 Hand and wrist postures. From Putz-Anderson (1988).

Lehman et al (1993) investigated the influence of the wrist position during peak grip force recordings, under both static and dynamic conditions. Peak forces were recorded when the hand was in neutral and several deviated positions. The grip strength of the hand was greatest when the hand was in the neutral position or slightly bent upwards (extended). Lower grip forces were exhibited at extreme wrist flexion, as well as in extreme radial and ulnar positions, for both static and dynamic conditions. At extreme wrist flexion and extension the peak grip strength was 45% and 74% respectively of the greatest strength. Ulnar and radial grip strength was 75% and 80% respectively of the peak recordings. The direction of motion was also found to affect grip strength; extension to flexion exertions produced larger grip forces than flexion to extension exertions. Radial to ulnar motion showed larger grip forces than ulnar to radial deviation. Figure 2.4 illustrate the reduction in grip strength for various wrist postures as a percentage of the maximum grip force according to Rogers (1987) cited by Putz-Anderson (1988).

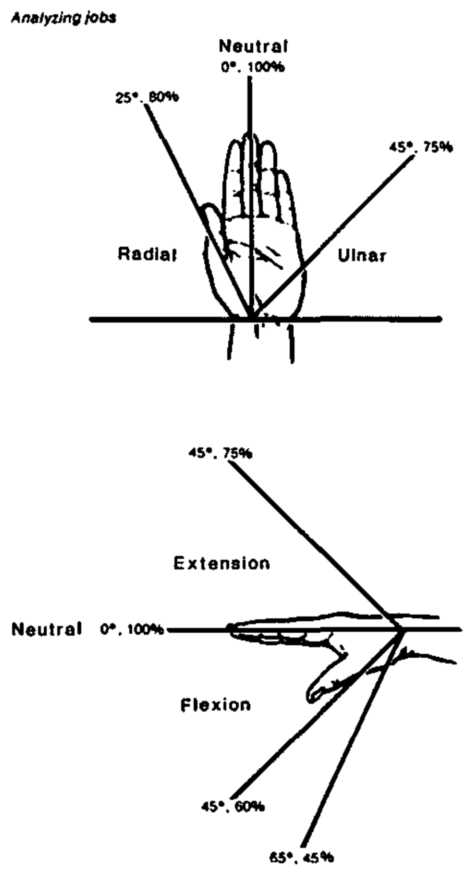


Figure 2.4 Grip strength as a function of the degree of wrist deviation expressed as a percentage of power grips as measured in the neutral position (Rogers1987)

Fransson and Winkel (1991) recorded the differences in grip force exertions when using the same pivot action tool (as with pliers), in the same wrist position but facing in different directions (ulnar and radial respectively). Intuitively it would have been possible to generate higher forces at the tool end the further out from the pivot the strongest fingers (the long and middle finger) were acting, (rather than those generated with the little finger). Hall *ibid* could show that this is generally not the case, as illustrated in Figure 2.5, but the differences were small. It would seem the further away from the pivot point the larger was the distance between the shanks, which forced the fingers to operate in a more open and less powerful position.

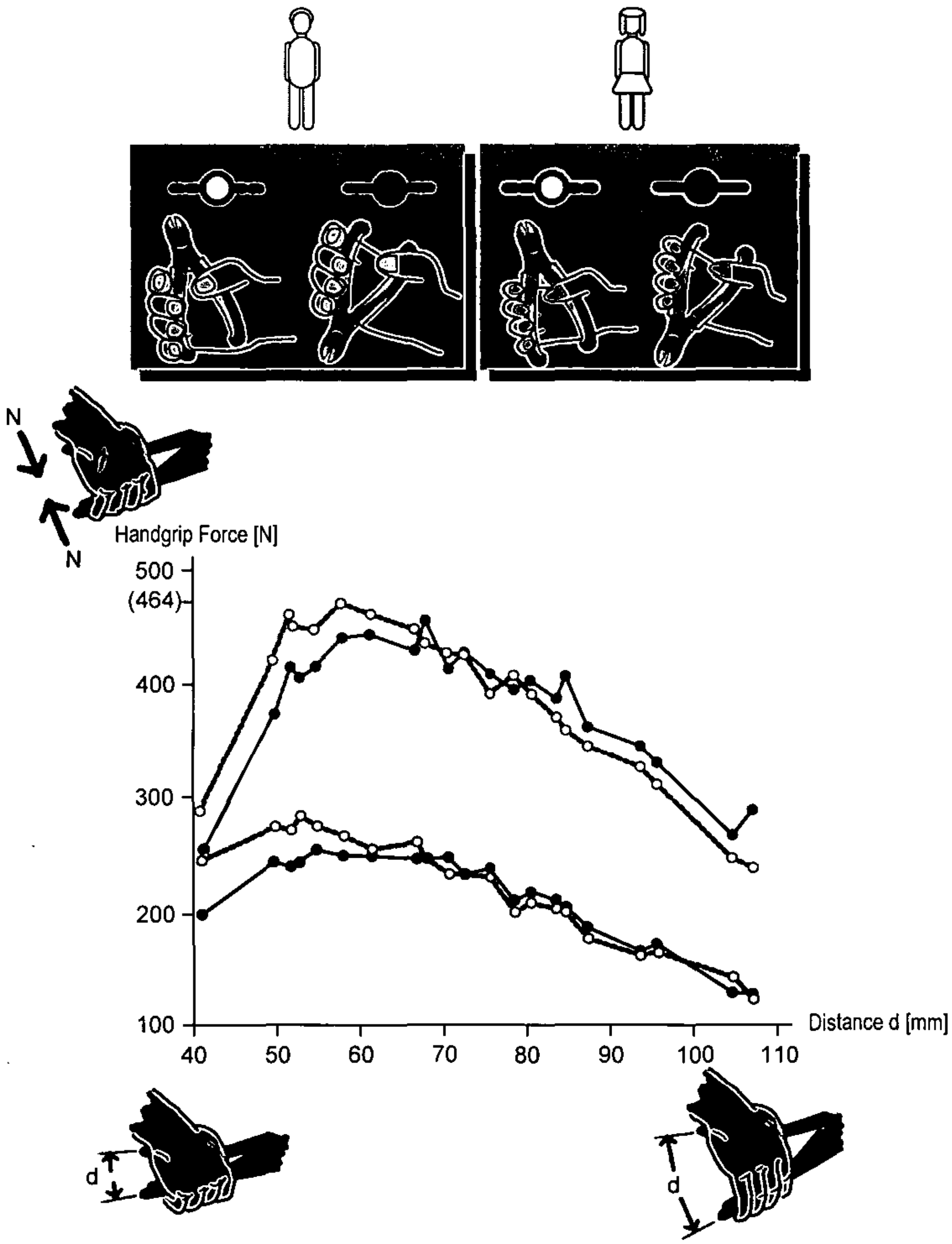


Figure 2.5 **Mean peak hand grip forces when using a pivot action tool in the normal (thumb forward) and revered (thumb back) direction. Modified from Fransson and Winkel (1991)**

Numerous researchers have studied human grip forces. An excellent report of the research in this field is available in the dissertation by Hall (1995). Fransson and Winkel (1991) showed that by using a specified multiple regression model, male and female maximum peak grip forces may be calculated in a power grip situation when the wrist is held still in a neutral position. The model is based on hand anthropometry data and includes parameters such as hand length, hand width (metacarpal), and average length of the fingers. The model explained 87% of the variation, $p < 0.001$.

2.4.2 Directions of applied force in hand tool use

In the journal Forskning och Praktik, (1993) (Research and Practice, 1993), hand tools which had either been identified as hazardous or problem tools, were of the kind frequently used in the direction along the fingers (as when using a screwdriver in a power grip (Figure 1.3, page18), rather than across the fingers. Examples of such tools were screwdrivers and other rotating tools, but also ratchets, wrenches, files, and scrapers. Figure 2.6 shows the frequency to which these types of tools were reported. This was seen in relationship to other tools at which forces were acting across (transverse to) the length of the finger. Such transverse directions are according to Radwin and Seoungyeon (1992) the most common when picking up and holding small objects and when pushing and pulling pivot action tools such as pliers.

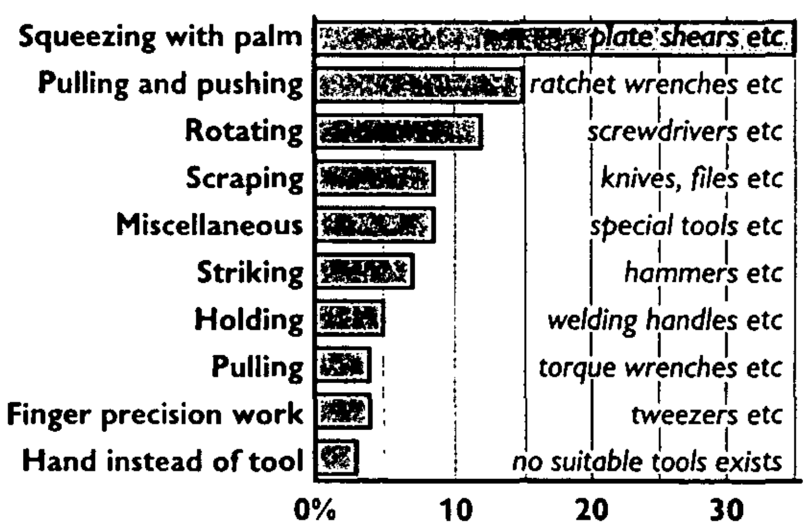


Figure 2.6 **Hazardous or problem tools identified in Swedish engineering industries. The abscissa shows the frequency at which these types of tools were reported. From the journal Forsaking ouch Practice, (Research and Practice, 1993)**

Considering the normal forces, F_n, produced by the hand, friction forces F_f which, by definition, are acting in the direction along the surface of the skin (or handle), are directly influenced by the frictional properties of the hand-handle interface. Thus the force capabilities of the human hand (referred to above) may be more or less efficiently utilised, and under certain friction conditions result in fatigue and when generated frequently, with the hand and wrist in awkward postures, possibly generate musculoskeletal overuse syndromes. Johansson and Westling (1984b) concluded, "Too strong a grip force may cause damage to the object or the hand as well as unnecessary muscular fatigue".

2.5 Palm tissue, physiology and neurology

The hand gathers sensory information about its friction partner through mechano-receptors and proprioceptors (Westling and Johansson (1984). Coetaneous end organs and structures that transform mechanical, thermal, chemical, or electrical energy into neural signals lie within the dermal layer, or at the dermal-epidermal interface (Figure 2.7). The hand also provides housing for tendons, muscles and eccrine (sweat) glands, all essential for establishing stable grasp. Palm creases reflect axes of joint movement.

Characteristics of skin relevant to the generation of friction, and perceived discomfort, include the structure of the epidermis and dermis, papillary ridges also called dermal ridges, or dermatoglyphs, primary or sweat ridges, the sensory receptors and their innervations. Papillary ridges extend over grasping surfaces as evidenced by human hands, gorilla knuckle pads and prehensile monkey tails, all of which are equipped with ridges of a similar kind (MacKenzie and Iberall 1994). These act like the ridges on automobile tyres, to increase grip and facilitate weight bearing by increasing surface area. The concentric arrangement of the papillary ridges allows some asperities to be perpendicular to shearing forces to facilitate good surface contact and friction.

Epidermis of the palm (and the feet) can be 5 mm or more thick and fully regenerate every 20 to 30 days (Quilliam 1978 in Gordon 1978). Epidermis grows from a base foundation of spinal cells. Newly created cells push the old towards the periphery, which at the surface become flat cells and form layers, not unlike slate, which eventually fall off like leaves off a tree. The control of this growth is still subject to investigation and a number of factors may have influence on it, including loss of surface structures and changes in the water gradient (Forslind et al, 1999). Forces acting both in the normal and tangential direction stimulate this growth. Prolonged and forceful action against the epidermis will create calluses. Glabrous skin is hydrophilic (absorbing water easily) and is detected as wrinkles in the palm after prolonged immersion in water (for example as when having a bath).

The glabrous skin is loosely attached to the palm, but when stretched to a limit it will be sturdily attached to the underlying tissue in the hand. The average values for the ultimate tension strength of palm and feet (sole) skin are 8.5 MPa and 9.3 MPa respectively. This can be compared with vulcanised rubber for which the ultimate tensile strength is within the region 10 to 15 MPa depending on rubber quality. The Standard Error, SE, (S. D/Mean x 100) is 21.6. The data above are reported by Yamada and Evans (1970) following mechanical examination of 15 to 20 specimens from cadavers in each decade over a span of 10-80 years.

The epidermis consists of a system of collagen fibres linked together. If we see the collagen system as a web comprising oblong chains that can move in conjunction with each other, we have an explanation as to why epidermis can return to the normal condition shortly after maximal tension i.e. visco-elasticity. This process is repeated over and over, each time an operator is for example, using a hand tool, touching a control or operating a handle. Thus this function is very basic. The palm skin is thick and hairless. The dorsal skin however is fine, supple and mobile. Dorsal skin contains hair follicles reinforcing and protecting the underlying tissue. To facilitate uninhibited flexion the skin contains numerous lines and creases. The skin of the palm is attached to the underlying fascia, which is a major tendon mesh, the basic aim of which is receiving and distributing external forces acting on the palm, and protecting deeper nerves, tendons, arteries veins etc. (Calliet, 1994). Subcutaneous lipids have important functions, receiving and distributing external forces and protecting underlying structures. These lipids may be seen as solid structures, they cannot be compressed more than to a certain degree, and palm skin, which is attached to the subcutaneous lipids and initially fairly flexible, ends up being a very stiff structure and thus allowing a steady grip to be maintained. On the palm side of each finger there is a substantial lipid volume. On joints, however, there are no such protective lipids, thus joint capsules and tendons are unprotected against external surface loads such as from hand tools. Across the base of the fingers, on the palm side, there is a major lipid structure, stretching from the ulnar to the radial side. Here the skin is flexible and durable and this is a common site for blisters (Renlund 1987). The finger bones are basically a supporting platform. The metacarpal bones of the finger digits have no flat surfaces on their palm side. On the contrary, they are fairly rounded in shape and thus have very limited ability to receive applied forces. However, the rounded shape makes them very strong (Renlund 1987).

Tactile sensation and discrimination are important to ensure precise dextrous motor activity of the hand. The palm plays a unique role in hand function. Heller and Schiff (1991) demonstrated how complex and resistant to simple formulation the "simple" skin senses really are and researchers into pain are confronted with difficult but important paradoxes.

According to Heller *ibid* pain is "a subjective" phenomenon but we often try to measure it "objectively". Heller *ibid* also shows that there are alternative ways to conceptualise touch and subject's active movement can modify the sensory experience, for example "it is rather difficult to tickle oneself".

Heller *ibid* suggests a few examples:

> "When running the fingers over a page such as this one, feeling the smoothness of the paper perhaps roughened a bit by the ever so slightly raised imprint of the text, a haptic sensation is perceived. If the paper is glossy, it may feel cool to the touch. A pencil held transmits vibrations to the fingers, just slightly, as it scratches the rough surface of the paper. Soon, however, we may even stop being aware that we are holding the pencil. Similarly, the constant pressure of clothing fades from constant perception unless there is movement or change of posture. The sensations, produced by these events, are a function of the underlying morphology (form and structure) and physiology (biological functioning) of the neural end organs that lay within and under skin."

Contained within the layers of the skin are structures responsible for our ability to "feel". Depending on the body site under examination, skin might be flat or furrowed, loose or tight, hairy or smooth (glabrous), thick or thin. On fingertips, ridges and valleys of skin form intricate patterns of whirls and loops. These distinctive patterns reflect the infinite variety of random undulations in the papillary layer of the dermis, below the skin's surface (Quilliam 1978). These ridges have been implicated in texture perception (Lederman 1978). According to Johansson and Vallbo (1979), the density of pressure sensitive nerve endings is seven times as high in the fingertips as in other parts of the palm. Such high density reflects our ability to detect minor details with touch, but does not mean that the fingertips are more sensitive to loads than other areas of the palm. In fact research by Hall (1995) showed that the fingertips tolerate more load than other parts of the palm.

A cross section of hairy skin (Figure 2.7) is also representative of glabrous skin with only a few exceptions. On hairy skin there are numerous fat glands which are physiologically linked to the roots of hair.

Figure 2.7 shows the locations of cutaneous organs and free nerve endings, which provide us with tactile and haptic information. 'Haptic' refers to the functionally discreet system involved in a seeking and collection of information by the hand. The term "haptic" comes from the Greeks meaning "able to lay hold on". Some cutaneous structures such as Pacinian corpuscles are found primarily in glabrous skin, although they also exist at a much lower density in hairy skin. Free nerve endings, fine sensory fibrils (the end of neurons) on the other hand, are found throughout the body (Heller and Schiff 1991). There are several cutaneous end organs and mechano-receptors that are suspected of being responsible for transducing tactile stimuli into neural signals. According Montagana and Parakkal (1974) the mechanoreceptors in the skin consist of

- a dermal nerve network consisting of bare intraepidermal tactile nerve endings
- Meissner corpuscles
- Pacini corpuscles
- Merkel type "discs"

These end organs and free nerve endings are scattered throughout the depth and breadth of the skin. The density varies considerably depending on the location. Figure 2.7 is a generalisation that illustrates the locations of some of these structures in relationship to one another. Johansson and Vallbo (1979) reports that in the glabrous tissue of the palm, there are some 17,000 pressure sensitive units, i.e. nerve cell with axon and associated end organs in the skin. He suggested that receptors in palm skin, particularly in the fingers provide us with information of the friction between the fingers and an object so that the grip forces can be adjusted until a certain safety margin is reached to avoid slip.

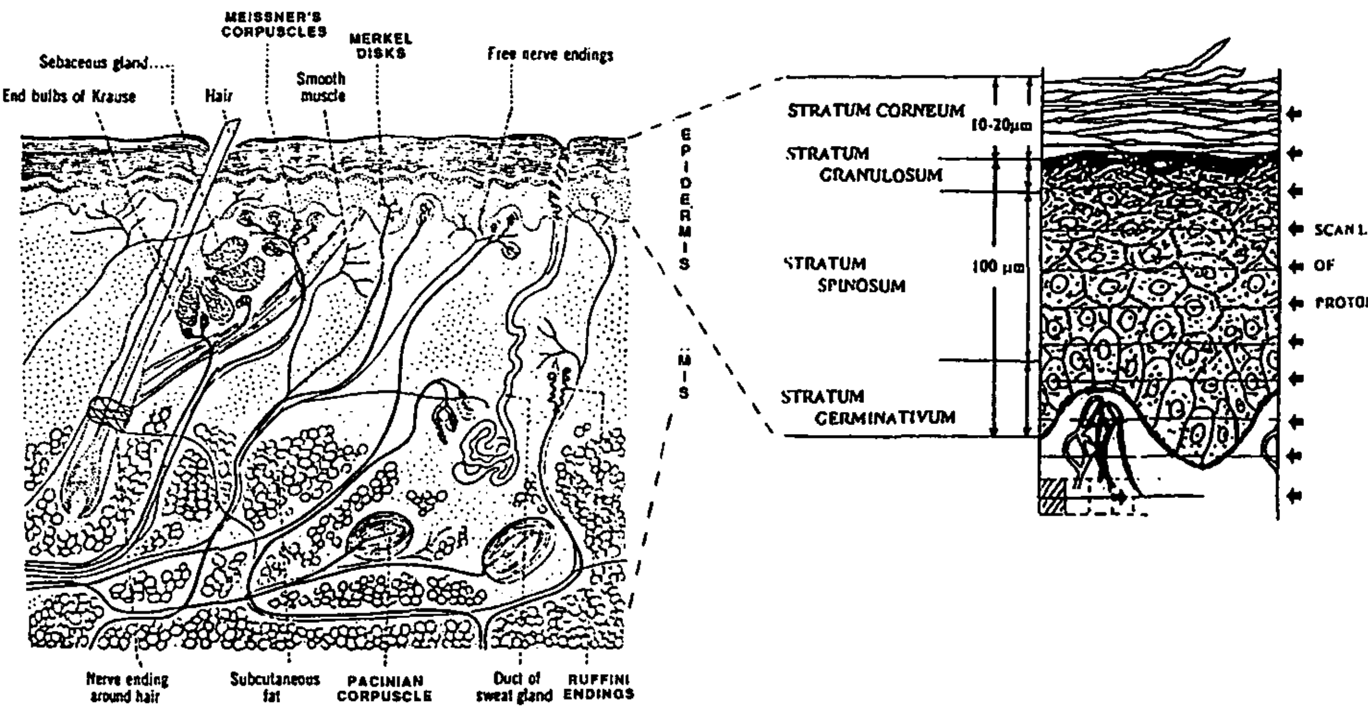


Figure 2.7 **A cross section through a typical portion of 'hairy' skin. (From Heller and Schiff (1991) and Forslind et al (1999).**

The overall density of neural end organs is greater in glabrous skin, and the surface of glabrous skin is ridged. The outmost layer of skin is called the epidermis, which can be subdivided into several other layers. The surface of the skin, the stratum corneum, is made up of dead or keratinized cell bodies from the deeper subdivisions of epidermis that have migrated outwards as the skin renews itself from the inside out. Below is the dermis, a layer of nutritive and connective tissue. The dermis is a "felt-work" of bundles of white fibres and elastic fibres. Within it are located blood vessels, nerve endings, hair follicles and sweat glands. Major blood vessels run below the dermis, within the subcutaneous tissues, and small branches supply the dermis. In addition, the sweat glands are found here, as are fine nerve endings that also seem to be involved in cutaneous sensation. As energy moves in a wave into the skin e.g. as a result of an applied force, it produces shearing forces that dissipate with distance from the sources according to inverse square law (Heller 1991). The wave changes as it passes through different tissue layers or encounters obstacles such as blood vessels or bones (similar to breakers on a beach). These obstructions may reflect, refract, absorb or otherwise distort the wave front in one way or another. Therefore, the events that are "witnessed" by the sensory nerve endings within the skin, may be quite different from those originally presented at the surface. Cutaneous receptors are tightly packed in regions such as the fingertips and lips. The sensitivity to tactile stimuli is, in many ways, related to this density of innervation.

2.5.1 Stress tolerances in palm skin

Armstrong (1985b with reference to Bennett 1975) reported the kind of pressure the palm skin can be exposed to without injury and claimed that blood flow will be reduced to 50 % if the tissue is exposed to a force acting in the direction normal to the tissue and resulting in a pressure of 50 kPa. Continuous pressure for days to weeks will result in an open wound when the pressure is 10 kPa (Husan 1953). Research on animals indicated that the product of surface pressure and time is a constant. Thus 1 kPa for 40 hours is, according to Husan *ibid* as injuring as 40 kPa for one hour. Male subjects react with pain from palm at pressures in the range 700 to 845 kPa depending on location. The thumb / thenar region is most sensitive and the fingers are most tolerant to externally applied pressure. Females respond similarly, but at pressures two thirds of those males (Fransson-Hall and Kilbom 1993). The effect of sustained pressure has also been investigated (Hall 1995). According to this research, male subjects accept on average, external pressure of 100 kPa to the hand during a whole working day and females accept 40 kPa. When the pressure is repeated on the same location the sensitivity will increase. After ten repeated identical experimental exposures to the palm, sensitivity had increased with on average a factor 1.42. Sensitivity did not differ between manual workers e.g. automobile assembly workers and "white collar workers", nor was any correlation with age reported. Table 2.1 below describes some subjective and biological effects of contact pressure on palmar skin and other organs. Johansson et al (1999) investigated subject's perception of discomfort pressure (determined as the pressure at which 50% of the subjects judged the pressure as uncomfortable). For the fingers, the central palm and the thenar area, the discomfort pressure was 188, 200 and 100 kPa respectively. When exploiting the Borg CR-10 scale (Borg 1982) for evaluating perceived palm pressure at 150 kPa, the mean rating was 3.4 (*moderate-to-somewhat strong pressure*). The values varied from 1.0 (*very weak*) to 6.6 (*very strong*). The discomfort threshold was 22 to 40 % of the pain pressure depending on location in the hand.

Pressure N/cm^2	kPa	Comments
0.6	6.0	Mean contact pressure between index finger digit pulp and a non textured surface when finger force is 1 Newton (Bobjer et al1993).
1.0	10.0	Long time pressure may result in damage to tissue (Husan 1953).
4.0	40	Mean contact pressure between index finger digit pulp when finger force is10 Newton (Bobjer et al 1993). Acceptable external pressure to the hand during a whole working day for females (Hall 1995).
5.0 5.0-15.0	50 50-150	Reduces flow of blood 50 % (Bennett 1975). Contact pressure in the most exposed area of the palm and fingers for nippers, drills and pens under a typical work cycle (Hall 1995).
7.0	70	Mean contact pressure between index finger digit pulp and a non textured surface when finger force is 20 Newton (Bobjer et al 1993)
10.0	100	Contact pressure in the most exposed area of the palm and fingers for hand saws and screwdrivers under a typical work cycle and acceptable external pressure to the hand during a whole working day for males according to (Hall 1995). Discomfort pressure for thenar area (Johansson et al 1999).
15	150	The mean rating for perceived palm pressure was 3.4 (moderate-to-somewhat strong pressure). Discomfort pressure for finger (Johansson et al 1999).
20.0	200	Discomfort pressure for palm (Johansson et al 1999).
50	500	Contact pressure in the most exposed area of the palm and fingers metal shears under a typical put forceful work cycle. (Hall 1995)
70.0	700	Average perceived pain threshold for women (Fransson-Hall and Kilbom 1993).
84.5	845	Average perceived pain threshold for men (Fransson-Hall and Kilbom 1993).
850	8500	Tensile strength of human skin (Yamada and Evans 1970).

Table 2.1 **Palm pressure when using hand tools. Pressure on other organs under different physiological exposure is reported as reference levels.**

2.5.2 Blisters

Too much skin friction may cause the skin to blister. If the skin is tough enough to withstand a shear force, in the form of translation or rotation of the stratum corneum, an intact blister top will be formed. If the skin is not sufficiently durable an open sore develops. The minimal mechanical trauma dose needed to produce a persistent erythema (red colour skin), after five minutes of stimulation, is approximately 6 N cm/sec for males and somewhat lower for females (Marks and Black 1985). Blisters produced by friction are practically confined to the human species. They are not found, as a rule, in lower animals (Sulzberger et al 1966). The transformation of energy from a hand tool takes place largely through skin contact with a handle. Cellular layers of spinal cells slide apart at their weakest point, the epidermis-dermis intersection (Figure 2.7) and the volume between the cells is filled with lymphatic liquid and a blister is created. According to Samitz (1985), blisters are the most common mechanical injuries to skin. They appear basically on areas that support major external loads such as under metacarpal heads, and on the fingertips. Rarely do they develop on thin or loose flexible tissue. The thick, tough skin such as found on hands and feet, is necessary to form the roof of the blister. The major cause of a blister is the force that acts in parallel to the dermal surface, the friction force, F_f. The expression often used is "shearing", "shearing force", or "shearing friction force". Moisture and heat increase the risk of developing a blister (Bergfeld 1985). The time required to produce a blister varies widely between subjects. Using a linearly - to and from - rubbing machine, a blister would, in some subjects, be produced within three to four minutes in the palm of the hand. Fifty minutes or more of 'stroking' however failed to produce blistering in other subjects. Blisters are, however, readily produced within 30 seconds when twisting the eraser on the end of an ordinary pencil against the palm (Akers 1985).

2.5.3 Calluses

During prolonged and low mechanical exposure to lower shear and normal forces calluses will build up as a protective mechanism. Calluses develop where the spinal cellular layers are thick such as on the hands or feet particularly on the areas where the forces act against a bone. Repeated forces and friction will increase the thickness of the skin even more. The growth is dry and brittle and may rupture which creates an intense pain. Calluses will stay hard and brittle when exposed to lipids but they become soft and flexible when they have absorbed water (Samiz 1985).

2.6 Moisture, sweat and contaminants on palm skin

The surface temperature in the body core when at rest is regulated within close tolerances to about 37°C. The temperature of epidermis however is dependent on the ambient temperature, and only a little on the physiological workload. At an ambient temperature of 31 to 34.5°C there is a general sweat outbreak in resting subjects (Rothman 1954). When the temperature in the glabrous skin of the hand is within the range 32 to 40°C the conditions are perceived as comfortable but major individual differences exist depending on biological, medical and other factors. The hands (and feet) have a large surface in relation to their volume. At low ambient temperature therefore, hand temperature is difficult to maintain, particularly under low activity. Considerably greater increases in the supply of heat and blood circulation are required to the hands and feet to maintain a particular tissue temperature. Organs and tissue in and close to the epidermis will however accept major temperature changes. The temperature on the fingers may vary ±20°C without any damage to the tissue.

A resting human being, without clothes, is in neutral heat balance in an ambient temperature of 27°C. At that temperature there is no sweating, the body is in thermal balance, and the surface temperature of hairy skin is 33 to 34°C. If the ambient temperature is decreased, the body reacts by reducing the thermal transport to the skin and a reduction in skin temperature will follow. If, on the other hand, the ambient temperature is increased, more blood is transported to the skin where more heat can be transmitted to the ambient air through activities of the sweat glands and by insensible perspiration, so that excessive heating of the body core will be avoided. Increase of body core temperature is most commonly a function of physiological activities and only to a lesser degree a result of the ambient temperature.

2.6.1 The effect of hydration on epidermal friction

Moisture and sweat in palm skin are often considered to be a dominant factor affecting palm friction. The mechanisms for sweat generation are briefly discussed below, followed by studies reporting on the relationship between sweat and friction.

Hydration of the skin from the body follows two mechanisms: namely water eruption from the sweat glands and by insensible perspiration of water penetration through the skin (which is water permeable). The mechanism is called transepidermal water loss. Hydration may start in response to:

- emotional stress
- high ambient temperature
- physiological workload.

The number of eruptions taking place through the sweat glands per unit area is highest on the glabrous skin of the hands and feet. At a density of approximately 400 sweat glands per cm^2 in the palm, the sweat glands respond rapidly and distinctively to emotional stress. (Pain is shown not to, in itself, cause sweating; it is rather the fear for the consequences of the pain that causes sweat). On friction surfaces such as the palm, the sweat ducts open at the apex of papillary ridges, rarely in the furrows. The ducts are regularly spaced in the centre of the dermal ridgelines. The ambient temperature also has an increasing effect on palm sweating, but to a lesser degree and physiological workload has a limited effect on palm perspiration in indoor climates (Quinton 1983). The dorsal side of the hand however acts as an excellent cooling flange with a large area in relation to the volume of the hand. The high density of the sweat glands in the palm does however not mean that the palm always perspires most. Hand sweating is mainly activated by mental processes and is probably the most common form of sweating. Under mental (psychological) stress the sweat glands in the palms and on our feet are largely activated, but other parts of the body are only engaged to a minor degree. The most intense thermo-regulative sweating takes place on the forehead and the neck, and the lowest activity is from the palm.

When sweat is generated, by activating the sweat glands, volumes of sweat are displaced on the skin. Smaller quantities have a moisturising effect on skin but in larger quantities it may introduce hydrodynamic friction conditions, not unlike water planing of tyres on a road. The other mechanism, which introduces moisture to the palm, is the transepidermal water loss, i.e. the evaporation from skin that cannot be noticed as sweat (Nilsson 1977). The transepidermal evaporation from the torso responds rapidly to the ambient temperature within the comfort zone, although there is no obvious sweating. In humans, the palm shows the largest transepidermal evaporation per unit area (100 gram/m^2 per hour). This compares to the torso, which is in the region 10-15 gram/m^2 per hour (Nilsson 1977). This mechanism is likely to be functional in providing a good grip, as the cooling effect of the palm of the hand is small. The dorsal side of the hand will however act as a cooling flange even if the hand is engaged in holding e.g. a tool. A schematic representation of the papillary ridges in glabrous skin of the human hand is shown in Figure 2.8. Papillary ridges, also called primary or sweat ridges, refer to the visible epidermal markings, which may generate fingerprints. The shape of the papillary ridges and grooves that can be observed by the naked eye, are determined by the basic form of the underlying dermis where the ridges gain their shape from the primary and secondary dermal papillae. The grooves reflect the underlying "limiting ridge" (MacKenzie and Iberall 1994).

The spiral ducts of the eccrine sweat glands coil their way through the intermediate ridges and surface at the centre of the tops of the papillary ridges.

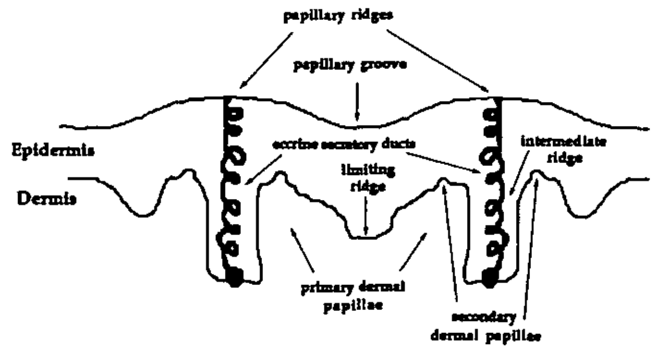


Figure 2.8 **A schematic cross section of the hairless skin of the human hand (MacKenzie and Iberall 1994).**

2.6.2 The composition and monitoring of sweat

The composition of sweat is 99 % water and 1 % solids (Rothman 1954). Of the solids, one half is inorganic salts, e.g. sodium chloride and one half is organic, e.g., urea. MacKenzie and Iberall (1994) suggested that the sweat composition in the eccrine glands of the hand should be compared across individuals, and the implications of this lubrication for grasping forces studied both experimentally and computationally.

The periodicity of sweat gland secretion is more regular on the palm and fingers than in the dorsal aspects of the hand. The frequency of such bursts increases with temperature and seems to vary from 2 to 7 bursts/min. Figure 2.9 shows this periodicity in the palm of the hand in Rothman (1954). Unfortunately there is no scale information on the y-axis in the reference by Rothman *ibid.* The relative inactivity of the sweat glands is followed by fairly uniform discharges. Interestingly there is an increase in sweat discharge when the hand is gripping a dynamometer, compared to the palm being at rest.

Traditionally the presence of moisture on the skin has been recorded by an ohm-meter measuring the electrical contact resistance. A normal hand was regarded to be within the range 5 to 20 kΩ (Bullinger et al 1979). Another instrument the "evaporimeter" (Nilsson 1977) was used by Cua, et al (1990b) to record the transepidermal water loss (TEWL) of the skin while directly monitoring the evaporation from various parts of the skin including the palm.

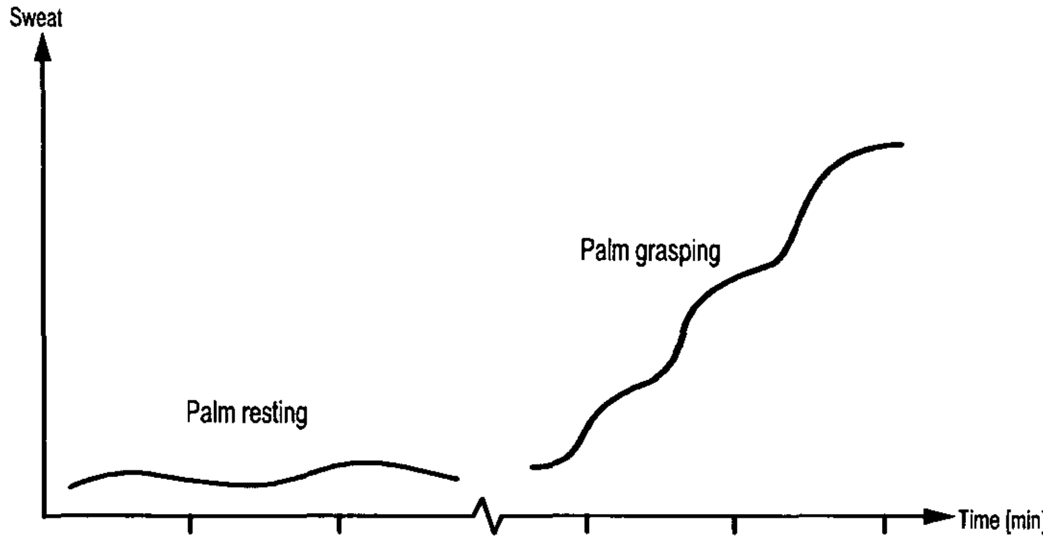


Figure 2.9 **Discharge of sweat from a single sweat gland of the palm at rest and during grasping. Time marking indicates one minute intervals (Rothman 1954). Left part; Secretion at rest. Right part; Discharge of sweat during the grasping of a dynamometer**

Thus, in addition to mental and thermo-regulatory sweating, the gripping of an object will induce sweat and moisture to the palm. According to MacKenzie and Iberall (1994) the ability of an individual to apply forces using palm opposition appears to be correlated with sweating.

2.7 Functional and medical consequences to palm exposure

Basically, all structures in the palm are sensitive to external load and may react with pain and inflammation (Renlund 1987, Putz-Anderson 1988).

- Nerves are sensitive to load. When exposed to force or hit by an object, they respond with a tingling sensation, numbness and pain, and eventually loss of function or paralysis in the innervated area. A well known condition is carpal tunnel syndrome when the median nerve in the carpal tunnel is compressed as a result of increased intrinsic pressure in the carpal tunnel, which is supported by the strong carpal ligament. The areas of a hand typically affected by the symptoms above are parts of the thumb, index, middle and parts of the ring finger.

- The inter-digital nerves of the fingers are particularly exposed. Each finger has a volar and a dorsal nerve branch. These are fairly exposed where they pass the inter-phalangeal joints where common tools such as scissors, pencils and other tools, which are held in between fingers, can compress them. The seams on gloves can also cause these problems.

- The most vulnerable tendon sheet is the flexor to the little finger, where it passes the metacarpal head. Frequent forceful hits on it, such as when pushing a chisel with a bare hand, can result in inflammation.

- Arteries that are exposed to forces may at times result in intensive pain.

- Veins are fairly invulnerable, but a constant load may result in some stasis of blood circulation.

- Fascila palmaris is a protection against high loads in the centre of the palm. When excessively exposed, it will react with pain, probably as a sign of rupture. Dupuytrent's disease is a growth of the fascia usually on the volar side, eventually leading to a major scar, a contraction of collagen, and bending of the fingers towards the palm side.

Figures 2.10 to 2.12 illustrate some musculoskeletal conditions (problems), their causes, symptoms and suitable actions suggested to avoid them (Sandvik 1995).

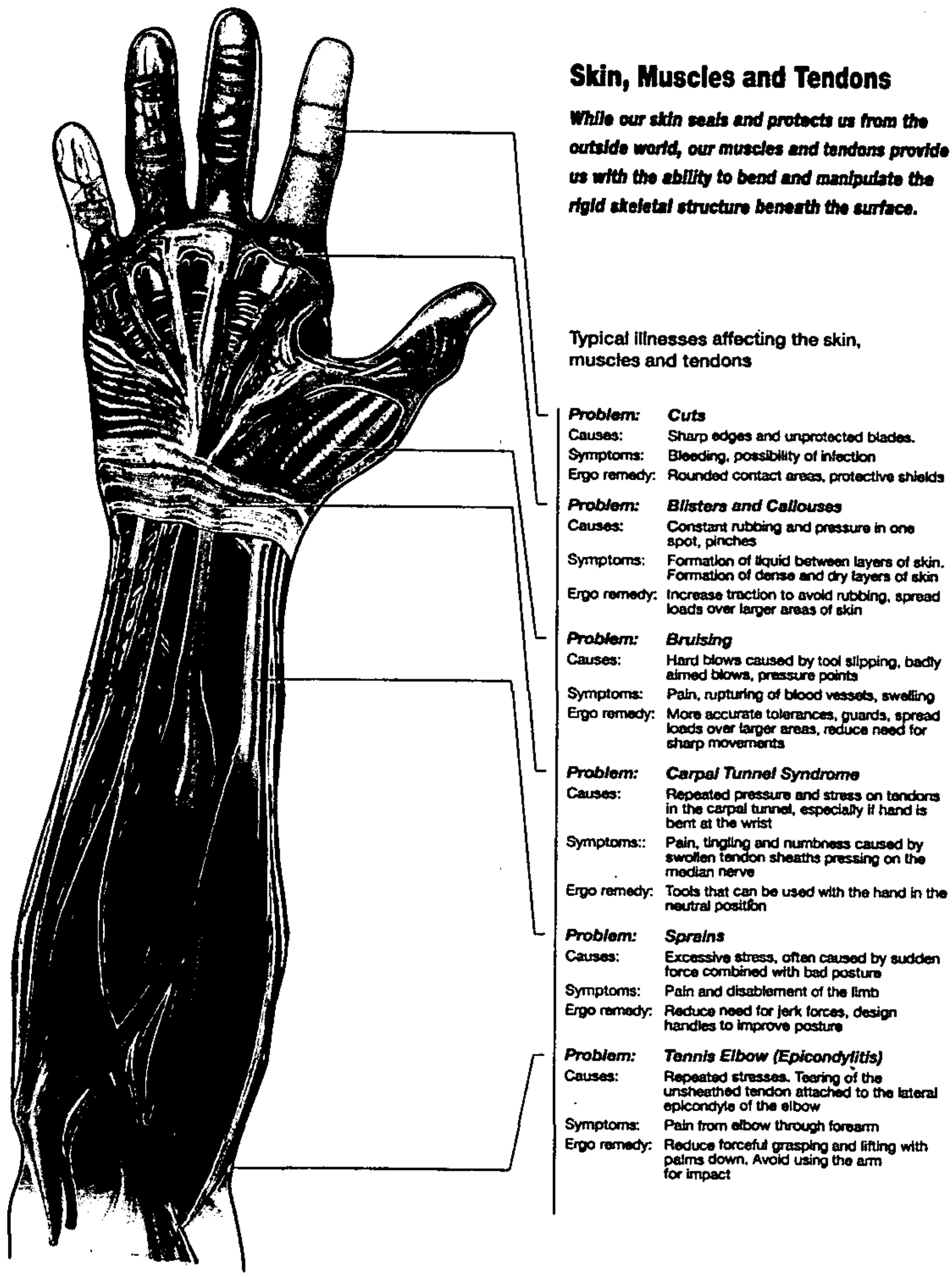


Figure 2.10 Examples of musculoskeletal trauma to skin, muscles and tendons, their causes, symptoms and suggested ergonomic remedy (Sandvik 1995).

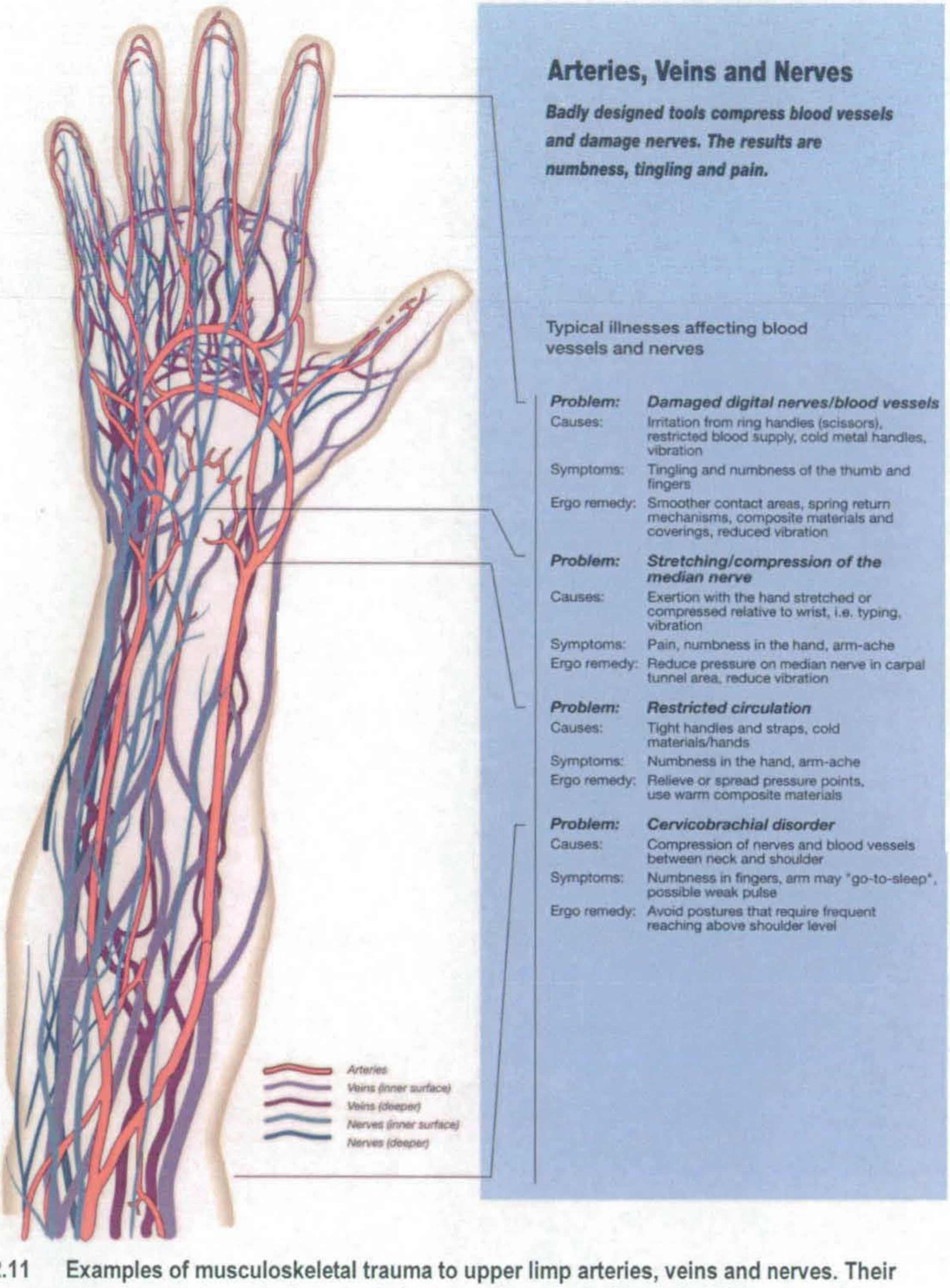


Figure 2.11 Examples of musculoskeletal trauma to upper limp arteries, veins and nerves. Their causes, symptoms and suggested ergonomic remedy (Sandvik 1995)

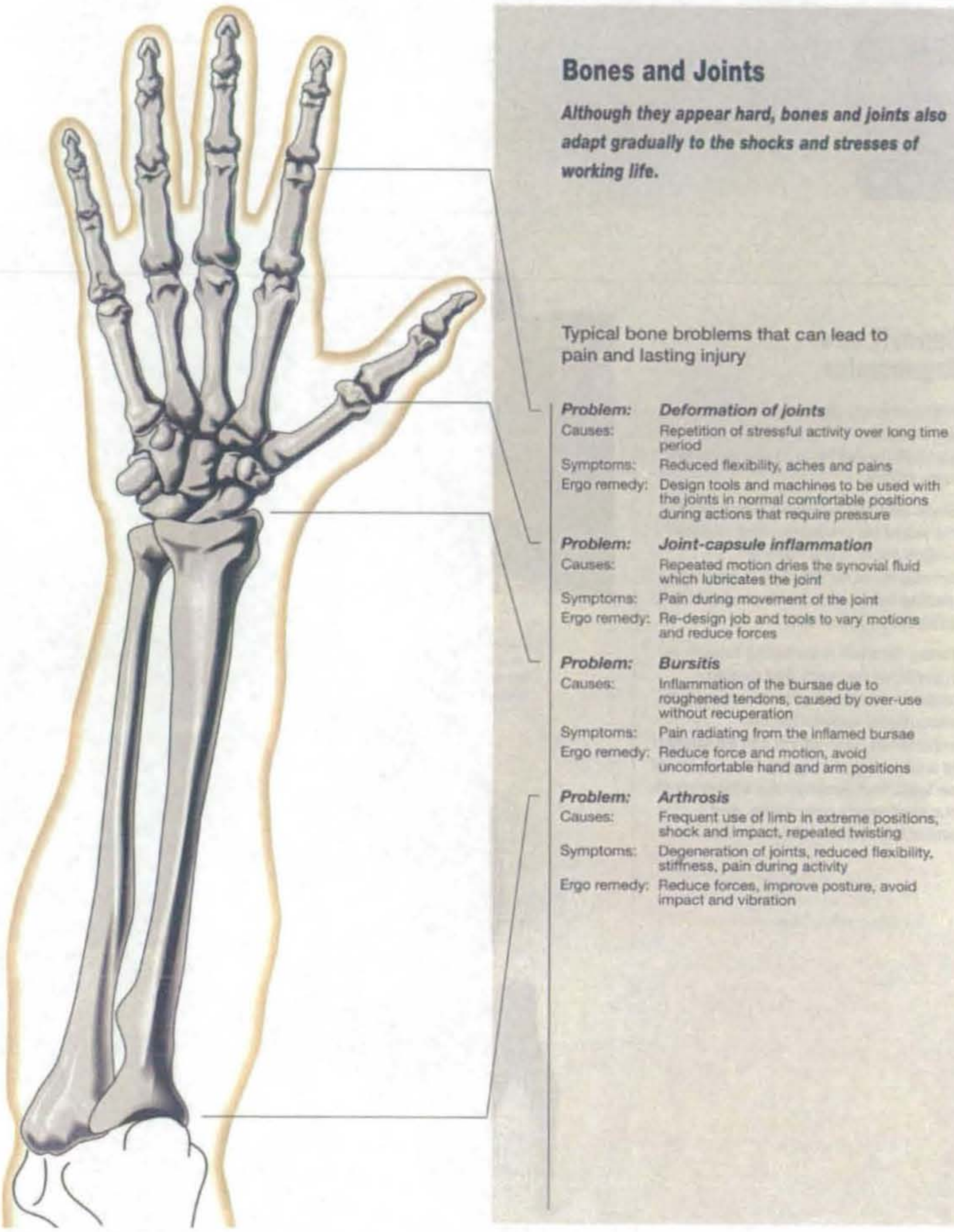


Figure 2.12 Examples of musculoskeletal trauma to bones and joints, their causes, symptoms and suggested ergonomic remedy (Sandvik 1995).

2.7.1 Repeated mechanical trauma to the skin

According to Samitz (1985) many present day jobs involve repetitive hand movements that damage the skin. Below is a citation from Samitz *ibid.*

> "Everyday in countless factories workers use their hands to perform the same task thousands and thousands of times. They assemble and they cut, they pull,

pound, pack and wrap, they grip handles and tools. Chronic mechanical trauma to the skin occurs in a variety of forms producing different kinds of effects to skin." (Table 2.2).

"Mechanically induced injuries to the skin e.g. through the use of tools may provide a means of introduction of bacteria, fungi, viruses and parasites. In addition, traumatised skin is often more permeable allowing the entry of chemicals that can irritate the skin or cause allergic contact dermatitis".

Lichenfication
Hyperpigmentation
Hyperkeratoses/calluses
Fissuring
Blistering/friction injury
Increased susceptibility to penetration of bacteria, viruses, and parasites
Increased susceptibility to the effects of chemical irritants and allergens
Irritant and foreign body reactions to non-absorbable dusts (asbestos), metal filings (beryllium), and fibreglass
Tattooing from occupational exposures to metals
Pressure urticaria
Scars and keloids
Cutaneous neoplasms secondary to burns and scars
Koebner phenomenon (psoriasis) from friction
Raynaud phenomenon ("white/dead fingers") and sclerodactyly from vibration

Table 2.2 Examples of damage to skin resulting from chronic mechanical trauma (as reported by Samitz 1985).

Samitz *ibid* concludes that a wide range of occupational skin problems emphasises the need to understand more clearly the impact of the work place on the skin and thereafter to develop guidelines for controlling hazards. In particular, the effects of repeated mechanical trauma require specific attention. Susten (1985) reviewed published medical literature in this field and the U.S. Health Statistics (population service and occupational health reports) to determine the long-range impact of repeated mechanical trauma to the skin in the work place.

Susten *ibid* writes;

"Chronic exposure of the skin to repeated small mechanical or micro traumas such as pressure, friction, vibration, minor punctures and shearing can cause a variety of skin changes. These alterations occur mainly in the hands, feet and knees. In the work setting such findings are often regarded as unimportant lesions that are indicative of an industrial craft or occupation. A "badge of the trade"."

However such mechanical trauma may have serious consequences, often unrecognised. Table 2.3 shows the number of awards for disability owing to corns and calluses for years 1969 to 1973. It is noteworthy that eligibility requires a full year of disability.

		Estimated No. of awards[b]	
Occupational group	**Dot codes[a]**	**Male**	**Female**
Misc. Jobs (classified by SSA[d])	No codes	23	0
Metal fabricating	800-809	10	0
Metal working, NEC[c]	610-619	10	0
Miscellaneous personal service occupations	350-359	5	0
Production and distribution of utilities	950-959	5	0
Building and related service occupations	380-389	4	0
Food and beverage preparation and service occupation	310-319	4	4
Protective services	370-379	4	0
Transportation occupations, NEC	910-919	2	0
Math and physical sciences	020-029	1	0
Lodging and related service occupations	320-329	0	4

*ICD (1968).
[a] United States Dept of Labor. Dictionary of Occupational Titles
[b]Eligibility for award required a full year of disability.
[c]Not classified elsewhere.
[d]Social Security Administration.

Table 2.3 Number of awards for disability owing to corns and calluses in USA for the years 1969 to 1973 (Susten 1985).

According to Susten *ibid* the Franklin Research Centre (FRC) Philadelphia USA, under contract to NIOSH, looked into problems caused solely by "friction and pressure" which was later defined as repeated mechanical trauma and included skin lesions resulting from repeated minor punctures, cuts and chronic vibration (Klingman et al 1985). In all, 600 articles and book titles were identified. In the qualified literature job categories were identified involving workers or jobs prone to repeated mechanical insults. The job categories were wide ranging and included meat cutters, painters, barbers, and jewellers, flooring installers, farmers, musicians, athletes and garbage collectors. Not unexpectedly, hands and fingers were common sites of injury.

On the basis of the index titles contained in the Supplementary Data System (SDS) at the Bureau of Labour Statistics USA, it was anticipated that this database would provide information for estimating costs and identifying causes of skin injuries. Six subcategories provided data that pertained to chronic skin trauma, namely objects handled, repetition of pressure, vibrating objects, leaning, kneeling, and undefined. Compensation costs to work related repeated mechanical traumas were estimated to have a national economic impact of at least $14-17 million. Susten (1985) claimed this figure to be an underestimation and argued that it did not include the costs of skin diseases that are not recognised by physicians or workers as having a mechanical trauma factor in their aetiology. The estimate of occupational dermatitis may be 10 to 50 times under-reported (according to the Standards Advisory Committee Cutaneous Hazards 1978). In addition 14 % of the civilian wage and salary work force in the US are not covered by workers compensation (Susten *ibid*).

Moreover, Johnson (1979) provided estimates of skin diseases based on findings from interviews and standard dermatological examination among a national probability sample of civilians aged 1 to 74 years. The data categories that appear to be directly relevant to the topic were corns and calluses. For these categories 3.2 per 1.000 of the identified corns and callosities were judged to be significant by the examining dermatologists i.e. conditions that should be seen at least once by a physician.

Susten *ibid* reported that case histories of skin disorders rarely addressed the potential contribution of mechanical traumas, and those that did generally included only an isolated sentence or two in the discussion section. Words such as "friction", "pressure", "abrasion", etc. were rarely emphasised in bibliographic citations i.e. the key words and titles of clinical reports concerning job related dermatological problems.

Hall (1995) investigated the levels of contact pressure on the palm when non-professional subjects in a laboratory used six hand tools. The results, which are interpretations from graphs, are shown in Table 2.4. These results show that peak pressure for screwdrivers and metal shears exceed the pain threshold (600 kPa for women and 845 kpa for men reported by Hall *ibid*),

Tool	Distal phalange		Most exposed area	
	Thumb	Index finger	Typical work cycle average	Peak recordings
Pen	70	30	50-150	250
Nippers	20	30	50-150	250
Drill	20	40	50-150	250
Saw	90	75	100	350
Screwdriver	50	20	100	600
Metal shear	20	100	500	1000

Table 2.4 Contact pressure in kPa on the palm during laboratory use by non-professional subjects. Data are from distal phalange on thumb and index finger. Peak recordings are from any of 15 palmar locations in each subject (Hall 1995).

Björing et al (2000) found that by employing softer handle materials when pushing forward with an electric impact drill (Bosch PSB 450), with forces of 40, 80 and 160 Newtons, decrease of the total pressure in the hand could be observed. The highest feed forces generated the highest pressures on the skin between the thumb and index finger, namely 343kPa. As handle material was shifted to softer varieties (62.5, 49.0 and 28.5 Shore (A) respectively), the pressure was reduced to 208, 177 and 115 kPa respectively. Similarly the pressure on the distal phalange on the index finger was reduced from originally 116 kPa to 78 kPa when the softest 28.5 Shore (A) handle cover was used. Softer material did not affect muscular activity.

2.8 Discussion of the hand in friction partnership

The biomechanics of the hand and the innervation of the glabrous skin of the palm represent very complex human systems. Hands are very basic to human beings and have been mainly unchanged since before humans started to stand upright. To research elements of this system, such as forces acting in the interface between palm skin and the surface of tools, requires an insight in several areas slightly on the periphery of ergonomics and in sectors which are not a common literature base for industrial designers.

Medicine, which is the faculty where such information belongs, is however well organised for literature search. A link to the database MEDLINE provided by the Karolinska Institutet, Stockholm, and the Search Service at Loughborough University Library proved to be efficient and very helpful in identifying relevant sources for information.

It was interesting to notice the number of diagnoses and cases of awards for disability as a consequence of repeated mechanical trauma to the skin, and the related national economic impact of at least $14 to17 million in the US (Samitz, 1985). Although these figures include skin locations other than palm, the financial cost is dramatic specifically, Samitz *ibid*, as anticipation of an underestimation holds true. It was however disappointing to find Samitz *ibid* reporting that case histories of skin disorders rarely addressed the potential contribution of mechanical trauma to the skin. The database dedicated to occupational injuries in Sweden, ISA, might be more helpful in identifying such details. Reports from a search in this database are reported in Chapter 3 "Friction, safety and performance in hand-object interaction". Other organs than the skin may also be injured as a consequence of inappropriate friction. Too low friction may demand excessive forces with increased risk for musculoskeletal injuries as one possible consequence. The references in section 2.7 "Functional and medical consequences to palm exposure" may act as guidance to the dedicated reader on sources of more information.

The classification system for hand function by Napier (1956) and the more recent by Cutkosky and Wright (1986) proved to be helpful in determining valid locations and directions for application of load to a hand simulating holding tools. It seems clear that the pads of the distal phalangy are exposed sites both when precision and power grips are adopted. Palm skin is remarkably tough and shows tensile strengths at levels of vulcanised rubber. The levels of palm pressure identified (Hall 1995) as peak and as means over a typical work cycle are however better suited as a basis for establishing pressure limits in a laboratory situation. Consequently pressures reaching towards 300 kPa were planned for in the series of experiments in this thesis.

The direction in which forces are applied in tool use were identified in the Special Issue dedicated to hand tools in the Swedish journal Research and Practice 'Forskning & Praktik' (1993) published by the National Institute for Working Life (NIWL) Sweden. It seems that the types of tools, which frequently are reported as problem tools, and which were identified as hazardous, are those that expose palm skin to forces in the direction along the fingers (i.e. distally).

The present chapter reported factors contributing to the generation of sweat and the onset of sweat gland activity e.g. thermal conditions, emotional stress and physiological workload, and according to Rohman (1954) probably also by pressure being applied on palm skin. The following chapters will show how a method and the required instruments were developed to account for these task, user and environmental demands.

Chapter 3. Friction, safety and performance in hand-object interaction

3.1 Introduction

This chapter discusses the need for both high and low friction in hand tool use, and how increased muscle involvement (in order to gain a steady grip for example on a low friction surface) may contribute towards a musculoskeletal injury. The effect that glove use has on grip forces and texture discrimination is also reported. Literature studies on accidents involving hand tools are reviewed based on data from the UK, USA, and Swedish sources. A unique analysis of trauma from slips with hand tools was specifically performed for the purpose of this thesis by the author. This trauma refers to: type of tool, type of injury, body part injured, number of accidents and absenteeism from work. Incidences of illnesses arising from the use of slippery tools are reported with reference to diagnosis and body parts affected, and also the consequent average number of days off work as a result of musculoskeletal injury.

3.2 Friction as a safety factor

Tools and handles can increase a person's productivity by extending and amplifying manipulative abilities. Since productivity is associated with a worker's livelihood, workers are motivated to carefully select and, in some cases, customise their own tools, when given the opportunity. Many workers do not have this ability, or are unable to select their equipment. Indeed, in many countries it is the responsibility of the employer or manufacturers of tools and equipment to select and design respectively items that are safe and efficient to use (Directive 98/37 EC). It has been shown by Putz-Anderson (1988) that proper attention to the selection and design of tools and workstation layouts can minimise the risk of cumulative trauma disorders. Pheasant (1990) and Armstrong and Chaffin (1979a) claim that the principal ergonomics risk factors associated with musculoskeletal problems in production line workers (and other people who perform repetitive manipulative tasks) are excessive force, wrist position, working posture and repetition rate. Some of the task demands known to contribute to such factors according to Pheasant (1990) are shown in Table 3.1, along with the related diagnoses.

Task demands	disorder
Repeated extension of wrist and / or fingers – e.g. repeated backhanded throwing actions	Epicondylitis, tennis elbow
Repeated "clothes wringing" action (flexion / extension with supination / pronation and power grip)	Tenosynovitis, esp. De Quervain's
Repeated radial and ulnar deviation, especially with forceful grip, e.g. using a spanner	Tenosynovitis, esp. De Quervain's
Repeated pronation / supination with ulnar deviated wrist, e.g. twisting with pliers	Tenosynovitis, esp. De Quervain'; tennis elbow; carpal tunnel syndrome
Repeated gripping actions with flexed wrist	Tenosynovitis of finger flexors (trigger finger)
Repeated flexion / extension of wrist, especially if combined with pinch grip or power grip	Carpal tunnel syndrome
Prolonged pressure on elbow, especially if elbow is flexed	Ulnar nerve entrapment at elbow
Repeated application of force with hand, with wrist in extended position	Ulnar nerve entrapment at wrist
Tools causing radial deviation of wrist, especially if combined with extension and pronation	Tennis elbow
Tools with triggers – especially if handle is too large so that proximal interphalangeal joint is extended	Tenosynovitis of finger flexors (trigger finger)

Table 3.1 Ergonomic risk factors for upper limb musculoskeletal disorders (Pheasant 1990)

3.3 The effect of friction and tactile feedback on grip forces

Exertion of hand force is an important factor in work performance, fatigue and chronic musculoskeletal disorders (Dickinson 1997, Armstrong and Chaffin 1979b, Armstrong 1983, 1983c, 1986c, Silverstein et al 1987, , Dickinson 1997). Much of the evidence for the association between hand force and cumulative trauma disorders has been qualitative and consequently has not supported development of a quantitative definition of excessive force for specific tasks. One reason for the scarcity of such evidence is the difficulty of measuring hand force exertion in manual work in industry. For manual tasks, involving a frictional coupling between the hand and the object, it may be possible to estimate hand force requirements using equations from tribology as gripping force Fn can be calculated based on information on friction forces Ff and the coefficient of friction μ, as $Fn = Ff/\mu$ (Chapter 1).

Low coefficient of friction in the hand-handle interface may require higher grip forces in tool use. In addition, as mentioned in Chapter 1, several researchers have shown that gloves reduce the tactile feedback and reduce a subject's capacity to generate high forces in grip force exercises.

Thus, both reduced friction in the hand object interface and impaired tactile feedback will require the generation of more muscle and tendon tension to hold and operate traditional manual hand tools but also to support power tools such as chain saws or angle grinders. This may result in unnecessary stress and strain on the wrist and arm, and increased risk of musculoskeletal injuries. Well designed handles with suitable friction can, in these cases, be a design alternative.

One particularly work intensive industry involving the hand is meat processing in which a major problem is injuries from knives as a result of the handles being slippery with blood and fat. As a result, excessive grip forces are demanded to avoid the hand sliding down towards the blade (Natarajan et al 1984, Riley et al 1985,, Malker 1991). Unfortunately these high forces will increase the risk of Cumulative Trauma Disorders, particularly as the hand is often used in extreme wrist postures (Armstrong et al 1982). A mechanic may increase the risk of injury if tool handles drastically change their coefficient of friction when exposed to water, oil or grease. Accuracy and quality in performance may also be impaired.
Some tools, for example chisels, need to be handled both with considerable precision and with force, while in some professions e.g. mechatronics, the need for optimum friction and tactile feedback is even more essential. A dentist must be able to rely on stable frictional characteristics of their tools to avoid sudden and drastic changes in the coefficient of friction, for example when water or body fluids come into contact with the handles of their instruments. Thus it is important for the industrial designer to design for appropriate friction depending on tasks, users and environmental demands.

Maximal prehension grip forces (using the power grip) have been investigated by numerous researchers and are well presented in Hall (1995). Mathiowetz (1985) and Dempsey and Ayoub (1996) reviewed maximal precision grip (pinch grip) forces. Several laboratory studies of grips (e.g. power gripping and precision grip) along with design recommendations have been performed and are reported separately in Chapter 4 'Design recommendations for handles in the literature'. Johnson (1988) reported that subjects used significantly less grip force (16%) to operate a powered screwdriver equipped with a high-friction (vinyl-covered) handle rather than a low-friction (aluminium) handle. Frederic and Armstrong (1995) researched hand friction but found that the effect of friction on pinch force exertion was significant only at high loads i.e. 50% or more maximal pinch strength (on an aluminium surface).

3.4 Statistics on accidents involving hand tools

The hands are frequently injured when using tools and when handling objects and supporting the body. According to a specific investigation into occupational hand injuries performed by the Swedish insurance company (Kullman and Larsson 1984). concerning Swedish conditions (1981-1982), 36 % of all reported occupational injuries involved the hand. These hand injuries accounted for approximately 800,000 days of sick leave per year in a total work force of 4.53 million. However, hands are exposed to risk in many different ways and can be injured without the presence of a tool. For example hands may be struck against moving parts, pinched by moving belts or injured by production machines.

Industry	Frequency of hand injury (%)
Food processing	56.0
Wood working industries	50.0
Metal working industries	43.5

Table 3.2 The frequency of hand injuries in the 'most injuring' sectors in Sweden according to AMF (1984).

The highest frequency of hand injuries in Sweden was observed in the food processing industry (Table 3.2). The highest frequency of *disabling* hand injuries occurs in wood working industries, which is a major industrial sector in Sweden. Of all hand injuries in Sweden hand held power tools (e.g. electric or pneumatic) and other (non-powered) hand tools (e.g. knives) were together involved in 7 %. US data (Aghazadeh and Mital 1987) show that hand tool related injuries comprise about 9% of all work-related compensatable injuries. Some of these injuries may have occurred as operators' hands were slipping on the hand tool handle. Specific analyses of such occurrences were performed by the author in relationship to his thesis and are reported below in section 3.4.4

Well-designed hand tools (regardless of type) will improve user performance, quality of work and operator comfort (Armstrong 1986c). In the professional situation, tool use has consequences for the individual operator, the company, as well as to society. Many hand tool injuries are cumulative in nature and working with improperly designed tools may result in chronic ailments (et al 1986c, Putz-Anderson 1988, Mital and Kilbom 1992a, Mital and Kilbom 1992b). Below are statistics focusing on accidents and injuries where hand tools were involved. The results for Great Britain and U.S.A below are compilations of reported data. The results from Sweden contain additional information from accidents, injuries and illnesses where operators' hands have slipped on the hand tool handle. The data were collected from the databases SISILO, NIOSHTIC, ARBLINE, ERGONOMICS ABSTRACTS and the National Institute of Occupational Health and Safety in Sweden.

3.4.1 UK statistics

In the UK, reporting accidents and ill health at work is a legal requirement. The information enables the Health and Safety Executive, HSE and local authorities to identify where and how risks arise and how to investigate serious accidents (HSE 4/97). The Health and Safety Executive in the UK presented statistics on accidents and injuries relating to the use of hand tools in the UK as reported under *RIDDOR* (Reporting of Injuries, Diseases and Dangerous Occurrences Regulations) for the years 1993/94 - 1994/95 (Smith, 1997b). The data presented in Table 3.3 shows that injuries from non- power tools result in a higher number of injuries than power tools. Both types of tools generate roughly the same number of severe (major) injuries, 92 and 81 respectively, but non-power tools were involved in nearly 4-fold the number of injuries than power tools of the kind that resulted in 3 days or more of sick leave, i.e. 2046 and 526 respectively. The relative risk of an injury from the respective tool category is, however, not possible to calculate from these figures as no exposure data were presented.

Agent	Major	Over 3 days	Total
<u>Non powered hand tool</u> Summary of non powered hand tools, not specified as to type	81	2046	2127
<u>Powered hand tools</u> Summary of powered hand tools, specified as to type below	92	526	618

Table 3.3 Injuries involving being struck by hand tools and portable power tools 1994/95 (Smith 1997b)

3.4.2 US statistics

A report by Aghazadeh and Mital (1987) describes the situation in the USA for the year 1980, and involves all types of industries. The data were collected from Federal and State agencies and not directly from the industries concerned. This was because most of them did not want to publish their injury data bearing in mind that their statistics might be detrimental to their public image. However, data from 23 States provided very useful information. Table 3.4 lists non-powered hand tools that are mostly involved in accidents and injuries. Non-powered and powered hand tools were responsible for 80% and 20% of compensentable hand tool injuries respectively (Aghazadeh and Mital 1987). Thus the data corresponds very closely to the UK data referred to above.

Hand tools	Number of cases	Percent of all case
Knife	30168	51.8
Hammer	6838	11.7
Wrench	6072	10.4
Shovel	3850	6.6
Rope, chain	2290	3.9
Crowbar	2047	3.5
Scissors	1654	2.8
Screwdriver	1420	2.4
Saw	940	1.6
Pliers, tongs	676	1.1
Axe	517	0.9
Chisel	476	0.8
Pick	373	0.6
Fork	328	0.6
Blowtorch	187	0.3
File	143	0.2
Hatchet	94	0.1
Punch	92	0.1
Plane	31	0.05
Total	58196	1.00

Table 3.4 Non-powered hand tools that are most involved in accidents and injuries in USA 1980 (Aghazadeh and Mital 1987).

In relating specifically to amputations, Aghazadeh and Mital *ibid* reported that in a sample of 194 hand tool related amputations, 86 related to non-powered tools and 108 as a result of the use of powered tools. The tool related figures represent 3.9% and 5.1% respectively of all hand amputations in the USA.

Aghazadeh and Mital *ibid* used these statistics as a basis for estimation of the total USA costs associated with hand tool injuries. Table 3.5 summarises their findings. They estimated a total number of 265,570 disabling injuries for which the annual indemnity and medical costs alone 1980 came to $ 400 million (approximately $1,500 per case). Direct total annual costs were close to $10 billion when calculating the total direct costs by assuming an equal cost for:

- workday losses

- wage losses
- insurance costs
- other direct costs

Indirect costs (disturbances in production, training of new staff etc.) were estimated to be four times the total direct costs according to standard practice in the field of occupational safety (Aghazadeh and Mital 1987).

Type of costs	Estimated annual costs	Comments
Indemnity and medical costs	$ 400 million	Data collected from federal and state agencies in 23 States in the USA over the years 1979-1987.
Direct total cost	$10 billion	Equal costs were assumed for workday losses, wage losses, insurance costs and other direct costs
Indirect costs	$40 billion	Four times the direct costs
Summary of costs	$50.4 billion	Number of hand tool injuries

Table 3.5 Summary of estimated annual costs related to hand tool injuries in USA (Aghazadeh and Mital 1987).

Marras et al (1988b) reported that the vast majority (70 - 80 %) of hand tool related injuries in the USA were due to the use of non-powered tools. In the rail industry in the USA, hand tool related injuries represented a loss of 3 to 4 million worker-hours per year and accounted for more lost time than injuries from manual handling. They were exceeded in severity only by injuries from slips and falls (Rockwell 1982). Quisenberry (1985) reported that in the mining industry in the USA, hand tools were involved in a total of 21% of all hand and finger injuries during a 5-year period. In this industry, tools such as wrenches, screwdrivers and hammers are usually larger, heavier and require more force than those found in workshops. As a result they may cause more severe accidents if they slip out of the hand injuring the user or are dropped from above with the risk of injuring someone else. Combined with the greater mass of the tool, there is also risk of over exertion injury due to a greater load on the body. Dampness also contributes to a tool slipping from the worker's grasp (Quisenberry 1985).

Cumulative Trauma Disorders CTDs), which traditionally are associated with smaller, lightweight tools also occur in underground coal mining where heavier, and larger, hand tools are used (Marras et al 1988a). Examples of such tools are wrenches, screwdrivers, pliers, knives, axes and pry bars. They are frequently used for routine work, but also for maintenance and repair of machines and vehicles. Most injuries were due to over-exertion and 'struck-by' accidents. Over-exertion occurred in about 11% of the cases and had a considerable number of days lost associated with them, namely 23 days per case. "Struck-by" accidents with these types of tools are more frequent, but account for only 8.5 days of lost work per case. The types of injury include:

- breaks (bone fractures)
- torn muscles
- dust in the eyes
- cuts
- inflammation of joints, tendons or muscles
- dislocations
- strains and sprains

Table 3.6 shows the most hazardous hand tools used in the underground coal mining industry in order of workdays lost. Hammers, axes, wrenches and knives accounted for 2,374 (43.1%) of accidents, resulting in 19,051 days lost (over a six-year period). It is interesting to note that the tools most characteristic of this trade (i.e. jack-leg, drill, scaling bar and pry bar) were most frequently involved in accidents. It appears to be a challenge for industrial designers and ergonomists to contribute to the development of these speciality tools.

Tool	Number of accidents	Average days lost per accident	Total days lost
Scaling bar	760	31.05	23601
Jack	1139	19.50	22205
Pry bar	677	20.75	14065
Hammer and axe	1104	10.05	11105
Pneumatic drill	555	17.51	9717
Wrench	430	13.20	5688
Knife	840	2.69	2258
Total	5505		88639

Note: A scaling bar is similar to a pry bar but generally longer, four to eight feet, and used to remove loose rock from the roof.

Table 3.6 **The most hazardous type of tools in underground coal mining during a six-year period 1978 to 1983 in order of total days lost per accident (Marras et al 1988a)**

3.4.3 Swedish statistics

In Sweden (1989), in all occupations, the work force numbered 3,817,200. The types of hand tools listed in column two and three of Table 3.7 were identified from filed reports to the National Health System in 1989 (Malker, 1991) as causing most ergonomics-related accidents and injuries among professional users in metal working industry, automotive and electronic industry in Sweden.

Column four in Table 3.7 refers specifically to non-powered tools in the metal working industry (production of steel and metal objects), which caused injuries to the hand, arm and shoulder in 1990. The ranks show the most frequently reported ergonomics-related problems as perceived by the users. The research was performed by a project group who interviewed health and safety staff, unions and employees in order to initiate product development and redesign (Kardborn 1998).

The tools that dominate statistics are knives, hammers, sledges and tools by which torque is applied (e.g. on bolts, nuts, pipes) such as wrenches and screwdrivers. Knives are widely used in Sweden and are found in most production facilities and, as the statistics in this report indicate, also in the metal working sector. Hammers and sledges are builder's tools but torque tools are mainly seen in maintenance and repair situations and also in industrial assembly. These types of tools are common and mainly used without any formal training. The data do not show the number of tools in use or any exposure data.

Type of tool	Number and % of reported ergonomics-related hand tool accident/injuries in metal working, automotive and electronic industry		Rank order of subjective judgements by users as to the risk of accident/injuries in the metal working industry (MW)
All tools reported	9634	100%	
Knife	3664	38.03	2
Hammer, sledge	1382	14.34	1
Torque tools, screwdrivers, wrenches etc.	1287	13.36	3
Pointed iron bar level	599	6.22	5
Spade, rake, gardening tools	366	3.78	
Rope, chain, claw etc.	344	3.57	10
Saw	192	2.00	7
Shears, scissors etc.	182	1.89	4
Files	174	1.80	7
Needles, awls etc.	106	1.10	9
Wood, chisels etc.	98	1.02	
Other cutting tools	68	0.71	
Axes	67	0.70	
Rock drills, chisels etc.	34	0.35	
Pipette, pumps etc.	27	0.28	
Not specified	-		6

Table 3.7 Type of tools identified as causing most ergonomics-related accidents and injuries among professional users in metal working industry, automotive and electronic industry in Sweden (Malker 1991) and Kardborn 1998).

The subjective judgements confirmed the official statistics above. Thus a series of tools were identified which not only were involved in a large number of accidents, they also caused the user's problems when used professionally. The degree to which hand and handle friction plays a role in such trauma or problem is reported in section 3.5 "Trauma from slips with hand tools" below.

3.4.4 Trauma from slips with hand tools

The focus of operators slipping with their hands on hand tools, and consequently get injured, was introduced by the author when researching skin friction. A unique register of occupational accidents (immediate events causing an injury), injuries (trauma to the body) and illnesses is available at the National Institute of Occupational Health and Safety in Sweden. Its strength is the high frequency of data input, which is a result of the link to the national health and welfare system. In order to receive compulsory worker compensation, the affected worker completes a form detailing the particular situation and also a detailed description of the circumstances and conditions that resulted in the injury or illness. This includes information before and during the accident and details of the tool operator and the environmental conditions when the accident occurred. This included for example, the type of tool used, the way it was used and what transmitted the energy or chemical that injured the operator. Thus it was possible to identify the chain of events which eventually resulted in an accident in which the operator's hand slipped on the hand tool. The type of hand tool used and the sections of the body that were injured are specified. In addition, the data system provided information on the number of illnesses, the average number of days off work as a consequence of occupational overuse (i.e. Work Related Occupational Syndrome (WROS) or Repetitive Strain Injury (RSI)), and what part(s) of the body were affected. This system registers all filed injuries reported to the National Health Care System regardless of whether the injury eventually is compensatable or not. The form allows for open answers by the injured worker, the content of which is coded in detail by clerical workers and fed into a database which is open for researchers who may request specific search profiles. This database (ISA 1998), covering the year 1997, was used by the author for the purpose of this thesis. The aim was to identify specifically such accidents in which the operator's hand slipped using a hand tools. That year 670 such accidents were registered (Table 3.8). In addition, 1,418 illnesses caused by occupational overuse (WROS/RSI) were registered where hand tools were reported as an external factor in the chain of events that eventually resulted in the illness (Table 3.10). The statistics below are discussed in Section 3.5.2

Tool code	Type of tool	Number and%		Average days off work
3497	Knives, scalpels	277	41.34	17.3
3534	Torque tools e.g. screwdriver, wrench, spanner, wrench	204	30.15	8.5
3532	Hammering tools e.g. hammer, sledge	36	5.37	11.2
3093	Bending e.g. crowbar	35	5.22	11.7
3295	Holding- cutting e.g. pliers tongs.	26	3.88	10.2
3401	Saws	13	1.94	33.1
3452	Planing- and grading tools e.g. file rasp.	12	1..79	7.8
3	Hand held no-powered tool or equipment	11	1.64	10.1
3615	Tools for cleaning e.g. brush, broom, scraper and cloth.	10	1.49	11.5
3491	Axe	9	1.34	45.3
3224	Shearing tooling- Scissors, metal shears.	8	1.19	5.3
3493	Other cutting tools for wood, plastics etc.	7	1.04	24.8
3894	Lifting- transporting tools e.g. jack, tray and stretcher.	6	0.90	9.5
3447	Perching tools e.g. needle, syringe.	6	0.90	7.7
3052	Peeling tool e.g. potatoes, bark.	5	0.75	4
3499	Other shearing tools	2	0.30	11.5
3536	Riveting tool	2	0.30	-
35	Not specified hand tool	1	0.15	-
	Total	670	100	13.7

Table 3.8 **Occupational injuries and average days off work, as a result of the subject's hand slipping when using a tool (The Register of Occupational Accidents, Sweden 1997).**

Code	Body part	Number and%		Average days off work
12* 22*	Fingers	303	45.22	14.9
02*	Face	159	23.73	0.2
13* 23*	Hand, wrist	136	20.30	25.2
14* 24*	Shoulder, arm	28	4.18	11.3
17* 27*	Hip, leg, knee	23	3.43	15.6
01*	Head not face	6	0.89	0.5
06*	Abdomen, pelvis	6	0.89	16
11* 21*	Eye	4	0.60	6.8
05*	Chest	2	0.60	25
03*	Neck, throat	1	0.15	3
04*	Back not neck	1	0.15	47
16* 26*	Foot, ankle	1	0.15	7
	Total	670	100	13.7

Table 3.9 **Body part involved in occupational injury, and average days off work, as a result of the subject's hand slipping using a tool. (The Register of Occupational Accidents ISA, Sweden 1997).**

Code	Sector of body	Number and%		Average days off work
14* 24*	Shoulder, arm	564	30.77	97.2
13* 23*	Hand, wrist	284	20.02	83.4
03*	Neck, throat	255	17.98	173.8
04*	Back not neck	187	13.18	167.9
17* 27*	Hip, leg, knee	59	4.16	214.8
12* 22*	Fingers	40	2.82	62.9
07*	Body generally	13	0.92	153.8
06*	Abdomen, pelvis	6	0.42	88.2
16* 26*	Foot, ankle	5	0.35	137.5
05*	Chest	4	0.28	26
01*	Head not face	1	0.07	10
Total		1418	100	122.3

Table 3.10 Occupational illnesses. Sections of the body that were affected, the number of illnesses and the average number of days off work as a consequence of occupational overuse (WROS/RSI).

3.5 Discussion of accidents and injuries, with reference to hand tools and palm friction

The aim of this section is to put the design of hand tools, and particularly the handles, in a health and safety perspective, and identify design factors to guide in the design of hand tool handles.

The accident statistics above refer to trauma where hand tools have been involved and in a dedicated research identify trauma resulting as a consequence of the hand slipping on tool handles. For the designer of hand tools, the type and severity of injuries caused by specific tools provide important information. Several of the statistics referred to above report trauma where particular types of tools are involved.

3.5.1 Accident and injury statistics

Although several statistics reports from UK, USA, and Sweden have been analysed, no clear data showing the significance of handle design to the incidence of accidents and injuries were found. It was clear that traditional non-powered hand tools show up in higher numbers in accident reports than powered tools. The number of injuries where non-powered tools were involved was approximately 4-fold the number of powered tool injuries.

The exposure to these two types of tools was, however, not known and both the frequency and duration of exposures may be different. A higher frequency of exposure to the more common non-powered tools was however likely to be the case and was also suggested by Marras et al

(1988a) and Smith (1997b). Non-powered hand tools appear in 80% of all reported hand tool accidents but the injuries seem to be less severe and result in fewer days off work than injuries from power tools.

The frequencies of hand tool related injuries (if looking at the combined use of hand-held power and non-powered tools) are fairly similar and ranging 7 to 9%, of all work related compensatable injuries in USA and Sweden respectively. These data should not be confused with data on hand injuries, as hands may be hurt where hand tools are not being used e.g. in falls and when hands are caught between objects, trapped, pinched etc.

The differences in methods for data collection, type of industry etc. makes it difficult to compare different sources of statistics, particularly between countries, and results may be difficult to interpret.

Injuries from power tools appear according to be more severe than those from non-powered tools. Aghazadeh and Mital (1987) investigated the incidence of amputations following the use of these two types of hand tools. They found that in the majority of cases (61.7 %), power tools had been used, while non-powered tools were involved in 38.3% of the identified amputations. Aghazadeh and Mital *ibid,* and Smith (1997b) respectively, report that non-powered and powered hand tools were involved in 71-80% and 20-29% respectively of compensentable hand tool injuries. One reason for the higher number of amputations in connection to power tools may be the higher power and forces acting in the hand handle interface and the eventual longer duration under which these power tools are used in the same posture. The more widely use of non-powered hand tools may account for the higher frequency of those reported injuries.

The Health and Safety Executive in the UK (Smith 1997b) showed that power tools such as drills, circular saws, and tools for cutting, grinding, and fettling resulted in most days off work in convalescence following accidents. From the statistics, power drills and circular saws appear to be particularly hazardous.

There is clearly a need for investigations into the frequency and duration of the use of various hand tools in order to calculate the relative risk of an injury from each type. For the industrial designer both types of tools represent a challenge. The author developed a research method aimed at developing ergonomic hand tools, Bobjer and Jansson (1997a), available in Appendix 4 "User participation in hand tool design". It is recommended that detailed analysis of task, user and environmental demands are performed along with analysis of accident and injury data for the understanding of hazardous design elements in the hand tool of concern. Textures and materials in handles are examples of such elements.

3.5.2 Hand slipping

The results from the dedicated survey in the Swedish database on occupational injury (ISA report 1998), and average days off work, as a result of the subject's hand slipping using a tool, reveal unpublished data. The highest frequency of such slip injuries relates to knives, screwdrivers, wrenches and spanners (Table 3.9).

Most days off work are accidents associated with sharp tools that are used with considerable energy. Such tools are axes and other cutting tools, saws, knives and scalpels etc. (Table 3.9). Regardless of tool type hands, fingers and wrists are most frequently injured (Table 3.10). Slips on knife handles are obviously risky due to the short distance between the hand and a sharp blade. This information opens a variety of design opportunities for the industrial designer.

Wrenches and spanners are designed for access in confined spaces and in awkward postures. They are generally designed with handles of steel, frequently polished and chromed to give a glossy finish. The understanding of the environmental conditions under which they are used, and details of the friction involved may guide the designer in the development of safer tools.

The parts of the body that is most frequently reported accidents when slips occur are fingers, the face, hands and wrists (Table 3.10). The highest numbers of days off work are found in relation to injuries to limbs, the back and the chest. It is no surprise that hands and fingers suffer in hand tool accidents, particularly when the analysis focuses on slips. The high number of severe back and chest injuries may be as a result of sprain, or the operator losing their balance and falling when control of the tool was lost. Further analysis would be necessary to identify the details in the total chain of events.

The use of databases may unfortunately involve errors. Due to the manual interpretation of open written statements and the transformation to codes, there may be a risk that a statistic includes errors and operators' slips, "slipping on the floor" for example may have been confused with slips on the tool handle. However slips at the active tool end e.g. the tip of a screwdriver, may also have been confused with "slips on the tool handle".

3.5.3 Musculoskeletal injuries

As to work-related overuse syndromes and repetitive strain injuries reported in relation to hand tools, some interesting data were observed. Table 3.10 shows the part of the body suffering from occupational overuse (WROS/RSI), the number of illnesses and average absenteeism from work as a result of hand tool use. Injuries to parts of the body that are most frequently reported are limbs and joints with a high degree of freedom (e.g. neck, shoulder and wrists). More days off work are however reported in relation to parts of the body which are affected by posture namely leg, back and neck.

In addition to accident and injury databases there are other sources of information available to the industrial designer providing details about the design of handles generally and aspects of friction specifically. Chapter 4 reports the findings from a survey of such sources.

Chapter 4. Published recommendations for the design of handles

4.1 Introduction

The choice of material for use in handles has traditionally been a function of the technological demands on the tool. Thus hickory and ash have long been a recommended strong material for use in handles for axes and hammers as these woods grow with long tough fibres, providing a durable shaft unlikely to break when exposed to shock and vibration. The texture on traditional handles generally follows the intrinsic texture of the material used. Man-made surface textures are seen as carvings in wood or bone or are made with leather or rope, or with silver and gold wires (e.g. on military arms and swords). It is difficult to know whether these textures served any other than a decorative purpose or gave an indication of status, rather than to influence hand handle friction. However, it is obvious that a safer and steadier control over the tool can be gained when the hand handle interface provides a high friction, and providing no drastic change in coefficient of friction takes place when the environmental conditions in the friction interface change. The aim of this chapter is to identify published design recommendations for guidance in the design of hand tool handles and specifically the choice of textures.

4.2 Bibliographies, testimonies and standards

A number of factors are known by ergonomists to affect performance in industrial production (Konz 1990; Wilson and Corlett 1995; Clark and Corlett 1995; Helander1995; Ayoub and Mital 1989). The testimonies given by international expert witnesses to the US Department of Labour in March 2000 on ergonomics standards publicly available on the internet (www.osha.gov) provide an excellent source of information on the effects which organised health and safety measures may have on society, companies and individuals. The US National Institute of Occupational Safety and Health, NIOSH, has published task, user and environmental factors known to affect the risk of developing a cumulative trauma disorder (Putz-Anderson 1988). In addition Fraser (1980), Armstrong (1986a) Freivalds (1987), Ulin et al (1995), Mital and Kilbom (1992a, 1992b), Radwin and Haney (1996) have published material on design factors of hand tools that may affect the risk of developing a cumulative trauma disorder. These include force, frequency, posture, static/dynamic movements, vibration and cold. Mital and Kilbom (1992a) emphasise the problem definition by investigating data pertaining to injuries, tasks and the tools. Ergonomic work analyses are suggested including observations of postures, handgrips and recordings of forces, focusing on weight balance, grip design and surface to answer the question "Does the tool give feedback of proper function?". A report by Wikström et al (1991) shows design criteria for ergonomic tools. Jansson (1999) presented task and operator factors affecting the risk of developing a cumulative trauma disorders (Figure 4.1). In addition environmental, e.g. contaminants, temperature and humidity, but also mental stress as well as factors of work organization may affect the risk.

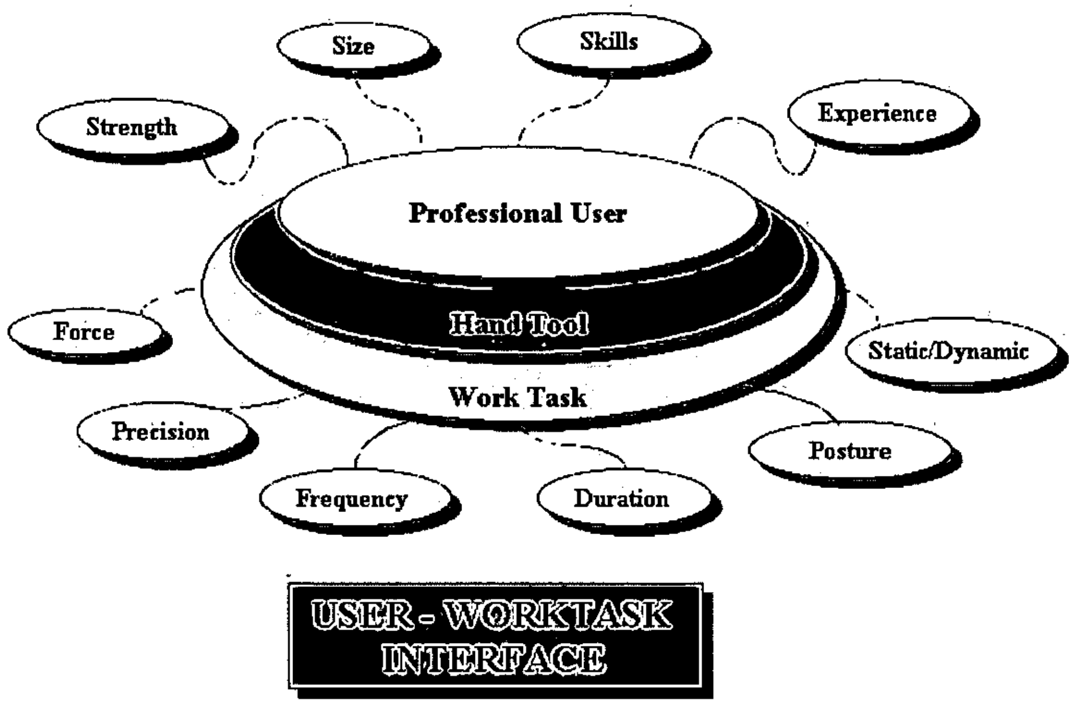


Figure 4.1 **Task and operator factors affecting the risk of developing a cumulative trauma disorders (Jansson 1999) with permission.**

The Directive 98/37/EC of the European Parliament, contains a series of CEN and EN standards, some of which include

- Ergonomic requirements for control actuators
- Ergonomic design principles
- General principles for design
- Human body measurements

The European Standard, CEN, holds legal status in the European Community. No Standards currently address handle design. It is, however, good practice that designers keep up-to-date with relevant standards. The data in encyclopaedias and databases may be very relevant and are easy to access. References may however be scarce and several unspecified basic sources may have been combined. Methods for data collection and errors in the original data material are rarely reported. This comment applies also for several of the details on hand tool handle design referred to above.

Further design recommendations for handles can be found in several databases for the dedicated reader e.g. Encyclopaedia of Ergonomics, edited by Karwowski (2001).

4.3 Literature survey on design criteria for hand, and power-tool, handles

In a literature search concerning the impact that handles on hand tools may have on the human operator, a number of design factors have been found. These include size, shape, material, texture/surface finish, grooves, sharp edges/ form fittings, energy expending, fatigue, RSI/ CTD, load and shock absorption. Table 4.1 shows a summary of such sources with reference to these tool aspects, identified through data bases and a literature search. The references are research papers, conference proceedings, and trade union recommendations and textbooks described in some detail below.

Tool, task and operator factors	Citations
Texture/Surface finish	Naylor (1955), Comaish and Bottoms (1971), Meagher (1987), Pheasant (1990), Mital and Kilbom (1992a, 1992b), NIOSH (1992), Greenberg and Shaffin, (1977), Konz (1990)
Shape/Size	Pheasant and O'Neill (1975), Greenberg and Shaffin, (1977), Pheasant (1986, 1994), Meagher (1987), NIOSH (1992), Mital and Kilbom (1992a, 1992b), ANSI Z-365 (2000)
RSI/CTD	Meagher (1987), NIOSH (1992)
Material	Pheasant and O'Neill (1975), Greenberg and Shaffin (1977), Peate (1997),
Energy expending	Naylor (1955), Comaish and Bottoms (1971)
Fatigue	Mital and Kilbom (1992a, 1992b), ANSI Z-365 (2000)
Load	Health and Safety Executive UK (1999)
Shock absorption	Meagher (1987)
Purpose	Meagher (1987)

Table 4.1 Literature references on design recommendations for handles on hand tools

4.3.1 Texture

Greenberg and Shaffin (1977) write.

> "Texture is of course not merely an aesthetic quality, it is also functional. A tool handle requires a readily identifiable texture to provide an input to the sensory nervous system to assist in maintaining the grip. It is desirable in fact to ensure that some distinctive surface texture is incorporated into an otherwise smooth plastic handle for this purpose. Flutings, ridges and indentations, which were intended to provide texture and increase frictional resistance might, in fact cause pressure injures to the fingers. Some doll roughening, palpable to the skin of the hand, but neither sharp nor injurious can serve the purpose better. Deep recesses of greater than 3 mm are not recommended because of the variation in morphology of the finger throughout the population. In particular a person with large fingers may create compression forces on the surface of the fingers, which are abundant in superficial nerves, arteries and veins or a person with small fingers may be forced to attempt compression of two fingers into one recess with similar result."
>
> "Metal handles may be used in some tools in place of wood or plastic, but to meet the requirements of shock absorbency, thermal conductivity, frictional resistance and texture, they have to be covered with a rubber, leather, or synthetic sheaths of a thickness appropriate to the material used. For a good grip a compressible gripping surface is best. They should be hard enough to resist imbedding of particles or dirt in the gripping surface.

Greenberg and Shaffin (1977) claim.

> "Highly polished surfaces should be avoided. Smooth surfaces should only be provided when small forces are needed frequently to actuate the tool. Non reflective ripple coatings should be used in most cases. Casts or machine surfaces should, if possible, be coated with matt paint or other similar material. Should this not be practicable such surfaces should be sand blasted or otherwise surface treated so that the sharp surface peaks are rounded thereby reducing the abrasive characteristics of the surface. For pushing or pulling

> along the tool access a slight rippled texture aids in avoiding slipping. For twisting and rotations shallow longitudinal grooves are best."

Konz (1990) recommend as one design option the improvement of coefficient of friction of the handle as a means to keep the tool captive in the hand. The covering material must however not be very soft as they may embed chips or splinters.

Putz Anderson (1988) writes with reference to textures and materials:

> "Flutes or ridges may be provided on the handle of tools such as screwdrivers if high torque ability is required. However if these ridges and flutes are very deep or have sharp edges they often cause excessive pressure on the soft tissues of the palm. Textured rubber handles will usually provide enough friction for a good grip. Form fitting tool handles such as those often found on pistol grips of power tools, or handles on heavy-duty pliers, should be matched carefully with the population intended to use them. Although handle finger grooves may look as though they were moulded to the hand, they are in fact only moulded to one particular size of hand. What gives good utility to a person with an average hand but becomes very uncomfortable for a person with an exceptionally large or small hand, if the fingers are stretched to fit form-fitting features of hand tool handles. Power is lost and the ability to operate the instrument is impaired. This happens because it is difficult to flex the fingers while they are held apart.

Pheasant (1994) in writing about surface finishes is not very precise in the description of the qualities of the hand handle interface.

> "If the handle surface is too smooth it will slip in the hand. If it is too rough it will be abrasive. Varnished wood gives a better purchase than either polished metal or smooth plastic probably because it is resilient."

Peate (1997) suggested that in order to fit work to the worker, thermoplastic friction tape should be used to cover handles and moreover to use handles that are easy to grip.

4.3.2 Size and shape

Mital and Kilbom (1992a) presented recommendations for design of hand tool handles with the following statements. Grip surface should be smooth, slightly compressible, and non conductive. Grip shape to be non-cylindrical, preferably triangular (periphery 110 mm). For power/force the entire hand should be used e.g. four fingers forming one jaw, thumb the other. For precision design for operation between thumb and fingers. For exertion of large forces handle to be designed as a pistol grip with an angle of 80° from the long axis of the tool. Grip and handle bent for hammers etc. to be 10°. Grip force for power grip to be maximum 100 N. Grip thickness for precision to be between 8 and 13 mm. Grip thickness for power force to be between 50-60 mm. Grip length for precision to be minimum100 mm. Grip length for power/force to be minimum 120 mm. Grip length to be minimum 125 mm for use with gloves. Grip guard to be minimum 16 mm. The scientific basis (knowledge base) for the recommendations above is presented in Mital and Kilbom (1992b). It contains 114 references covering the period 1928 to 1991.

> Pheasant and O'Neill (1975) tested a range of commercially available screwdrivers of different shape and size. Together with polished steel cylinders, other cylinders that had been knurled to give better purchase were investigated. When the effect of handle size was taken into account, none of the styles of the commercial screwdrivers were any better than a knurled cylinder of equivalent diameter, or worse than a polished cylinder.
>
> "Knife handles are often too small. Knives with small blades typically have small handles but ergonomically this may not be correct. The more difficult it is to grip the knife the more likely it is that the hand will slip down over the blade, especially if the handle is greasy from the carcasses."

Greenberg and Shaffin (1977) state that:

> "Handles should not have protruding sharp edges or corners."

According to Pheasant (1990),

> "Many hand tools are too small which makes them difficult to grip and may reduce the mechanical advantage in turning action (e.g. screwdrivers)."

According to Meagher (1987):

> "The texture at the tool-handle contact area is an important element because of the degree of friction that is present between a tool handle and the skin. The condition of which will vary according to factors such as environment and temperature, skin temperature and individual physiology. Incorrect hand tool designs can cause a variety of cumulative trauma disorders. Design elements of size, shape, texture, purpose, ease of operation, shock absorption and weight must be properly applied in the design process to fulfil the physical safety needs of consumers and working people and to prevent the presence of pathologic changes in the tissue of the hand and wrist".

4.3.3 Force, fatigue and posture

In the NIOSH publication "Cumulative Trauma Disorders", Putz-Anderson (1988) writes:

> "Proper attention to the selection and the design of tools and workstation layouts can minimise the risk of Cumulative Trauma Disorders."

The publication also provides guidelines for the design and selection of tools and handles. The guidelines were derived from numerous studies conducted over a period of 15 years and included recommendations covering hand tools, power tools and container handles.

According to the Health and Safety Executive (HSE 1999), high hand forces should be avoided where possible and handles should be designed so that they do not dig into the palm of the hand but spread the load over the largest possible area. The worst problems are often associated with repeated forceful gripping and turning actions executed with the wrist in a deviated position. In general the muscle effort required to perform a particular action will be reduced if the hand engages the handle in compression rather than shear. That is if the line of action of applied force is perpendicular to the surface of the hand rather than parallel.

The American National Standard Institute Draft Standard, ANSI Z-365, states:

> "Gripping forces for hand tools should be minimised to reduce the possibility of muscle fatigue. This can be done by redesigning the grip to allow relaxation of the hand muscles periodically by minimising the tool mass, by balancing the tool and by sizing and shaping the tool to fit the human hand."

4.4 Discussion of design recommendations for tool handles

The main bodies of information concerning hand tool handle design present qualitative data, which rarely is substantiated by references or investigative studies. Examples of such expressions are 'too smooth', 'many hand tools are too small', 'gripping forces should be minimized', 'ridges may be provided', 'polished surfaces should be avoided', and 'avoid form fittings and finger grooves'.

In strong contradiction to this qualitative approach, Mital and Kilbom (1992a) present quantified guidelines for the practitioner, the details of which are specified in Mital and Kilbom (1992b) "The scientific base (knowledge base) for design, selection and use of hand tools to alleviate trauma of the upper extremities." This text is strongly recommended for the dedicated reader. The guidelines are based on numerous published and unpublished studies and were produced following discussions with experts worldwide. One of six areas which Mital and Kilbom *ibid* considered necessary for further research was "studies of grip surface characteristics, for all type of grips but especially for gripping of contaminated handles". This appeared to be a valid statement as the consequences of different types of contaminants, including water and sweat were not discussed in the references referred to above.

Most of the qualitative and quantitative data presented above treat hand tool handles as isolated objects. However Meagher (1987) and Armstrong and Bobjer (1992) advocate the systems approach to the design of hand tools, and suggest the application of a design process to fulfil the physical safety needs of users to prevent unsuitable designs. They stress that design recommendations on hand tools, such as those mentioned as "Task and operator factors" in Figure 4.1 should be considered. Armstrong and Bobjer *ibid.* suggested dedicated research in order to identify the factors specific to the tool and its application. Such studies should form the basis for selection of qualitative or quantitative tool aspects e.g. found among the references in Table 4.1. Bobjer and Jansson (1997a) adopted these suggestions and developed a Corporate Manual for the Swedish company Sandvik Bahco, published in the scientific community (Bobjer et.al. 1997b). The focus was on the selection of materials and textures for use in the hand handle interface. A gap in the information was however observed, and the research presented in this thesis was initiated. This corporate manual was later used in the design and evaluation of an ergonomic tool for the electronics industry (Bobjer et. al. 1998) and evaluated amongst professional users (Bobjer and Jansson 2003).

Finally the author has noted that very few qualities of materials are discussed in the examined literature. This is a serious drawback particularly as with polymer technology a series of new materials has developed for use as handles, as recent methods of making production tooling have made a variety of textures and combinations of polymers commercially available.

4.5 Conclusions

Shape, size and application of textures on handles have always been an issue for the designer, being the user himself, or someone who makes tools for the market. The variety of materials available was traditionally limited and design textures, in addition to those intrinsic to the materials or use of basic production methods employed, are rarely seen. The introduction of machine tooling for mass fabrication of handles has provided possibilities for the new design of surfaces.

Modern industries demand even higher quality in production, more precision, higher performance and less risk of injuries or illness. Thus the opportunity for production of advanced handles is present, as is the demand for ergonomic hand tools. However it appears that the scientific base for the selection by industrial designers of materials, polymers in particular, but also their textures, is in demand. The following chapter presents a literature search dedicated to hand-object friction, and reports upon environmental and physical variables as the basis for a major research program to explore this area. Selected parts formed the basis for the present thesis.

Chapter 5 Friction in hand-object interaction

5.1 Introduction

This chapter describes the forces that act at the hand handle interface. The basic contributions of friction, adhesion, deformation and ploughing are described with reference to the related science of tribology. The chapter describes how friction occurs in traditional materials and in polymers, some of which show frictional properties that behave very much like human skin. A detailed survey of glabrous palm-friction research is presented. Most skin friction studies have focussed friction on hairy skin but they are reported here due to their methodological and chronological importance. The results are discussed with respect to hand tool application by industrial designers. Special attention is made to the characteristics of the friction partners, and the environmental conditions under which these studied were performed. Finally, the chapter identifies gaps in friction data from the perspective of industrial designers wishing to apply such knowledge to the design of hand tools.

5.2 The classic concept of friction

Friction is derived from terms meaning "to rub", "to crumble", "and to injure" (Akers 1985). Friction is frequently defined as the resistance that restricts or impedes the relative motion between two objects that slide against each other.

Early in the history of mechanics the French Academy of Sciences published a theory on the coefficient of friction (Amonton 1699 as described in Chapter 1). Amonton found that when two surfaces are in contact with each other, the relationship between forces acting between the surfaces (normal force, F_n) and forces required to introduce a displacement between these surfaces (friction force, F_f) were constant and independent of the level of the normal force. He introduced a factor, μ, to express the relation between the normal force and the friction force

$$\mu = F_f / F_n,$$

$$\text{or } F_f = \mu * F_n$$

and introduced the name "coefficient of friction". Later Coulomb (1785) found that the friction force, which is needed to start a sliding motion, was slightly *larger* than the friction force which was needed to keep two surfaces in sliding motion in relation to each other.

He introduced the term "coefficient of static friction", μ_s to explain the equation which involves the friction forces F_s, which are required to start two objects to slide against each other, and the "coefficient of dynamic friction", frequently abbreviated to μ_k, which involves the friction force F_k required to continue a sliding motion (were k stems from the Latin word 'kinae' meaning 'to move'). Amonton (1699) and Coulomb (1785) showed both μ_s and μ_k to be less than the value 1.0 when used in the equation above. According to their findings the coefficient of friction was a factor that reduced the friction forces F_f to values below those of the normal force F_n. Hence $\mu < 1$.

As the findings of Amonton (1699) and Coulomb (1785) were published in the early history of mechanics they have been regarded as the "laws of friction". These classic laws are expressed as follows:

- friction force, F_f, is directly proportional to the normal force F_n. The factor of proportionality is assigned μ.
- $F_f = \mu F_n$, where μ is considered the coefficient of friction μ.
- the friction forces F_f are independent of the size of the area in contact between the two objects.
- the friction forces F_f are independent of the velocity between the two objects.
- the friction forces F_f are dependent on the material properties in the two surfaces.
- the friction forces F_f are larger in static friction than in dynamic (kinaesthetic) friction under the same normal force.

It is now recognised that these laws do not always hold true. They are simple and general laws of friction and should be treated with great care, in particular when "new" materials, such as polymers, are involved. Often when using such materials, the coefficient of dynamic friction μ_k *exceeds* the coefficient of static friction μ_s (Suh 1986) and both may exceed the value 1.0.

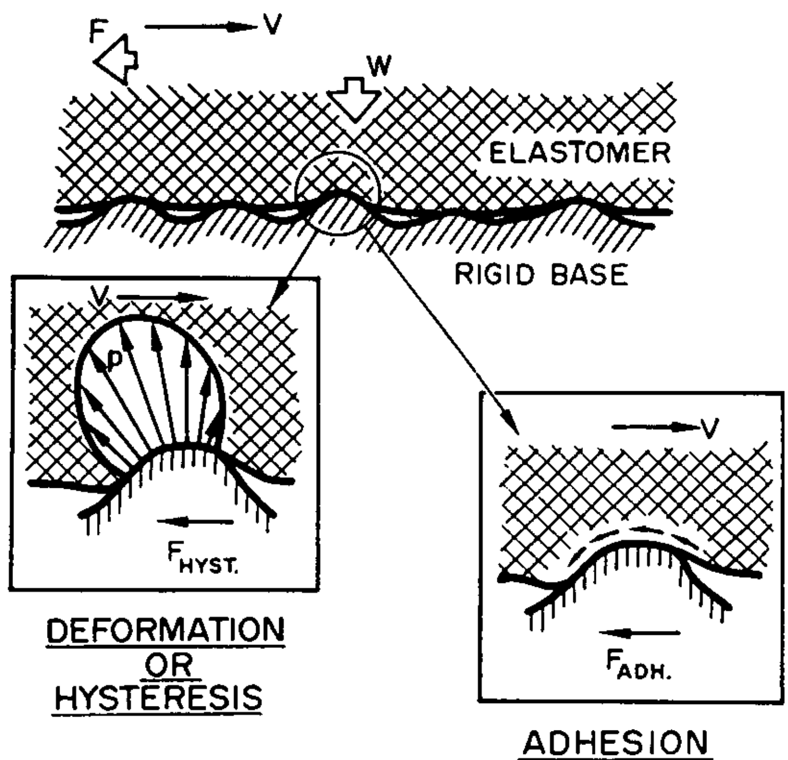
For many years friction was a science of its own. The rising demands to reduce friction in engineering systems, to save energy and increase longevity however, changed the focus towards lubrication and wear. The science of friction is incorporated with lubrication and wear into the science of tribology which more appropriately reflect material and environmental demands (Halling 1976, Moore 1975).

5.3 Generators of friction

It has been shown by several authors that human skin has several properties that largely relate it to polymeric materials, that is, synthetic materials made up of large molecules (Daly 1968, Wilkes et al 1973, Montagna and Parakkal 1974, Yamaguchi 1990. The traditional "laws of friction" should in fact <u>not</u> be considered to be valid for palm skin (Comaish and Bottoms 1971), palm tissue shows several properties that strongly separate it from those traditional materials which Amonton (1699) and Coulomb (1785) investigated.

Serina et al (1977) found the fingertip pulp to act as a visco-elastic material. This means that after being exposed to a force, stretching or compressing the skin, it does not return perfectly to the initial position. Some amount of energy is "lost" during such an exercise. In an ideal elastic material there are no such losses and it returns to its initial condition. The departure from perfect elasticity is termed the viscous character or visco-elasticity of the substance. Fingertip pulp was also investigated by Serina *(ibid)* who found different viscous characters depending on the rate at which the force was applied. A non-linear force-displacement relationship was identified. Thus when compressed under low load, for example, when gently grasping an object, the skin and underlying tissue becomes thinner and more spread out under the force. Increased load makes it even thinner but to a lesser degree. This reaction serves to distribute the pressure and protect the underlying structures. The lateral bulging of the pulp during compression (which can easily be seen) is an effect of this reaction. The skin-sample contact area is increased.

Figure 5.1 illustrates schematically how a microscopic asperity is in friction partnership with an elastomer (like skin) according to MacKenzie and Iberall (1994). If a hard asperity, e.g. a handle, slides against the surface of an elastomer, e. g palm skin, energy is initially fed into the asperity; however some energy is restored to the harder asperity by the elastic recovery of the elastomer behind the asperity. The initial major transformation of energy is reduced somewhat at the recovery. The net loss of energy to the elastomer accounts for the work required to maintain the friction partners sliding. There are numerous such microscopic asperities in friction contact and elastomers are known to provide high friction and are the most dominant material in car tyres. These events are characteristic for visco-elastic materials (such as skin).



V = velocity of sliding, W = applied load, p = pressure

Figure 5.1 **Illustration of the microscopic contact between an elastomer (which is like skin) and a rough rigid support base e.g. the hand tool handle. (Modified from MacKenzie and Iberall 1994)**

The friction contact is characterised by the draping (flexible form following coverage) of the elastomer over individual asperities. The total friction force, which is developed as the friction partners slide over each other, is the accumulation of several mechanical, molecular and chemical activities. Experimental results (Suh 1986, Yamaguchi 1990) indicate that the coefficient of friction is a function of the combined effects of;

a) asperity deformation (μ_d) i.e. deformation of microscopic protrusions on the surface, which is closely related to the module of elasticity (Young's modulus) for the material concerned.

b) ploughing in the surface by protruding particles (μ_p). This component is expressed in terms of height, width and radius for protrusions on the surface and thus related to the surface topography.

c) molecular adhesion between surfaces (μ_a). In polymers, the adhesion is determined largely by its molecular structure.

For viscoelastic materials like skin, the three components μ_d, μ_p and μ_a, contribute to friction to different degrees sequentially, as well as concurrently. According to Suh (1986), the coefficient of friction in viscoelastic materials appears not to be constant but to a different degree affected by the following factors.

d) dynamics of the friction partner interface (i.e. the direction and velocity of the relative motion between the surfaces in contact).

e) environmental conditions, such as temperature and lubricants.

f) surface topography.

g) material properties (e.g. molecular structure, Young's modulus and surface energy).

The relevance for palm friction is;

h) μ_d - the friction coefficient due to asperity deformation is often responsible for the static coefficient to friction μ_s (Suh 1986). For palm skin it may contribute largely to the coefficient of dynamic friction, μ_k, as the soft tissue and the dermal ridges in the palm are deformed continuously under sliding conditions.

i) μ_p - the ploughing component of the friction coefficient is normally low when a soft surface, such as skin, slides against a non abrasive surface.

j) μ_a - the adhesion components of the friction coefficient depend largely on the existence of lubricants at the interface. Oil, grease, hand lotions etc. have a reducing effect, but the affects of proteins and sweat is not fully understood.

The total coefficient of friction μ is frequently described as the sum of μ_d, μ_p and μ_a.

5.4 Topography

From a microscopic point of view, no surfaces are completely flat. The microscopic landscape is often compared with the shape of the Alps, showing a vast variety of peaks and valleys, all showing differences in factors such as height, depth, width, steepness, distances between peaks etc. When any surface is exposed to load these landscapes are deformed and the microscopic surface will change form until the full load is supported. For many materials the true (molecular) contact area has been shown to be directly proportional to the applied load, and in these cases the traditional "law of friction" $\mu = F_f / F_n$ applies, and μ may be seen as a factor of proportionality.

Several of the materials that have been created with the methods of polymerisation however behave differently from many other materials in that the coefficient of friction of polymers is a power function of the normal force with an exponential power 1. Thus the coefficient of friction is not <u>independent</u> of the normal load as Amonton (1699) suggested.

For visco-elastic materials, the area of true contact is proportional (but not linearly) to the load. The rate of increase of molecular area of contact decreases in relation to an increasing applied load. The exponential power is less than 1.0 and typically 0.7 (Suh 1986). The effect of this is that as the load is increased, most polymers show *lower* friction coefficients. With reference to human skin Wilkes et al (1973) showed that large skin extensions are produced by the application of small loads but as the load increases, skin becomes progressively stiffer, and loses its ability to deform and the coefficient of friction decreases. The following summarises the occurrence when friction is developed in viscoelastic materials (Bowden and Tabor 1976).

When surfaces meet (which by the naked eye appear to be smooth), they are in molecular contact only at a few points. The stresses on these individual contact points are then relatively high. The area of true contact is thus less than the apparent (nominal) area of contact. For a viscoelastic elastomer the initial area of contact at these few contact points is small. The pressure causes deformation however, leading to more points getting in contact. The adhesion component of the friction force μ_a is closely related to the true area of contact. At these points the molecular transformation of energy enables the two friction partners to adhere to each other. Lubrication reduces these energies and has the most profound effect on friction.

For viscoelastic materials a small increase in load will result in a corresponding increase of the contact area. Under these conditions the coefficient of friction is independent of the load, and Amonton's law of friction applies.

At heavier loads, however, the increasing size of the deforming asperities tends to interfere between separate, adjacent regions of deformation. Then the real area of contact increases less rapidly than at lighter loads, and the adhesion term, μ_a, rises less rapidly, as it is dependent on the area of direct contact. The coefficient of friction is thus reduced with increasing load.

In humans the pain threshold will limit the applied load but for polymers in friction partnership, at high loads, all the asperities may be deformed flat into the general plane of the surface. The real area of contact is then equal to the apparent (nominal) area of contact.

Surface roughness may affect friction in two ways, either increasing or decreasing it. Rougher surfaces will decrease the true area of contact resulting in a lessening of the adhesive component of friction, μ_a. On the other hand, rougher surfaces may increase the number and level of deformation zones where the friction partners meet. The microscopic protrusions may bend or break under the friction forces, allowing more contribution from the deformation component μ_d. However the adhesive component, μ_a, dominates over the deformation component, μ_d, with the consequence that rougher surfaces of polymer material tend to have a decreasing effect on the coefficient of friction.

If a hard friction partner material has sharp corners or edges, it may cut or tear the surface of the friction partner and material is removed. The ploughing force, F_p, is increased and the surface is seriously damaged. Wear produced this way may be described as abrasion.

Thus when assessing palm friction it seems appropriate to control for several additional factors other than just the load as initially suggested by Amonton (1699) and Coulomb (1785). According to MacKenzie and Iberall (1994) "a formal analysis of skin surface of the hand from a tribology perspective would be a valuable contribution to our understanding of human grasping", and suggests that both simulations and experiments are needed in this area.

5.5 Standardized topographic surface recordings and data presentations

Recordings of surface topographies are specified in ISO standards, among which ISO 4288: 1996 "Geometric Product Specification (GPS) - Surface texture: profile method - rules and procedures for the assessment of surface texture" is the most relevant. The standard basically present how a well described stylus is traced a defined distance (the assessment length), frequently 5.6 mm, over different locations on the surface, normally 20 times. The displacement is recorded and analysed according to well-defined algorithms. Details are presented in Appendix 2.

The author of this thesis contacted Scientists[2] at the Royal University of Technology in Stockholm to discuss experimental issues. They recommended five surface topography variables for further analysis by multiple variable regression models in search for relations between surface topography characteristics and coefficient of friction. These were:

> **Ra** - the universally recognised, and most used, international parameter of surface roughness. It is the arithmetic mean of the departures of the roughness profile from the mean line.
>
> **Rp** - the maximum height of the profile above the mean line within the assessment length.
>
> **S** - the spacing of adjacent peaks.
>
> **Sm** - the mean spacing between profile peaks at the mean line.
>
> **Del.q** - the rms slope of the profile.

Moreover these scientists suggested two new characteristics to the author. Their long experience in the field of tribology suggested generating a specific analysis of the standard unfiltered readings of topography, and load bearing data that are gained when using a standardised procedure for recordings of surface topographies. The two new topographic characteristics specify the uppermost part of the topography only and ignores, unlike the standard methods designed for engineering purposes, the details below. They have not previously been published and are referred to as T5 and H5 respectively. The specifications of these are reported in Appendix 4. Surface topography.

[2] Torvald Eriksson, Lennart Nilsson, Sören Andersson

5.6 Friction in human skin

Skin is the body's largest organ. The mean surface area for adults is 1.8 m^2. More than 95% of this area contains hair. Such "hairy skin" contains sebaceous (fat) glands, as these are linked to the root of hair. Our hands and soles of the feet are, however, covered with non-hairy, glabrous (i.e. plain, wrinkle free) skin. In mammals, there are striking structural differences between hairy and glabrous skin (Montagna and Parakkal 1974, Quilliam, 1978). In the palm, glabrous skin is designed to comply, hold, and resist pressure and shearing forces that are related to the demands of grasping. The non-glabrous, dorsal skin of the hand is designed so as not to impede flexion of the wrist and fingers. Another difference between these two types of tissue related to friction is that glabrous skin contains dermal ridges and many sweat glands and is hygroscopic (easily absorbs water). It is also resistant to penetration of lipids (lipofobic).

Glabrous skin in the palm has been the selected site for research in which skin has been exposed to friction for other reasons than quantifying the coefficient. In fact most of the reports presented in this chapter have been performed with different goals including the following;

- to study the nervous response to skin slip.
- to identify characteristics of skin mechanoreceptors
- to develop objective methods for testing of skin care products
- to explore psychophysical methods for research on perception.
- to investigate of characteristics of anatomic regions
- to identify and avoid formation of blisters.

Below is a brief description of friction research on hairy skin. More detailed information on glabrous palmar skin friction studies follow.

5.6.1 Hairy skin

Analysis of human skin from a friction point of view is fairly recent in medicine. Not until 1971 were the differences between hairy and glabrous skin identified (Comaish and Bottoms 1971). Naylor's (1955) work "The skin surface and friction" is frequently quoted as the first of this kind. His basic concern was load-carrying and the damaging effect of friction between the skin and straps and clothing. Naylor *ibid* chose the middle third of the anterior surface of tibia (frontal side of lower leg) because it is easy to access, the skin is flat and firmly supported by bone, and it lends itself well as a site on which to fit an elaborate mechanical device. Not until 11 years later did Sulzberger et al (1966) publish the next scientific research on the topic mainly continuing Naylor´s work, but expanded it to include other areas of hairy skin such as back, buttock, forearm, shins and thigh. Sulzberger (ibid) also included the palm and sole as he was concerned in the disabling effect friction blisters may have on, for example soldiers to whom they may pose a serious risk factor. Comaish and Bottoms (1971) included a variety of friction partners and several contaminants in their research examining both coefficient of static, μs, and dynamic, μk, friction, and also more bodily locations, with the clear aim to fill gaps in knowledge. They also researched palm friction. Highley et al (1977) focused on the effect of hydration, oils and detergents on friction. They used the volar forearm as an example of hairy skin in the research Thus several researchers investigated the coefficient of friction at various locations on hairy skin. Their references and the sector of the hairy skin they researched are presented in Table 5.1 and with details (Location, Direction of applied force, Type of friction, Friction partner, Normal force Fn, Velocity, Contaminant) in Appendix 1. These reports show strong variations in coefficients of friction, depending on the parts of the body that were investigated. It is difficult to see any consistency in the choice of independent or controlled variables among these reports. Among the reports major variations were found in surface load, area of contact, sweat intensity, presence of water, or different types of contamination, and effect of various detergents, materials and texture of the friction partner in contact with the hairy skin. These findings were supported by Sivamani et al (2003a) in the review "Coefficient of friction: tribological studies in man- an overview". This diversity makes it difficult to draw conclusions. Due to the structural differences between hairy and glabrous skin, the actual results of the recorded friction are however of lesser concern in this thesis. As to the understanding of skin physiology and the various methods used to record friction on human skin, these reports have been useful contributions to the work on palm friction presented in the current thesis.

Body location covered with hairy skin	Reference
Abdomen	Cua, et al (1990b) , Comaish and Bottoms (1971)
Ankle	Cua, et al (1990b)
Buttock	Sulzberger et al (1966), Cua, et al (1990b)
Dorsum of hand	Comaish and Bottoms (1971)
Forehead	Cua, et al (1990b)
Postauricular	Cua, et al (1990b)
Shins	Sulzberger et al (1966)
Thigh	Sulzberger et al (1966), Cua, et al (1990b)
Tibia	Naylor (1955), Comaish and Bottoms (1971)
Upper arm	Cua, et al (1990b), Sulzberger et al (1966)
Forearm	Highly (1977), Nacht et al (1981), Sulzberger et al (1966), Cua, et al (1990b)
Back	Sulzberger et al (1966)

Table 5.1 Published research on friction in body locations covered with the hairy type of skin.

5.6.2 Non hairy, glabrous palmar skin

In recent years studies have been focusing on the glabrous (non hairy) skin of the palm. Summaries of fourteen such reports are presented below. Their references and the sector of hairy skin they researched are presented in Table 5.2 and with details (Location, Direction of applied force, Type of friction, Friction partner, Normal force Fn, Velocity, Contaminant) in Appendix 1.

Body location covered with hairy skin	Reference
Palm	Comaish and Bottoms (1971), Cua, et al (1990b)
Palm, digit pulp of thumb and index finger	Bullinger et al (1979)
Fingertip	Lederman and Taylor (1972), Taylor and Lederman (1975), Smith and Scott (1996)
Digit pulp of thumb and index finger	Smith et al (1997a), Saels et al (1999), Westling and Johansson (1984), Bucholz et al (1988), Jones and Hunter (1992)
Digit pulp of index finger	Roberts and Brackley (1990), Mossel and Roosen (1994)
Digit pulp of thumb, index and middle fingers	Frederic and Armstrong (1995)

Table 5.2 Published research on friction in glabrous skin.

The most relevant findings with references to friction, glabrous skin and design of hand tools and objects are:

- factors increasing or decreasing friction
- effects of different skin conditions and treatments

- forces and velocities
- directions of applied friction and materials

These are presented below.

Bullinger et al (1979) performed a major investigation of friction between the normal, uncontaminated hand and different materials. Palm friction was investigated in 5 subjects, of which 3 were industrial operators. Experiments were performed with clean, freshly washed hands. Thirty different materials and 27 separate textures were investigated. Non-textured, polished and glossy surfaces of different material such as perspex, copper, brass, PVC and glass gave the highest coefficients of friction regardless of the level of surface pressure. These non-textured surfaces resulted in 20 to 30% higher coefficients of friction than the <u>same material</u> under textured conditions. These differences between non-textured and textured surfaces were found at pressure of approximately 5 kPa. When the load was increased to 40 kPa the situation was reversed, so that textured surfaces gave higher coefficient of friction than non-textured. The surface topography, recorded as R_Z, (also known as the ISO 10 point height parameter[3]) was reported to influence coefficient of friction to a large extent. No other surface topographies other than R_Z were investigated. Generally materials with low surface profiles (specified as R_Z) generated higher friction. Wood, suede and cork gave lower readings. Bullinger *(ibid)* suggested that the friction difference between materials depended on mechanical, physical and chemical properties in the materials. The research by Bullinger *(ibid.)* was only performed on five subjects and the textures were free of oil, water, grease etc. Large inter- and intra-individual variations were noticed for the five subjects. From a statistical point of view, the analysis was based on a very small sample and no statistical calculations were shown. The friction data were unfortunately not reported in real terms but expressed in relation to the maximum recording. Bullinger *(ibid.)* claimed that the velocity in the hand surface contact had no important influence on the coefficient of friction. Skin displacement readings were reported (Figure 5.2), but no results from recordings of velocity

Buchholz et al (1988) carried out research on static friction, μ_S, comparing a normal hand to a hand that was moist after it had just been exposed to running water. Buchholz *(ibid)* showed that under moist conditions, when porous materials such as paper and suede were used,

[3] ISO 10 point height parameter (also known as R_Z) is the average height difference between the five highest peaks and the five lowest valleys within specified length.

coefficients of friction increased 60 to 70 %. Non-porous materials however showed reduced coefficients of friction under these moist conditions. No details were given on the conditions of hand moisture in the "normal" or the wetted hands.

Johansson and Westling (1987) and Srinvasan (1990) had a closer look at the movements that took place in the friction interface. They viewed the movements and slips of the dermal ridges of the finger pad through a lens system. They noticed that a gradually increasing sliding motion is established when a friction force is applied on the skin. Initially, only smaller patches slide, until a situation develops when the whole contact area is sliding and true dynamic friction occurs.

Such movements in the friction interface were also investigated by Bullinger et al (1979). They showed that the friction force, F_f, increased linearly when the surface started to move across the palm until a particular reading was reached (μ_1), which they treated as the figure representing static friction. Most materials and textures show thereafter even higher friction values until the maximum (μ_2), was reached which was interpreted as coefficient of dynamic friction, μk (Figure 5.2). They also found that some textures gave raise to a stick-slip effect when in touch with palm skin. These stick-slips were considerable when the entire palm was involved compared to results from research involving only the distal pad of thumb and index finger.

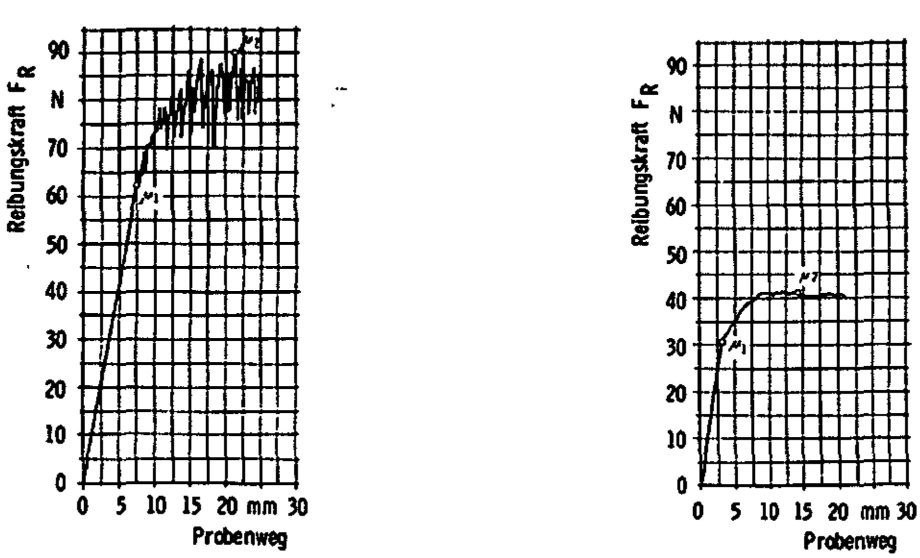


Figure 5.2 **Friction forces as a function of displacement. A none textured (left) and a textured sample (right) expressed in mm on the abscissa and in Newton on the ordinat (From Bullinger et al 1979).**

Other researchers have exposed a subject's palm to friction but primarily to trigger sensory motor processes in the cortex to determine the function of palm mechano receptors (Vallbo and Johansson 1984, Johansson and Vallbo 1979, Johansson and Westling, 1984a, 1984b, Westling and Johansson 1984, Cole and Johansson 1993)
, Flanagan et al 1995, Saels et al 1999). Most of these researchers used probes fitted with sandpaper, suede and silk, and subjects used the thumb and index finger in a pinch grip. These materials and the neurological results are however of less concern to the industrial designer. The methods for collection of friction data have however proved valuable in the design of the instruments used in the series of research studies in this thesis, discussed later in Chapter 6. 'Traditional equipment for skin friction research'.

5.7 Modification of friction

Several authors have demonstrated that an increase as well as decrease in skin friction, (whether glabrous or the hairy type), can be achieved by modifications to the skin, the forces, the velocities, and the materials. The paragraphs below present the findings in the studies summarised in Tables 5 and 6 in Appendix 1. Eight reports describe different ways to increase friction and eleven reports describe means to reduce it. The methods to increase friction varied from moisturising the skin by applying minute quantities of water directly on the skin or by applying commercial moisturisers and urine on diaper material. Other methods used were soaking the hands in water for several minutes, activating the sweat glands but also application of sticky rosin varnish on the friction interface. Reduction of friction was found when oil, grease, liquid detergents, the water-soluble liquid Hydrogel®, or talcum powder were applied on the skin. Washing the hands and the subsequent drying resulted in reduced friction but also deactivated the sweat glands of the palm. Details of these findings are presented below

5.7.1 Increasing friction

Hairy skin

- Naylor (1955) found that when hairy skin conditions changed from dry through moist to wet, friction on hairy skin followed an inverted U-shape curve form. Dry and wet skin reduced friction in relation to an intermediate moist condition that generated higher friction.

- Nacht et al (1981) showed an average 145% increase in friction among five subjects 2.5 minutes after the application of 2 mg/ cm^2 of water on the volar side of the fore arm.

- Nacht et al (1981), Wolfram (1983) and Zimmerer (1986) reported considerable increase in friction for the volar forearm (inside of the forearm) when either water, commercial moisturisers and urine (artificial as well as natural) had been applied directly on the skin, or on to patches of diaper material attached on subjects forearms.

Glabrous skin

- Comaish and Bottoms (1971) soaked a hand for 30 min. in water at 37°C and noticed increased friction.

- Buchholz et al (1988) compared normal with wet hands and showed that when porous materials such as paper and suede were in contact, coefficients of friction increased 60 - 70 %, but non-porous materials showed reduced coefficients of friction under such conditions.

- Roberts and Brackly (1990) applied 0.05 ml water on the palm interface and observed increases in friction.

- Smith and Scott (1996) applied a layer of sticky rosin varnish on a glass surface, and found extraordinarily high friction, (2.79, SD 1.2) when in contact with the skin, but also found stickiness to be present.

5.7.2 Decreasing friction

Hairy skin

- Naylor (1955), Sulzberger et al (1966), Comaish and Bottoms (1971), Highly et al (1977) and Nacht et al (1981) explored friction on **hairy** skin and noticed an immediate reduction of friction when oil and grease were present on the friction interface

- Sulzberger et al (1966) showed that extensive wetting of skin results in a decrease of friction. Nacht et al (1981) recorded coefficient of dynamic friction, μ_k initially and hours after the wetting. He showed an immediate reduction in friction but after two hours of exposure a strong increase in friction was noticed to levels above the base line.

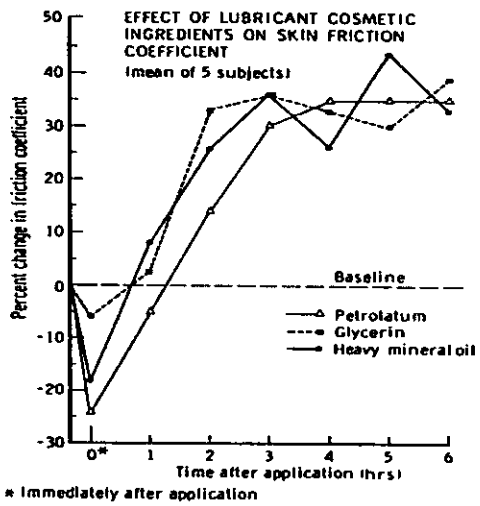
Glabrous skin

- Taylor and Lederman (1975) used liquid detergent and observed reduced friction from 0.6 to < 0.15.
- Buchholz et al (1988)compared normal with wet hands and showed that non-porous materials reduced coefficients of friction
- Roberts and Brackly (1990) applied a water-soluble liquid Hydrogel resulting in a strong reduction in friction.
- Johansson and Westling (1984b) showed that washing and drying the glabrous skin of the palm caused a transient decrease in glabrous skin friction, which they suggested was as a result of removal of sweat from the skin. This effect was however eliminated within minutes of carrying out gripping activities with skin friction returning to the higher pre-drying levels.
- Smith et al (1997a) used chemotherapy to reduce palm sweat and thus reduce friction. The treatment significantly reduced the palm friction on smooth and finely textured surfaces.
- Seals et al (1999) used the dry lubricant talcum powder which created a strong reduction of palm friction from the within the ranges 0.52-1.18 to 0.24-0.34.

5.7.3 Oil and grease on skin

Secretion of sebum from the sebaceous ducts on hairy skin will affect the adhesive properties of this type of skin. Nacht et al (1981) suggested that some of the sebum might be squeezed out of the ducts when exposed to high loads. Similar effects may be obtained with lubricating oil or grease. After the application of heavy mineral oil, or glycerine, on the volar forearm the coefficient of friction were found by Nacht *(ibid.)* to be reduced 5 to 25% from a baseline. Two to six hours after this application however, friction had risen to 25-40% above the baseline (Figure 5.3). Nacht *(ibid.)* suggested that two mechanisms took place sequentially.

Initially, the lubricating effect of the agents dominates. Then, as the agents gradually were absorbed into the skin surface layers, the hydrating effects overcame the diminishing lubricating effect, and a gradual increase in friction coefficient took place due to hydration induced by the agents' occlusive properties. Derek (1977) suggested that the stratum corneum



cells act as dry lubricants (not unlike talcum powder) and cause low friction on dry skin.

Figure 5.3 **Changes in friction coefficient induced by lubricating cosmetic ingredients on volar side of fore arm. (From Nacht et al 1981)**

5.7.4 Wet, moist and dry skin

When using the hand in prehension there is a complex interplay between the muscles, mechano-receptors, skin and the sweat glands. Healthy sweating provides boundary lubrication of the palm surface of the hand, good adhesion and good grip. With contact, the skin is deformed, activating mechano-receptors, and creating heat through friction. Both deformation and heat may lead to secretions by the sweat glands, which in turn affect palm friction.

When moist, the epidermis emits proteins that may increase the friction. A dramatic rise in friction has been noticed for hairy skin. Nacht et al (1981) showed an average 145% increase in dynamic friction among five subjects 2.5 minutes after the application of 2 mg/ cm^2 of water on hairy skin on the volar forearm μ_k, when in contact with a Teflon friction partner. The effect lasted 10 to 15 minutes (Figure 5.3). Under very moist and wet conditions there is a reduction of friction, which may be attributed to a dilution of the sticky character of these proteins or hydrodynamic friction (Christensen et al 1977).

5.7.5 Direction of applied force

Major differences in finger friction have been reported depending on the direction of the movement whether along, (distal-proximal) or across the finger, (towards or from the little finger side). Jones and Hunter (1992) found that forces acting proximally on finger pads (as when an object is pushed into a pinch grip) generate higher friction (by on average a factor of 1.45), compared to forces acting distally on finger pads, (as when an object is pulled away from a pinched grip). In addition, Bullinger et al (1979) found that transverse finger friction exceeds the distal friction values by, on average, a factor of 1.39 at 40 kPa. Thus, both forces acting in the proximal or transverse directions generate higher friction than forces acting distally on finger pads. Bullinger *(ibid.)* suggested that this difference can be attributed to the size and orientation of the dermal ridges, of which 70% are oriented along the fingers and have to be transversed when approached this way, apparently improving the friction properties of the skin. Bullinger *(ibid.)* also suggested that the greater flexibility of the fingertips (twice as large in the transverse direction compared to distal values accounts for the higher friction in the transverse directions.

According to Jones and Hunter (1992), it may be that the mechanical properties of the intervening soft tissue (compliance in particular), is different in the distal-proximal directions compared to the transverse directions.

5.7.6 Velocities in the friction interface

Of the fourteen studies of palm friction, presented in Table 5 in Appendix 1 six considered only static coefficient (μ_s) while five investigated only dynamic friction (μ_k). Two studies reported both μ_S and μ_k while one document reported average data of μ_s and μ_k. Of the six documents that covered dynamic friction μ_k, all specified the velocities in the friction interface at the incidence of friction recording. The velocities varied within the range 1 to 260 mm/s (Table 5.3). The detailed effect that velocity has on the hand-object interface was, however, unclear as the independent variables and the experimental conditions were different. Thus, it would appear difficult to make comparisons between the studies above. With reference to the impact that velocity has on friction for other materials with similar tribologic qualities as skin (Suh 1986, Yamaguchi 1990), a most significant and positive correlation can be expected, particularly for velocities below 200 mm/s. In an applied situation - specific tasks, e.g. when using a hand tool, may require anything from static to dynamic material contact. For an industrial designer such environmental information is a basic requirement. In the present research the effect of velocity on coefficient of friction has therefore been given high priority.

Reference	Velocity mm/s
Bullinger, et al (1979)	3-140
Cua, et al (1990b)	150
Jones and Hunter (1992)	<15
Roberts and Brackly (1990)	10
Mossel and Roosen (1994)	1.0
Smith and Scott (1996)	80-260

Table 5.3 Range of velocities in the friction interface used in research of glabrous skin

5.7.7 Forces and pressure in the friction interface

The forces acting in the direction normal to the friction interface, F_n, in the identified studies of palm friction , see Table 5 in Appendix 1 varied within the range 0.03 N to 39.2 N.

A summary is presented in Table 5.4 below. The areas of the friction interface over which these forces were distributed are unknown which restricts the calculation of the surface pressure that the palm skin was exposed to. According to Hall (1995), referred to in Chapter 2, pressure during typical use of equipment such as screwdrivers, nippers, pen, drills, saws and metal shears range from 20-100 kPa while peak pressures range from 250-1000 kPa. For electric drills, Björing et al (2000) reported palm-handle pressure of 343 kPa.

Reference	Normal force
Comaish and Bottoms 1971	F_n = 0.03 - 10 N (graph interpretations)
Taylor and Lederman, S. J. (1975)	F_n = 1.12 N
Bullinger et al. (1979)	Palm F_n= 40 N Fingers F_n = 15 N
Westling and Johansson (1984)	F_n = 1 -15 N
Bushholz, B et al (1988)	F_n = 19.6 N and 39.2N
Cua, et al (1990b)	F_n = 2.0 N
Roberts and Brackly (1990)	F_n = 0.32 N
Jones and Hunter (1992)	F_n = 17.96 19.75 22.39 N
Cole andJohansson (1993)	F_n = 1- 20 N
Mossel and Roosen (1994)	F_n = 0.1 – 1.3 N
Frederic and Armstrong (1995)	F_n = 9.6 -69.5 N
Smith and Scott (1996)	F_n = 0.1 – 1.3 N
Smith et al (1997a)	F_n = 21 N
Seals, P., et al (1999)	F_n = 21 N

Table 5.4 Normal forces applied in 14 investigated reports

5.7.8 Materials investigated

In the fourteen reports above, thirty-one different materials were investigated for their friction properties (see Table 5.5). The most researched material was aluminium, which was included in 5 different studies. Suede (4 studies), sandpaper (3 studies), brass and Teflon (2 studies) were researched in multiple investigations. Most of the other materials were investigated in the study by Bullinger et al (1979). A given material may, however, come in different qualities and the name alone carries little information of importance for the transfer of forces in the friction interface. Examples of useful data would be surface treatment, topography and surface energy, modulus of elasticity and hardness, all of which can be recorded using standardised methods.

Material	Reference
Adhesive tape	Bullinger et al (1979)
Aluminum	Taylor and Lederman (1975) Bullinger et al (1979) Bushholz, B. et al (1988) Frederic and Armstrong (1995) Smith and Scott (1996)
Beech	Bullinger et al (1979)
Brass	Bullinger et al (1979) Seals et al (1999)
Cast iron	Bullinger et al (1979)
Cellidor	Bullinger et al (1979)
Copper	Bullinger et al (1979)
Cork	Bullinger et al (1979)
Enamel	Bullinger et al (1979)
Glass	Bullinger et al (1979)
Latex glove	Roberts and Brackly, C. A. (1990)
Paper	Bushholz et al (1988)
Polyamide	Smith, et al (1997a)
Polyamide	Smith and Scott (1996)
Pressed material	Bullinger et. al. (1979)
Polyetene sheet	Comaish and Bottoms 1971
PVC	Bullinger et al (1979)
Plexiglas	Bullinger et al (1979)
PVC	Smith and Scott. (1996)
Rayon	Cole and Johansson (1993)
Rubber	Bullinger et al (1979)
Sandpaper	Westling and Johansson (1984) Buschholz et al (1988) Cole and Johansson (1993)
Silk	Westling and Johansson (1984)
Steel	Bullinger et al (1979)
Suede	Westling and Johansson (1984) Cole and Johansson (1993) Jones and Hunter (1992) Bullinger et al (1979)
Skiver	Bullinger et al (1979)
Stainless steel	Mossel and Roosen (1994)
Teflon	Cua, et al (1990b) Smith and Scott (1996)
Varnished wood	Bullinger et al (1979)
Vinyl	Bullinger et al (1979)

Table 5.5 Material used in friction research of glabrous skin

5.7.9 Variances in experimental conditions

Of the fourteen identified studies of palm friction reported above, only a few significant results were reported. Major differences were reported within as well as between individuals, even under the same experimental conditions. Johansson and Westling (1984b) reported ±20% differences within subjects under the same experimental conditions. Buchholz et al (1988) reported differences between subjects under the same experimental conditions ranging from -11.7 to +9.9% of the pooled mean. Bullinger et al (1979) reported a mean of 81% deviations between subjects from the pooled mean when investigating coefficient of dynamic friction. According to Buchholz et al (1988) the variances can be attributed to the subjects' difficulties in adopting the requested normal force. Bullinger et al (1979) accepted the large differences as intrinsic palm skin properties. In examining the fourteen reports above it was clear that variances in palm qualities, however, were rarely reported, e.g. the presence of sweat or the area of skin contact under the different forces applied or the velocity in the skin-sample interface at the moment of friction recording. Differences in these variables may have been a reason for the large variances.

Surface load and pressure

Comaish and Bottoms (1971) and Buchholz et al (1988) showed that friction of hairy skin is negatively related to surface load. The relationship was expressed as $F_f = \mu\ (F_n)$ to the power of m, where m < 1. Frederic and Armstrong (1995), who specified the power function to 0.6, confirmed these findings with reference to glabrous skin. The normal forces applied in the 14 reports above, ranged from 0.03 to 69.5 Newton, (Table 5.4), but the range of pressures used in the friction interface is unknown and may have contributed to the few significant results.

Experimental samples

The procedures of cleaning the subjects' hands are well reported in the investigated studies but the details on the treatment of the friction partners, for example, how often these objects are cleaned or changed due to wear or collection of debris etc. are more difficult to find. Such information is valuable in the interpretation of the quality of the data.

5.8 Discussion

Research in which skin friction has been a variable has not always been aimed at identifying the coefficient of friction. Methods and instruments used in such studies have, however, contributed to the understanding of the complexity of human skin and have been a prerequisite for involving skin as a partner in research aiming at investigating friction specifically.

The science of skin friction is fairly young. The considerable difference in friction between the glabrous and the hairy skin was not documented until Comaish and Bottoms (1971) showed the remarkable difference in friction between the palm and dorsal side of the hand. They recognised the need for reducing the influence of materials and textures on friction and to standardise the engineering side of the friction partners in order to concentrate on human skin variances.

In developing the hand-held friction device "the Newcastle friction meter", Comaish et al (1973) paved the way for a series of exploratory studies where skin on many sites of the body are recorded (Cua, et al 1990b; Nacht, et.al, 1981; Cua, et al, 1995). The instrument allowed for a comparison between gender and age and also variations as to skin conditions and the exposure to contaminants and skin treatments. One major drawback was however that this instrument was not designed for researching different materials, various textures, velocities (including static, low and high velocities) and normal forces covering the range from the lightest touch to near the pain threshold. The present chapter shows that dedicated research to identify friction in textured surfaces is scarce. Some information was gained from the series of grasping-lifting-transferring-lowering and releasing studies in which the digit pulp of thumb and index finger were used. The prime aim of those studies was however to investigate central nervous system response when friction and normal forces were stimuli, and mechanoreceptors in palm skin were used to trigger such responses. Some references of relevance to the research presented in this thesis are: Johansson and Vallbo (1979), Westling and Johansson (1984), Johansson and Westling (1987), Jones and Hunter (1992), Cole and Johansson (1993), Frederic and Armstrong (1995), Seals et al (1999)

The range of materials was restricted to those of less general concern for the industrial designers - namely sandpaper suede, silk, rayon and brass. The report covers 30 materials and 26 textures but no contaminants. The research was based on 4 to 5 subjects only and the coefficient of confidence reached levels of 70%.

Bushholz et al (1988) presented the second work. The research covers six materials, namely adhesive tape, aluminium, paper, sandpaper, suede and vinyl and included hands which were clean and dry but also wet from running water. Differences in friction from porous and non-porous materials were reported. This information is highly relevant as to the selection of material in applied situations. The surface pressure was unfortunately not recorded nor the velocity in the friction interface.

5.8.1 Force or pressure

In the studies presented in this chapter, normal forces were reported and only in a few exceptions, the pressure in the friction interface. Forces are easy to record, but as the coefficient of friction is pressure dependant (Comaish and Bottoms 1971) the information on force alone is of less relevance without information on the area over which it is distributed. As several studies suffer from lack of pressure details it is difficult to draw conclusions on friction based on forces only.

Adopted forces varied within the range 0.03 N to 69.5.N among the fourteen studies of palm friction, presented in Table 5.4. Too much force over a skin area will cause pain as described in Chapter 2. Thus the area of skin contact need to be considered when determining the suitable forces for palm skin friction experiments.

5.8.2 Velocity

It is difficult to compare the identified reports as the velocity in the friction interfaces varied considerably and ranged from 1 to 260 mm/s. Polymers with properties similar to glabrous skin are known to be velocity dependant (Yamaguchi 1990) and it seems reasonable to expect palm skin to behave similarly, requiring fairly similar velocities for comparisons. Table 5.3 show the diversity of velocities reported in the identified palm friction studies. In the engineering context, static friction i.e. when there is no velocity, is frequently compared to dynamic friction where there is displacement and velocity. But due to the visco-elasticity of palm skin, as described in Section 2.5, there is no clear point at which static friction turns to dynamic friction. Johansson and Westling (1984a) have shown that only underlying palm tissue, and not the epidermal surface, moved at velocities lower than 2 mm/sec. Within the speed range 2 to 4 mm/s however, a gradual slip starts to take place starting at minor locations in the skin-sample contact area. At velocities exceeding 4 mm/sec a general slip is manifest, which was regarded as a condition of dynamic friction μ_k.

Including velocity as a controlled variable in palm friction research seems therefore to be justified.

5.8.3 Skin hydration

The hydrophilic qualities of glabrous skin, which is in contrast to the hydrophobic hairy skin, may be of relevance in understanding the friction generating elements of the human side of the partnership. Several of the identified references indicated hydration of the skin as a factor acting to increase friction. One possible explanation is that the increased water content probably increases the elasticity of the skin and thus its ability to drape around irregularities on the friction partner and also allows it to stretch so that the molecular contact area in the friction interface increases. Several ways to increase the water content of skin are reported in the literature, ranging from applying water on the friction interface, immersing the hand in water, and wrapping subjects in blankets to make them sweat. Other more subtle ways to increase the water content are the application of oil or grease on the skin. After an initial lubricating effect (which reduces friction), the occlusive effect seems to hydrate the skin (and probably increase the elasticity) and the evaporation of water from the tissue is strongly reduced. As the lubrication vanishes, a hydrated and more flexible skin appears, rendering a significant increase in friction (see Figure 5.3). Thus, in order to allow comparison of different friction studies and friction materials, a need arises for controlling the hydrated state of the palm.

5.8.4 Direction of displacement in the friction interface

The role of the dermal ridges (dermatoglyphs) in the generation of friction is not clear. No references have been found to show their contribution to friction, but the shape, size and dynamics of the dermal ridges have been suggested to contribute towards improved friction in relation to hairy skin (where they do not exist). The basic shape of the dermal ridges on the distal pads follows generally the same oval pattern of which 70% are oriented in the direction along the fingers. It seems therefore reasonable to anticipate a difference in coefficient of friction between the lateral and distal (as when an object is pulled away from a pinched grip) - proximal (as when an object is pushed into a pinch grip) directions. This was also the case (at 40 kPa) according to Bullinger et al (1979) who found that coefficient of friction in the direction transverse fingers exceeds that in the distal direction, by on average a factor of 1.39. More surprising is that Jones and Hunter (1992) could show that coefficient of friction acting proximally on finger pads (as when pushing an object into a pinch grip) generated higher friction, by on average a factor of 1.45, compared to forces that are acting distally on finger pads (as when pulling an object from a pinch grip). According to Jones and Hunter *(ibid.)* it may be mechanical properties of the intervening soft tissue, and particularly the compliance, is different in the proximal directions compared to the transverse directions. It seems therefore appropriate to use a factor of approximately 1.4 to lateral as well as to the distal directions to reach the coefficient of friction in the proximal direction. Most identified studies of palm friction are performed in distal or transverse directions. Such results, and those reported in this thesis, appear accordingly not to be comparable to proximal (when an object is pushed into a pinch grip) without considering the factor 1.4.

Thus the glabrous skin on human hands appears to be 40% more effective in resisting friction forces acting in the proximal direction than distal. Expressed differently, the musculoskeletal system which provide forces for prehension, will be less strained when friction forces are acting in the direction towards the palm rather than from, or transverse to, the finger tips.

5.8.5 Gaps in knowledge of hand-object friction

Industrial designers use a variety of materials and textures for application on objects that are held and handled in industries and homes. They are used in a variety of environmental conditions and with hands which are wet, dry or greasy. The literature survey above answers only a few of their needs for facts about friction properties. The literature nevertheless gives an insight to the many factors that affect hand friction. Only scattered details are provided of what friction can be expected due to task, user and environmental demands. A need arises to collect friction data while a variety of conditions are controlled for or used as independent variables in experimental situations. Moreover, in order to draw general conclusions from the materials and textures researched, textures and materials need to be described using standardised methods and instruments e.g. from the science of tribology and surface chemistry.

Although many variables interact in the generation of friction, multiple regression methods can help in establishing their relative importance. By these statistical methods more and general results may be reached rather than the specific results from individual samples.

Textures of interest range from coarse to fine, including hand made milled topographies, etched and spark eroded surfaces.

Interesting contaminants in the friction interface are both water-soluble liquids like glycerol, but also animal fat (e.g. lard), hydraulic oil and grease from the automotive industry. Sweat is also of interest and the effect of hydrated skin.

Several types of material should be considered such as thermoplastic elastomers, construction plastics (resins), metal, steel, textiles, paper. In addition wood and other not man-made material should be considered. Such studies have been performed by the author, briefly reported in Appendix 5 this thesis and in (Bobjer 1998).

The quality of experiments largely depends on the validity of the methods and reliability of the instruments used. Chapter 6 reports on and scrutinises existing methods and instruments for data collection as a basis for designing a hand friction laboratory to generate data for industrial designers and other applied human factors scientists.

Chapter 6 Traditional equipment for skin friction research

6.1 Introduction

The aim of this chapter is to review existing methods and equipment for acquiring skin friction data. A major issue was whether the current approaches were appropriate for the intended research, which is the subject of this thesis. If they were not, then a new approach would need to be developed.

Since 1955 a variety of mechanisms and machines have been used to record the coefficient of skin friction. The first equipment was designed for friction measurement on the hairy type of skin. Friction measurements on glabrous skin demanded more delicate instrumentation due to the smaller palm areas. Comaish and Bottoms (1971) were the first to perform recordings of this nature. Most of the equipment was designed for the analysis of one dependent variable, namely the coefficient of friction. The independent variables were generally the normal force and very few other variables were controlled. The exception was Lederman and Taylor (1972) who used perception of roughness as a second dependent variable.

Below is a description of some of the equipment used in previous research on skin friction, together with comments on their qualities.

6.1.1 Sledge

This method is based upon a sledge being pulled along a horizontal plane on which is laid a sample of skin (see Figure 6.1). Pulling force was used as a dependent variable. The drawback was the difficulty in controlling the speed of movement and thus the difference between static and dynamic friction. This method was used by Comaish and Bottoms (1971). Due to the limited length of homogenous skin in humans this method rarely lends itself to analysis in vivo.

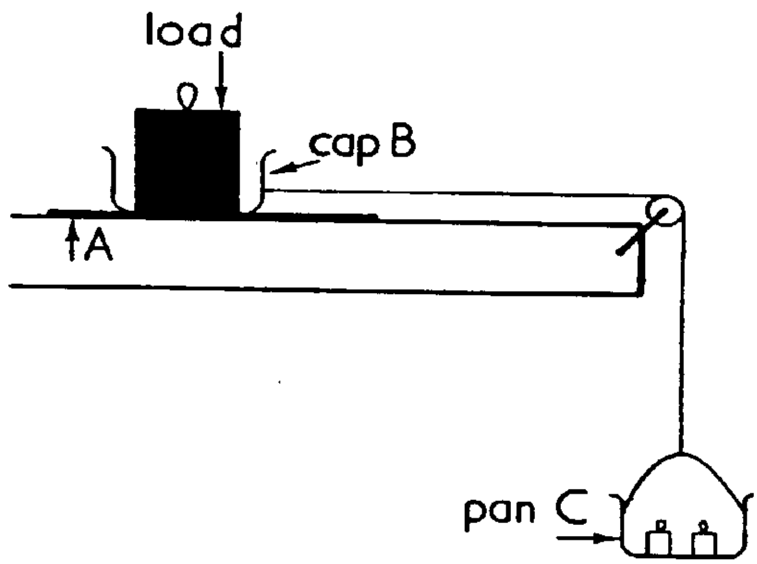


Figure 6.1 **A sledge pulled at a horizontal plane. From Comaish and Bottoms (1971).**

6.1.2 A pendulum

In the pendulum type of machines, swing angles and distance to stop after encounters with a friction partner can be recorded. Only dynamic friction can be recorded and the rapidly decreasing velocity will cause difficulties when interpreting the recordings. Akers (1985) described the method.

6.1.3 Rotating flange machines

Rotating flange machines work on the principle that torque reaction from a drive unit is equal to the friction torque. Knowing the Normal force Fn, the geometry of the equipment and the location of the contact surface, an instant reading of the coefficient of dynamic friction is possible. Such an instrument, the Newcastle Friction Meter (Comaish et al 1973, see Figure 6.2) has been used by several researchers (Comaish et al 1973, Cua, et al 1990b, Nacht et al 1981). It lends itself to analysis of dynamic friction only. It was not suitable for detailed analysis of textured materials due to the use of a disc or annular ring and the different loads were hard to arrange.

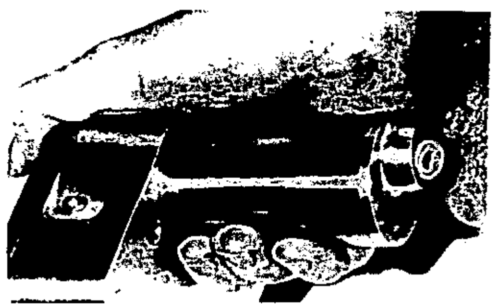


Figure 6.2 The Newcastle Friction Meter used by several researchers (Comaish et al 1973)

6.1.4 Rotating cylinder machines

Rotating cylinder machines are of wheel type and align with the skin on its periphery, as illustrated in Figure 6.3. According to Akers (1985), it is difficult to accurately control the load on the friction interface since it tends to be higher at the end than in the beginning because skin is viscoelastic and will move with the wheel. Highly et al (1977) and Bullinger et al (1979) used such an instrument.

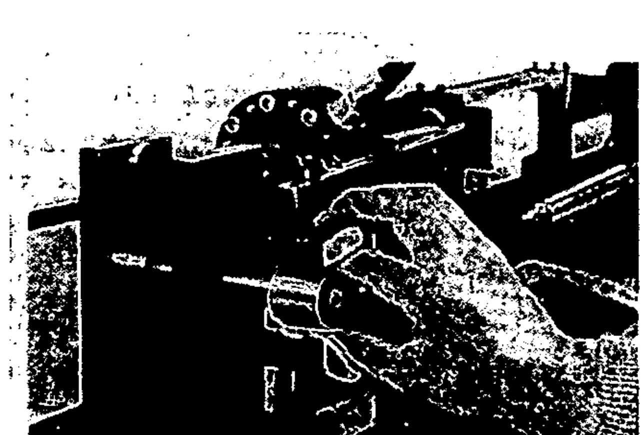


Figure 6.3 Rotating cylinder machine used by Bullinger et al (1979)

6.1.5 Linear rubbing machines

A variety of linear friction machines have, according to Akers (1985), been used to measure coefficient of friction and to produce injuries to skin. Goldblum (1955) used such a machine to simulate scratching fingernails. Other rubbing heads could be attached. The advantage of this machine was its ease of construction. The disadvantage was that it required constant observation during operation, since the head tended to jump at lower loads and to move the underlying tissue at high load. Naylor (1955) used a similar mechanism in which the forces could be recorded dynamically. The head had to be supported laterally by a frame glued to the skin area being rubbed. Sulzberger et al (1966) used a linear machine in which the effects of fluids (water and different lubricants) were recorded. These were delivered accurately to the rubbing interface by means of an attached perfusion pump. Frictional resistance and temperature at the rubbing head was recorded. Comaish and Bottoms (1971) described a linear friction machine by which erosions and blisters could be produced. Spring-activated steel bars stretched the skin to maintain a constant tension on the skin of the forearm. This method is clearly very instrumental and unsuitable if a subject's perception of the friction sensation is to be investigated.

6.1.6 Twist friction devices

Sulzberger et al (1966) Akers and Griffin (1968) designed, according to Akers (1985), twist friction machines of a similar type that recorded friction forces between human skin and various sock materials. Electric step motors produced 1 to 200 to and fro cycles per minute and which could be spring loaded in the range 2 to 50 Newton. Twist angles were adjusted from 10 to 178°. The authors found the method unreliable.

6.1.7 Pinch pull and pinch twist

Several researchers recorded friction on the thumb and index finger digit pulp while objects were pulled away from a pinch grip vertically or horizontally, or lifted up from a table or twisted between the fingers. An example of this method is shown in Figure 6.4.

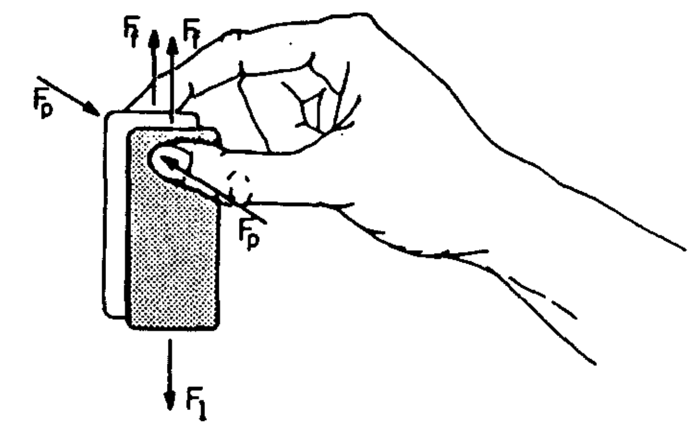


Figure 6.4 Objects being pulled away from a pinch grip. (From Buchholz et al (1988)

Buchholz et al (1988) used such a set-up when objects were pulled vertically by a pressure cylinder as the subject rested the lower arm on a horizontal armrest.

Several researchers have, in numerous experiments, applied gravimetric loads to objects held by subjects in a pinch grip which, without any prior notice, pulled the objects vertically downwards (Cole and Johansson 1993; Johansson and Westling 1984a, 1987; Johansson et al 1992; Westling and Johansson 1984, 1987). In these experiments, most of the equipment and the cup in which weights were dropped were hidden away from the subject (see Figure 6.5).

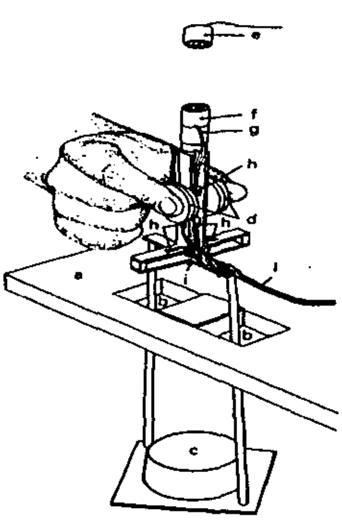


Figure 6.5 Equipment used by Westling and Johansson (1984, 1987) in which gravimetric loads held by subjects in a pinch grip were suddenly allowed to fall vertically

Jones and Hunter (1992) performed similar experiments where the subject's hand was supported. Objects were horizontally pulled away from the hand (distally) and pushed respectively towards the hand (proximally) with the fingers engaged in a pinch grip (Figure 6.6).

Kinoshita et al (1997) attached disks on both sides of a wheel. Subjects pinched this arrangement between their thumb and index finger. The disk on one side was forced to rotate while the other disk was fixed. The rotation generated a circular movement around the centre of digit pulp.

These pinch, pull and twist methods are simple and obvious in their function. In order to gain consistent results, however, training of the subjects was essential. The displacement and velocity in the friction interface was rarely recorded, nor was the area of the friction interface. It is open to discussion whether, in some experiments, it is static or dynamic friction that was being recorded.

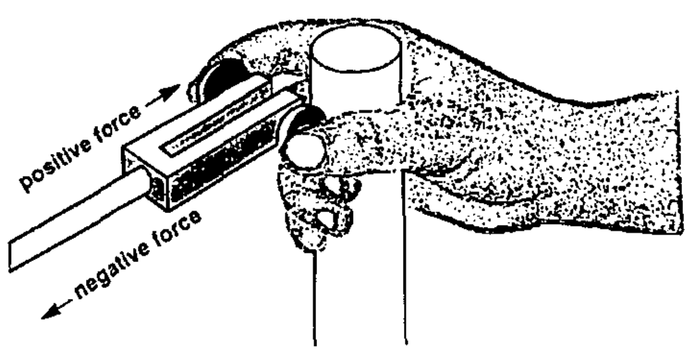


Figure 6.6 **Equipment used by Jones and Hunter (1992) where objects were pulled and pushed respectively in the horizontal direction along the length of the fingers that were engaged in the pinch grip.**

6.1.8 Counterweight lever

Roberts (1992) applied friction material on one side of a miniature see-saw and placed calibrated weights on the other (Figure 6.7). The equipment was required to be kept horizontal as indicated by a spirit level attached to the platform. Friction forces were recorded by strain gauges as the subject moved the digit pulp on the friction material. This is an elegant and simple device that engages the subject to participate in the generation of displacement. However, it is restricted to the recording of only one level of load at the time. The weight of the contaminant was not accounted for and would bias the results. This equipment suffered from the same disadvantages as the equipment above concerning velocity and the recording of the area of the friction interface.

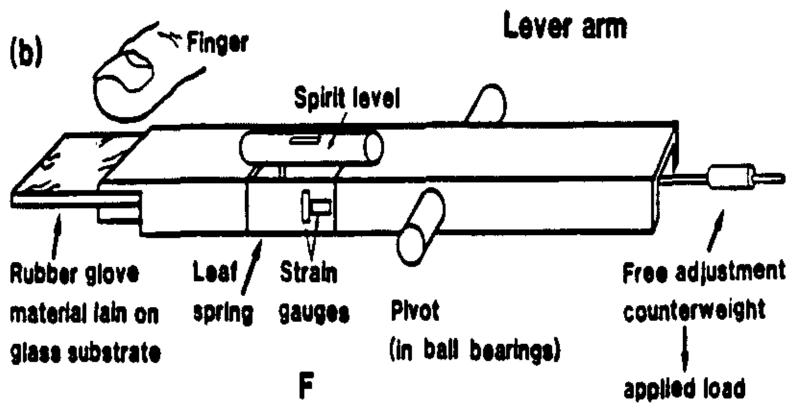


Figure 6.7 Illustration of the miniature seesaws used by Roberts (1992). Friction material was placed on one side and calibrated weights on the other side

6.1.9 Squeeze and pull

Bullinger et al (1979) enclosed the dorsal side of subjects' hands in plaster, leaving the palm side open for friction experiments. The hand was inserted, palm up, in a mechanism on which calibrated weights were placed (Figure 6.8). Objects of different materials and textures were placed between the palm and the weights. Friction forces were recorded as objects and weights were pulled distally over the palm. This equipment was very mechanical and separated all friction generating activities from the subject. It seems unlikely in this type of experimentation that any investigation of perceived friction would result in valid data.

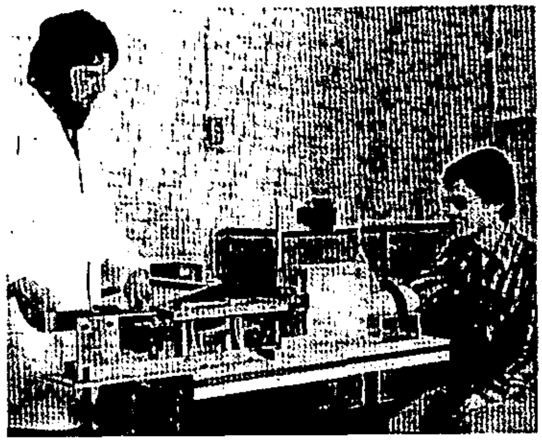


Figure 6.8 Friction forces were recorded as objects and weights were pulled distally over the palm. (From Bullinger et al, 1979)

6.2 Discussion of traditional equipment for skin friction research

The different methods and instruments for recording of skin friction presented above include both simple and very complex arrangements. It appears that the simplest of equipment often lacked any means to record displacement and velocity in the friction interface. This was a major drawback as it was then unclear at what velocity the friction forces were generated, i.e. whether it was static or dynamic friction that was recorded. The most complex pieces of equipment were so mechanical that they most likely distorted the subject's perception of friction or other sensory motor variables. Other equipment was designed to record dynamic friction only and designed only for one specific friction material. In none of the methods was the area of the friction interface, or the pressure and pressure distribution over it, accounted for although comments on such matters were noted. The most complex "machines" seemed to treat the subject as simply an extension of the skin and no personal involvement or assessments by the subject were requested. On the other hand, the simple equipment required motor skill and some periods of training in order to produce valid data.

Among the methods identified above there is no single method appropriate for all the aims of the author's research. Some of them did however contain design elements useful to incorporate in the laboratory set-up for the series of research reported in this thesis. The method used by Roberts (1992) in particular showed subjects rubbing the distal pad of their finger on a flat specimen applied to one side of a miniature see-saw. Friction forces were recorded by means of strain gauges. Jones and Hunter (1992) logged friction forces at high sampling rate to computer files when normal forces were generated from fingers on to research samples.

The aim of a major series of research studies, of which three experiments are reported in this thesis, was to research the influence of many different environmental variables, and skin conditions, on friction. Water and lubricants such as oil and grease were accommodated on the friction recording device. The total series was planned for approximately 10 textures and more than 100 materials.

It was considered that research sessions should be short enough not to fatigue the subjects, particularly as subjective estimates of perceived sensations were requested. Changes of samples should therefore be fast. The weights of samples varied and means to quickly calibrate the instrument to compensate such differences were required in order not to affect the readings of the normal force by differences in sample weights.

No such considerations seem to have been raised in the identified methods. Moreover, the range of friction forces generated while using the identified equipment was fairly small in comparison to what would be planned in the present series of research.

According to tribology text books, e.g. Bowden and Tabor (1967), the kind of factors needing attention in friction research include:

- task factors (velocity, load, area of the friction interface etc.)
- environmental factors (temperature, humidity and contamination etc.)

Rarely were such conditions considered in the studies referred to above. When the issue concerns friction and involves humans it seems appropriate to take into account individual factors such as skin condition. It also appears natural to pay attention to factors such as perceived friction and discomfort, stress and strain in the exposed limbs and tissue.

Thus an efficient method that required novel instruments for rapid data collection of multiple variables was required. The details of the development this equipment are presented in Chapter 7.

7 Development of laboratory equipment and instruments

7.1 Introduction

The aim of Chapter 7 is to present the equipment that was developed for the three experiments presented in this thesis. Usability and data collection criteria for the equipment are described. A flowchart of the set-up is given together with descriptions of the functions of the entire data collection system including gauges, amplifiers and mechanical layout with reference to tolerances, product name and supplier. Methods for calibration and data management are also reported. The actual procedures used in the experiment are described in Chapter 7.

7.2 Design of the research equipment

To avoid some of the drawbacks found with the methods reported in Chapter 6, and to allow for the current research aims to be met, it was felt that there was a need for novel and user friendly hand-friction recording methods and related equipment. This section present the criteria for equipment suitable for application at the digit pulp of subjects' fingers, to record coefficient of static and dynamic friction, perceived discomfort, velocities, normal and friction forces under normal, sweat and hydrated skin conditions but also the contaminated conditions lard, glycerol, engineering grease, paraffin oil, hydraulic fluid and associated experimentation.

7.2.1 Design criteria

- The equipment should be easy to access and the function should be easy to understand and use. Samples of materials, textures and contaminants should be visually recognisable by the subject who should experience no risk of hand or skin injury or surprising events during the experiment. The aim being obviousness and trust to achieve a quick introduction to the experimentation and obtain reliable data.

- The active participation of the subject should be given high priority. The subject's own activity should generate the friction, the discomfort, but never any pain. The aim being to design for the subjects' perception of touching the samples and to report that on a discomfort scale while collection of friction data should be managed without any involvement of the subject. To meet these demands it was desirable that subjects should be allowed to concentrate on as few variables as possible while conducting the experiment. The most important were the location of the digit pulp on the sample, the normal force Fn, the velocity in the displacement v, and the perceived discomfort.

- Due to the high number of individual palm exposures, the changing of friction samples and application of contaminants should be quick and easy, so as to not fatigue the subject. The subject should sit comfortably on a stool during the research session with the elbow adjusted to be at the same height in relation to the height of the test samples.

- The duration of a research session should never exceed three hours and breaks should be allowed for.

- The equipment should be movable to allow transportation to national and international industrial sites for additional research if required. Gauges and amplifiers and their spares should be commercially available and provide calibrated tolerances.

7.2.2 Validity and reliability in equipment and experimental procedures

The following constraints were applied to the design of the equipment.

Validity

- The equipment should allow friction to be measured which is representative of the situation that exists when palm skin is exposed to manipulating the handles on hand tools and controls under static and dynamic conditions.

- It should be possible to apply contamination and skin treatments, representative of those that hands are exposed to in industry and homes, under controlled conditions, rapidly and with the smallest possible inconvenience to the subject.

Reliability

- The instruments, the mechanical design of the gauges, amplifiers, wire harness, computer software and displays should be of high technical standard limiting the total system instrumental error to less than 4%.
- Calibration should be possible both with respect to the total system and to weight differences in researched samples including the eventual applied contaminant.
- The calibration equipment should be robust, reliable and provide valid calibration.
- Contactless reading of the velocity at the skin-specimen interface should be possible while providing the smallest possible inconvenience to the subject.
- Recordings of skin moisture should, according to instrumental demands, require 30-60 s of direct skin to probe contact. Not more than 15 seconds should elapse between the ending of the moisture recording and commencement of skin exposure.
- To record the skin-interface contact, a non-textured sample of similar size as the researched samples should be used and located at the same place as these where they are exposed to skin friction in the test situation.

7.3 Recorded performance

The reliability of the experimentation is determined by a number of instrumental, data collection and analysis factors.

7.3.1 The instruments

Instrumental errors referring to Normal force and Friction force gauges and amplifiers were < 0.01%. The error from the skin moisture recording instrument Evaporimeter™ was ±15%. Overall mechanical and electrical errors identified by gravimetric calibration using precision weights was ranging < -0.5% to 2.0% using a sampling frequency of 10 Hz.

7.3.2 Data recording

To reduce data sampling errors (i.e. extreme variation in the results), specific procedures were adopted. After each subject's research session, the data collected were imported to Stat View and manually inspected for obvious errors in scatter grams. In the coefficient of friction files, the "sort in descending order" command was used to present the logged files on the screen. Friction data $\mu > 5.00$ was detected in less than 0.1% of the rows. Such data, and the related data on the same row, were treated as flaws and deleted from further analysis. This limit was based on information in the literature survey (Bullinger et al 1979) that palm-object-coefficient of friction exceeding 2.5 was never was observed. That data was, however, based on only five subjects. A margin of 100% was therefore added to that figure accounting for the uncertainty of the upper limit for skin friction, acknowledging that this correction will increase the likelihood of accepting too high coefficient of friction numerals.

7.3.3 Overall data recording and instrument reliability

The sum of errors in the present series of experiments due to data recordings and instrumental reliability was less than 4%. In those experiments where skin moisture was sampled, an additional ± 15% error could be incurred.

7.3.4 Data analysis

Three levels of normal forces were investigated in the experiments in this thesis, 1N, 10N and 20N. The limit for saving the related friction data was ±10% of these nominal levels. Data were logged at finger velocities ranging from 2 to 128 mm/s but are reported as mean velocities at intervals of 2 - 4 m/s, 4 - 8 m/s, 8 - 16 m/s, 16 - 32 m/s, 32 - 64 m/s and 64 – 128 m/s.

7.3. 5 Data management

Algorithms such as gates and windows were used to select, sort and log to file only elements of the independent variables that were of concern to the research.

Thus μ would be logged to file only:

If;

Friction force Fn was within 10% of the nominal levels 1, 10 or 20 Newton,

And:

The velocity v was >0 in the pulling direction.

Then

Coefficient of friction, μ, was filed in six classes depending on the related velocity in the friction interface (Section 7.3.3).

7.4 The equipment set-up

The research equipment was specified by the author and designed jointly by the author and the industrial designers of Ergonomidesign and produced by Ergonomidesign model technician.

With this equipment the researchers and technicians were able to quickly change exposure conditions and data logging details. The equipment allowed the subjects to see the changes that took place, and they had full control of the sequence as they participated actively. All subjects sat upright on a stool and could move freely whenever they liked as a result physical activity was low. Subjects estimate of discomfort were reported verbally to the researcher after viewing the Borg CR-10 scale (Borg 1982). This scale was selected following recommendations from Professor Borg. Throughout the experiment the enlarged scale was displayed vertically 1 metre in front of the subject. All experiments took place indoors at ambient temperatures ranging between 20 and 22°C.

A schematic presentation of the laboratory equipment is shown in Figure 7.1. Photos of the laboratory in Figure 7.2 and 7.3 show how a finger is located on a sample at friction data sampling. Figure 7.4 shows the calibration equipment.

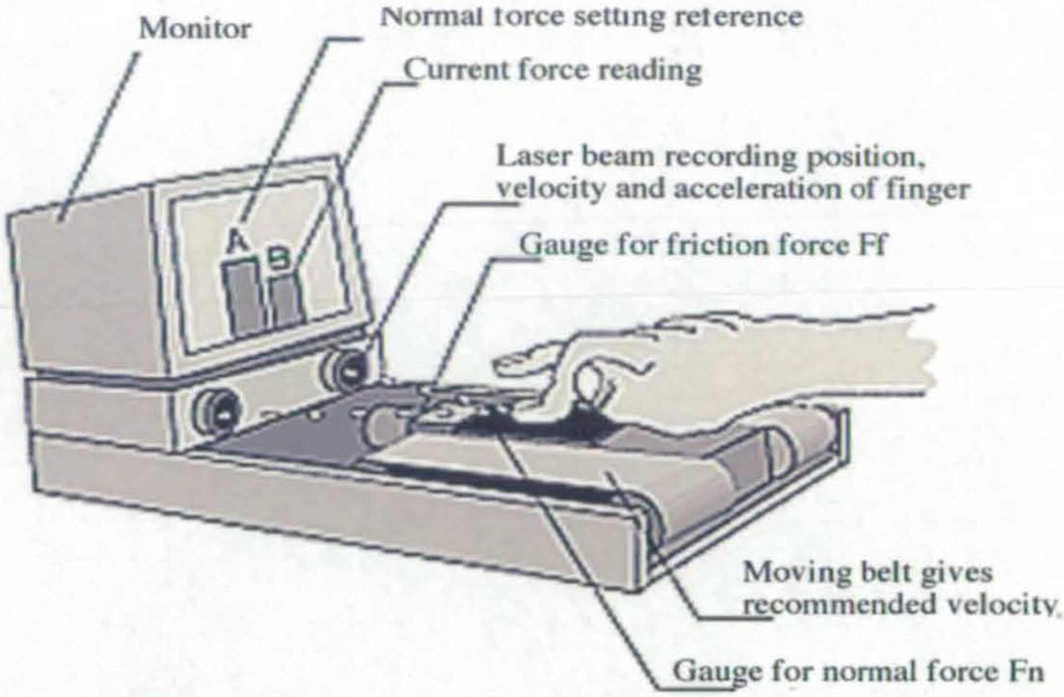


Figure 7.1 Illustration of the research equipment in the present work

Figure 7.2 View of the palm friction laboratory

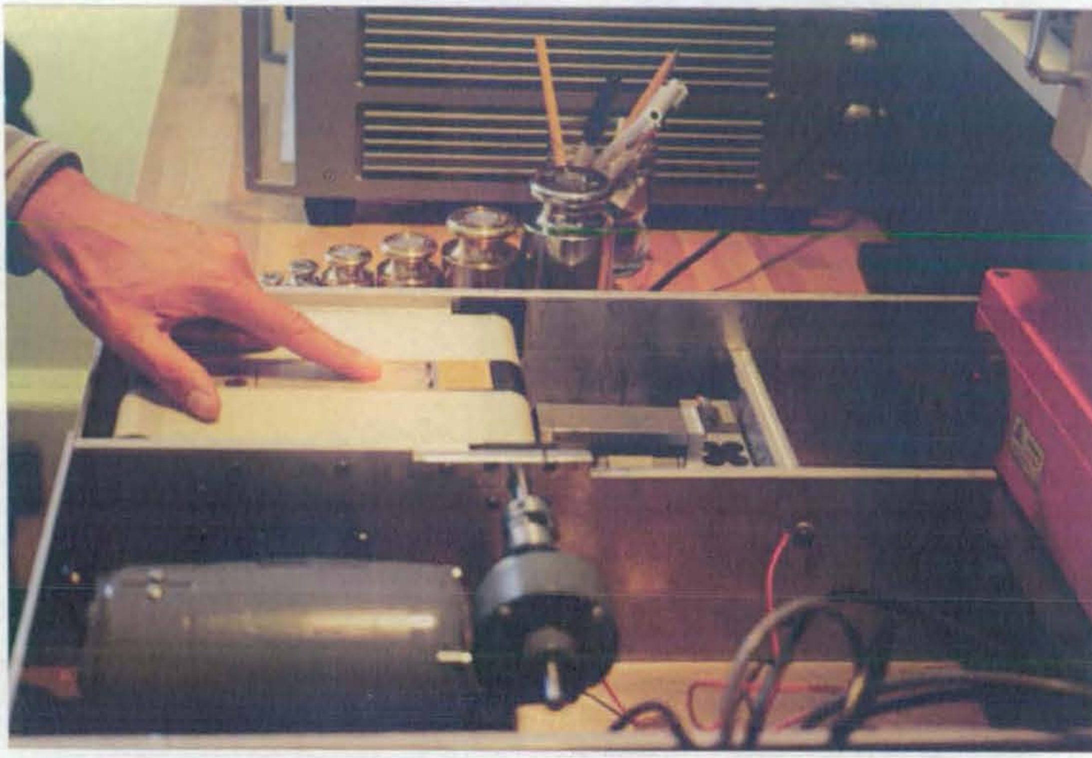


Figure 7.3 **The index finger located on the researched sample and pulled towards the subject's body. An electric motor drives moving belts which the subjects touch while training to reach the recommended velocity**

7.4.1 Calibrations

The normal and friction force gauges were calibrated using gravity and precision laboratory weights, see Figure 7.4. The normal force gauge was calibrated with weights placed centrally on the platform for each of the samples. To calibrate the friction force gauges, a low friction wire and link system was used by which forces from weights placed in a bowl were transferred to the surface of the researched samples. The deviations detected by the calibrations were used as a basis for calculating algorithms by which the errors were minimised. The coefficient of friction was computed as F_f/F_n based on a 10 H_z sampling rate. The weight for each sample, including the contaminant, was manually initiated and set to zero prior to each recording in less than 1 second. The error in terms of coefficient of friction was -0.5 to +2.0% of correct value within the range of the normal and friction forces in this study.

The evaporimeter was calibrated according to the instructions provided with the instrument, using the equipment recommended.

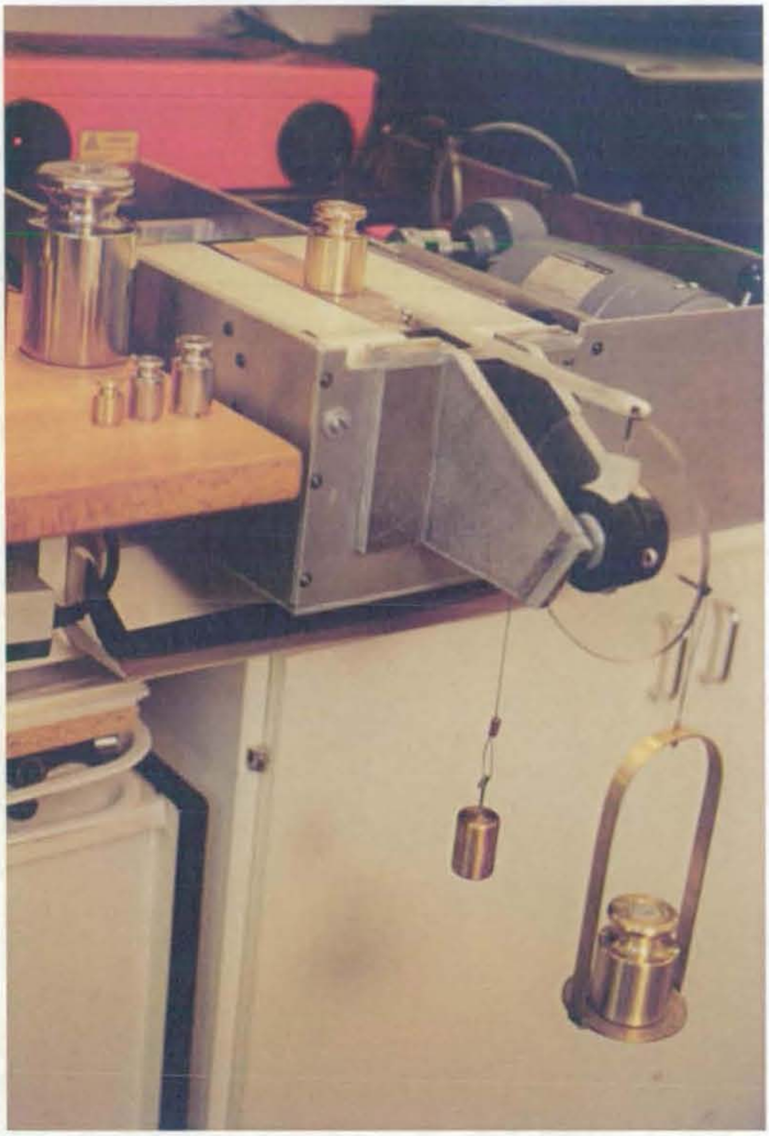


Figure 7.4 Instruments for calibrating the gauge system for Normal, Fn, and Friction, Ff, forces

7.4.2 Schematic diagram of the laboratory set up

A schematic presentation of the laboratory equipment is presented in Figure 7.5. Detailed presentation of the symbols representing gauges, amplifiers, displays and logging are described in Section 7.4.3 "Symbols and explanations".

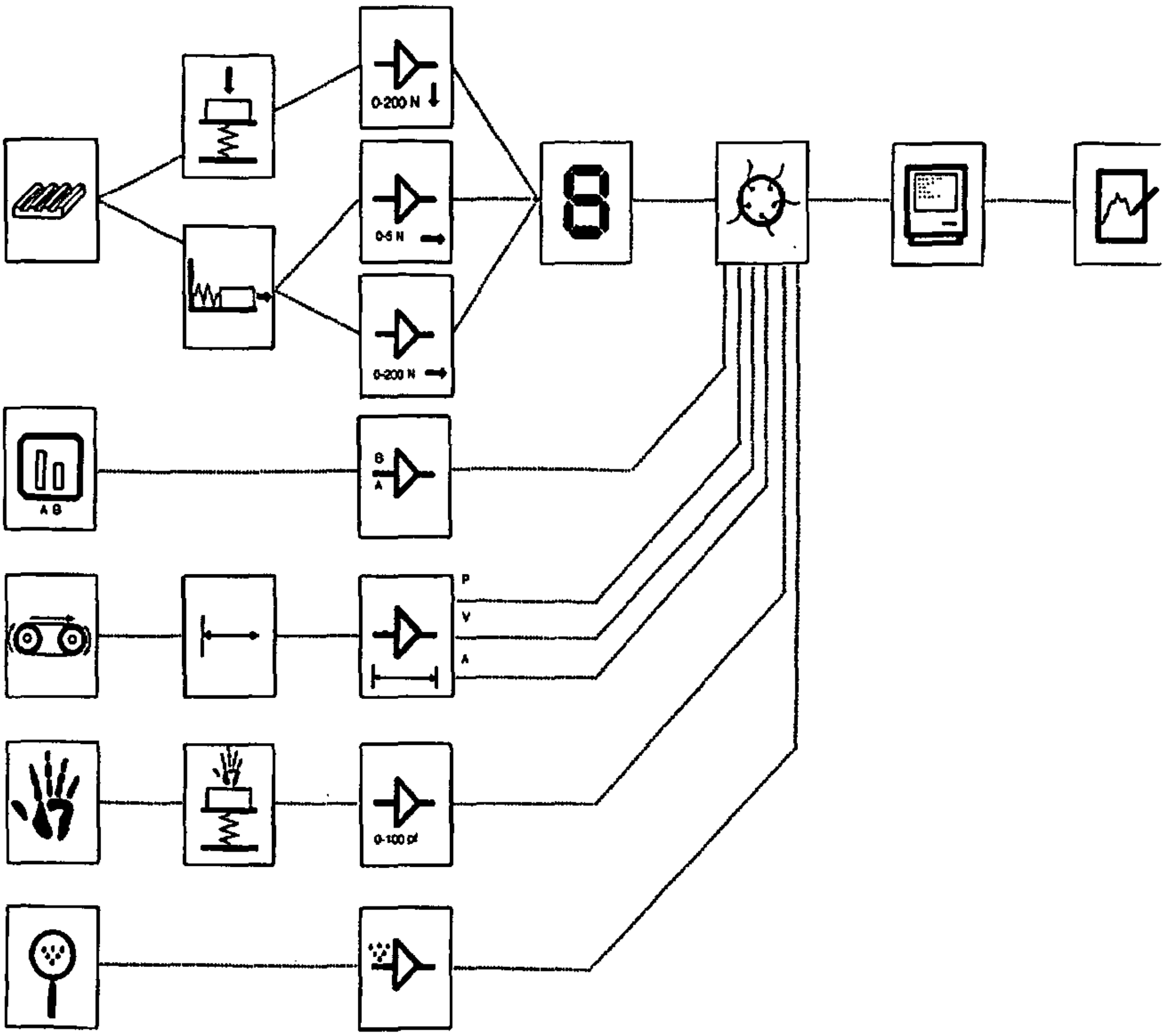
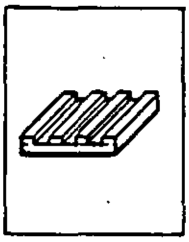


Figure 7.5 Schematic presentation of the laboratory equipment

7.4.3 Symbols and explanations

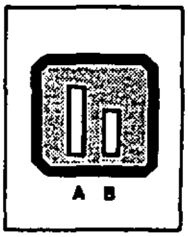
Variables

Samples



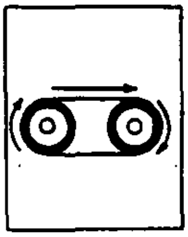
Samples of textures were easily fitted on to the research equipment with springs pressing the samples towards a stop on the subject's side of the equipment. The size of each specimen was 130 x 35 x 5 mm, thus allowing for the widest of fingers. The length allowed the maximum velocity to be reached, while the thickness provided volume for grooves.

Illustration of normal forces



A 12" screen was used for a graphic presentation of the predetermined nominal force (bar A), and the current force (bar B). The screen was viewed at a distance of 0.75 m.

Velocity

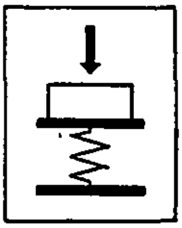


The subjects were trained to successively reach requested peak velocities by resting the thumb on moving belts to the side of the samples. The velocity of the belt could be adjusted within the range 0 to 150 mm/sec. This guidance was not needed after the training

Skin moisture

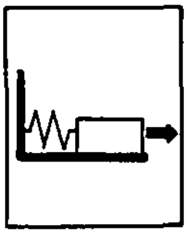
The dermal evaporation was recorded with an evaporimeter type EP1According to the manufacturer's instructions a probe was positioned in direct contact with the area of concern for 45 seconds. TEWL recordings were taken during the last 15 of these seconds.

Gauges



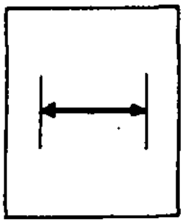
Normal Force

The normal force F_n was recorded using a strain-gauge Baldwin Messetechnik HBM type PWC 3 Nominal 0 to 20 N, error < 0.01 %. The displacement was 0.35 mm. Dedicated equipment allowed the scales to be set manually to zero by the researcher every time a new test sample was fitted (as they varied in weight).



Friction force

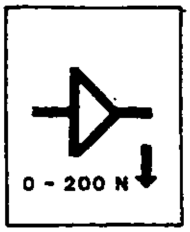
The friction force F_f was recorded using a small and a larger strain gauge mechanically fitted in series. The smaller HBM U1 strain gauge recorded 0 to 5 N error ± 0.075 %. The larger strain gauge HBM PWAH3 recorded 0 to 20 N error < 0.01 %. The displacement for each strain gauge was 0.35 mm. Both gauges were mechanically linked to the platform that carried the samples. The platform rested on leaf springs that were pre-set with tension in the direction towards the subject in order to eliminate initial play in the link system.



Displacement

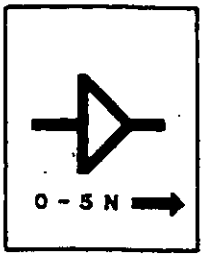
The position of the finger was recorded with a laser beam (SAPOS DM 100) at 1600 Hz. The beam pointed at the small skin part under the nail. The recording range was 100 mm, the recording distance was 310 to 410 mm and the accuracy was within ± 0.1 mm.

Amplifiers



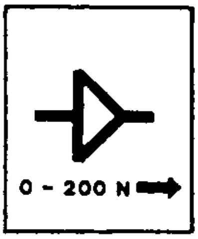
Normal force

The signal from the normal force gauge was amplified using a HBM MGT 32 analogue amplifier with an output signal of 0 to 10 V.



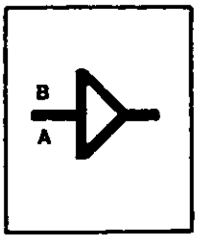
Small friction forces

The signal from the smaller of the friction force gauge was amplified using a HBM MGT 32 analogue amplifier with an output signal of 0 to 10 V.



Large friction forces

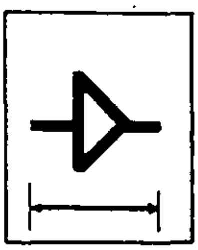
The signal from the larger friction force gauges was amplified using a HBM MGT 32 analogue amplifier with an output signal of 0 to 10 V.



Screen display

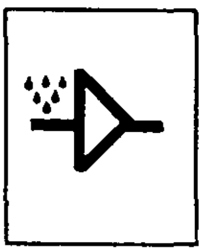
The predetermined normal force (A) and the current force (B) were presented on a TV monitor with the help of an IBC analogue video mixer AVM 2000. The force (A) was identified using calibrated loads and then set to be applied randomly at1, 10 or 20 Newton levels using a dial on the mixer. A Panasonic N3 video camera was used as a video signal carrier.

Velocity



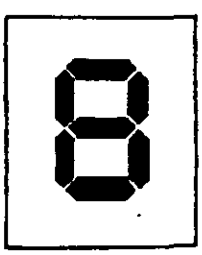
The signal from the laser was used in derivation to achieve instant velocities from the friction interface. The output signal was 0.1 V/mm/s.

Skin moisture



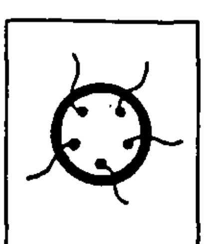
An evaporimeter (EP1 ServoMed Stockholm Sweden) was used to detect the rate of water emitted from the palm and the relative humidity in the ambient air. The range was 0 - 300g/m^2/h, with an accuracy of ± 15 % or ± 2 g/m^2/h. The output signal was 5 to 10 V.

LED-display

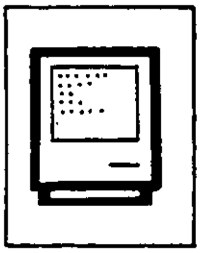


To visually inspect the basic level (not adjusted by algorithms) from each gauge an LED-display was used.

Wiring

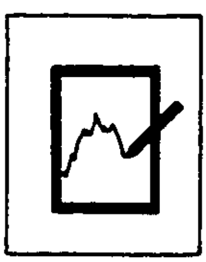


The signals were wired to a connecting box.



Data logging

All outputs were linked to a Macintosh SE computer equipped with the hardware Strawberry Tree Analogue Connection ACSE. AD-conversion was performed by the software Strawberry Tree Analogue Connection Work Bench and Analogue Connection Quick Log. Control data that remained unchanged over a research session was fed directly into the computer using the keyboard. For statistical analysis, SAS/STAT Version 6.03 was used, as well as StatView version 4.1



Prints

Printouts and graphic presentations were presented on Macintosh Laser Writer Plus.

7.5 Pilot trials

A series if pilot trials were performed in order to establish ranges and limits for the experimental conditions. The same laboratory staff (3 – 5 people) were involved in each trial. Studies were performed to evaluate:

1) what forces subjects could be expected to apply with the index finger within set limits

2) methods to record the area of skin-sample contact

3) skin displacement in static and dynamic friction

4) velocities in the skin-sample interface while using hand tools

5) how to apply contaminants

6) means to perform skin treatments.

7.5.1 Normal forces

Studies were performed to evaluate the highest and lowest forces subjects could be expected to apply during the experiments with the digit pulp of the index finger. The criterion was to keep the forces within acceptable tolerance limit (± 10% of the nominal force) more than 95% of the times data that were sampled. Each staff performed sets of 20 strokes on a non-textured sample (No.5) along the complete recording distance, at 1, 10 and 20 N. Reference data were recorded when pulling a metal block weighting 100 gram in a string, more than 10 times, along the complete recording distance, on a not textured sample surface located on the laboratory scales.

The criteria were met at all three forces but it was found that a subject needed at least five training strokes per force level to reach this level. The limiting forces, 1 and 20 N were believed by the staff to be the limit of what can be expected to be tolerable for subjects. Forces of 1 N required considerable concentration, while forces of 20 N were believed to be close to the force limit for some subjects, considering the high number of treatments, (75, 60 and 96), in the three experiments, respectively

7.5.2 Area of skin-sample contact

Surface pressure i.e. Normal force / Contact area is essential in studies of friction (Suh 1986) Thus the detailed area over which the normal forces are distributed in the skin-sample contact were required to calculate surface pressure. Four methods for producing and recording the skin-sample contact area were considered and evaluated prior to the experiments.

Two skin areas may be relevant. The contact between the sample and the nominal contact area, i.e. the gross area covered by the fingerprint, and the true (molecular) skin-sample contact area. At first, attempts were made to find an instant method to record the gross interface area. In these, the electric capacitance, L, was recorded using a dedicated capacitive instrument and link that with the subjects in an electric circuit. The capacitance was generated as the subject pressed their finger pad on a flat cupper plate, which was covered with a thin plastic film (cellotape). The capacitance, expressed in picofarads, pF, would correspond to the area of skin-sample contact. Readings were performed with normal clean hands but also fingers gently covered with contact cream of the kind that is used in EKG recordings. Numerous tests at loads ranging 1-20 N showed far too diverse contact areas for the same individual finger and identical conditions to be acceptable as a screening method. Additional attempts to record the area of skin contact with defined areas, (holes of 10, 15 and 20 mm made in a 1 mm thick polyamide sheath), did not generate sufficiently consistent data to be accepted. It can be hypothesised that this method would be more relevant if the molecular contact area of the friction interface was to be recorded rather than the nominal skin- sample contact area.

Secondly, nominal finger contact area i.e. the 'fingerprint' area, was recorded on graph paper. Ink prints were taken and the area covered by the print was analysed using a mechanical 2-dimensional instrument. The method is presented in detail in Section 8.2.3. To evaluate the reliability of this method pilot studies were performed in which three laboratory staff performed five prints at each of the three normal forces 1, 10 and 20 N, in all 45 treatments. The coefficient of confidence was less than 25%.

Thirdly, attempts were made to explore the analysis of the nominal ink print finger contact area to analyse the contact area at each point where there was ink, rather than the gross area as, according to Suh (1986), such recordings would more accurately relate to the generation of friction forces. Photos were taken on the inked prints. These were digitised and a computer program was developed to count the pixels that were dyed. This area was compared to the un-dyed area of the fingerprint. Time and finance were however not available to use this method for a more detailed analysis of the collected prints.

Fourthly, the observation was made that more valid results would be reached if the analysed skin contact area was the same as when the skin is strained in the friction test situation (along the surface of the sample). These forces would be different depending on the coefficient of friction. Such recordings would require additional instrumentation for which there was no finance.

7.5.3 Skin displacement in static and dynamic friction

Palm skin is elastic. Bullinger et al (1979) showed that there was no clear step between μ_S and μ_K as shown in Figure 5.2 in Section 5.6.2. Several researchers, Johansson and Westling (1984a) as well as Srinvasan et al (1990), looked at the movements that took place in the friction interface. They viewed directly, and indirectly and through a lens system, respectively the movements and slips of the dermal ridges of the finger pad. They noticed that a gradually increasing sliding motion is established when a friction force is applied on the skin. Initially, only smaller patches slide, until a situation develops where the whole contact area is sliding and true dynamic friction occurs.

In the present series of research, where one aim was to detrermine static and dynamic friction, pilot studies were performed to define criteria for these two conditions. A 30 mm thick sample was made from glossy polycarbonate sheet material. A mirror was placed at an angle under the sample through which the digit palm skin in friction contact with the sample could be viewed. A laser beam, pointing at the tip of the finger, was used to record the displacements and velocity of the finger. By following the velocity and displacement on a CRT, and at the same time viewing the skin in friction contact, the behaviour of skin and hand was observed. It was observed that at initial finger displacement of a few mm, only underlying palm tissue moved while the skin still adhered to the sample. Finger velocities rarely exceeded 2 mm/s when this took place. With further displacement of the finger, generally 0.5- 1.0 mm, the velocity increased and within the speed range 2 to 4 mm/s, a gradual slip starts to take place starting at minor locations in the skin-sample contact area, as reported by Srinvasan et al *ibid.* At velocities exceeding 4 mm/sec a general slip is manifest. Following these findings coefficient of static friction μ_S are recorded when the velocity of the finger is within the speed range 2 to 4 mm/s, while coefficient of dynamic friction μ_K are recorded when the velocity of the finger exceed 4 mm/sec.

7.5.4 Velocities when using hand tools

Examples of tools which generally are used in dynamic friction conditions are long shafted tools like rakes and spades, where one hand is holding the tool while the other slide on the shaft for support and to relocate the required forces. Pilot studies were performed to determine the velocities in the hand-handle interface when using rakes. Three of the laboratory staff, who were familiar with the instruments for friction recording, used a rake and slided one hand on the shaft as in normal use. They were then asked to slide similarly on the friction sample and let the laser instrument record that velocity. In most trials, velocities of 100 mm/s were reached but never 150 mm/s or greater.

7.5.5 Administration of contaminants

The following trials were performed to evaluate different ways to apply the contaminants glycerol, paraffin oil and hydraulic oil the friction interface and in an amount representative of what hands and hand tools may be exposed to in industry and in the home.

Two ways of applying the liquid contaminants were evaluated. According to the first method the subjects dipped the pad of the index finger gently into a shallow bowl (like a tea tray), prior to friction exposure. The amount of liquid that eventually was dispersed on the sample depended mainly on how deep into the liquid the finger was exposed. When too deep the liquid would flood the instrument eventually causing hydro-dynamic friction. If too low, it was uncertain whether there was any lubricant in the interface. A suitable depth of lubricant was found to be 3 mm. In the second method, a pipette was used to apply the liquids on the sample for the subjects to spread over the exposed part of the sample. The first method was seen as efficient, comfortable and produced reproducible data. Consequently, it was used in Experiment 1, 2 and 3.

For the none-liquid contaminants lard and engineering grease other methods were required. At the 20°C indoor laboratory conditions they assume a creamy condition. With the aim of controlling the volume of these lubricants, attempts were made to fill a small spoon with these lubricants and empty them at the samples, for the subject to distribute over the researched distance while performing training strokes. Filling the spoons to the same measure was found to be difficult as bubbles of air appeared in the sample. Emptying the spoons completely was also difficult. This method was found to be unreliable.

From Suh (1986) it was found that the thickness of lubricants in a friction interface is dependent on the surface pressure in the friction interface. Following this information a 12 mm wide paint brush was used to gently apply a thin layer of these creamy lubricants on the samples. The amount was so small that subject could hardly see it. Separate sets of samples were dedicated for each of the contaminants. Excess of lubricants was removed, using paper towels when new subjects started these greased experiments.

7.5.6 Skin treatments

Three skin conditions were investigated. These were 1) normal clean, 2) sweat and 3) hydrated skin conditions.

The *normal clean* condition should represent a palm condition free from specific exposures of lubricating substances, nor should the skin be dry, wet or made particularly moist. The method used to meet these goals was adopted from Buchholz et al (1988) where the subjects washed and dried their hands on a paper towel 15 minutes prior to the commencement of the sample exposure. The subjects in the present experiments were asked if they for the last 24 hours had been exposing their hands to oil, grease, paint or solvents. A file was kept on the answer for an eventual grouping of subjests due to palm exposure. None of the subjects reported such activity.

Sweat skin. Analysis of sweat shows 99% water and 1% solids. Of the solids, one half is inorganic salts and one half is organic salts, e.g., urea (Rothman 1954). Solutions with a similar composition, but with 0.9% sodium chloride and no organic salts are commercially available at the chemist. This diversion from "true" sweat was however minor and accepted as an error. That solution was used thought the series of experiments as the "sweat" condition. A sweaty hand is however more elastic. In experiments 1 and 2, the "sweat" condition was investigated but in experiment 3 such elasticity was simulated in a hydrated condition (described below). To simulate sweat in the present series of experiments, one drip of water (0.05ml) of the solution presented above was applied, using a pipette, on the samples at the starting position for the finger at the far end of the sample. A unique set of samples were used for each of the three non contaminated conditions, normal clean, sweat and hydrated skin respectively. Between subjects, all samples were washed and rinsed in a dishwasher. In the *hydrated condition,* subjects kept their non-dominant hand in a surgical rubber glove, filled with luke warm water, for 30 minutes (over lunch). The method of immersing the hand in water over such a period was adopted from Comaish and Bottoms (1971) in the first of palm skin friction experiments.

Section B. Experiments and analysis

Chapter 8 Aspects of hand friction considered in this series of research studies

8.1 Introduction

Palm friction can affect performance, safety, health, efficiency and quality of the work produced in industry as well as elsewhere. Industrial and engineering designers belong to the category of professionals who may be in positions to select and recommend materials and textures that will be touched and operated by users' hands. As an applied ergonomist and a member of a design consultancy, the author was frequently involved in hand and hand tool related discussions where palm friction issues were addressed. The data in these traditional professions did not meet the requirements, so more in depth investigations were required. A research program was initiated and performed over a period of five years. Issues which specifically concerned textures and perception of discomfort when in static and dynamic contact with the palm side of hand and fingers were later selected for presentation in this thesis as Experiment 1, 2 and 3. Five additional experiments were carried out by the author but are not reported in detail in this thesis but are briefly described in Section 8.3.

From the literature studies, it was evident that the frictional properties of viscoelastic materials (like skin, e.g. elastomers) are dependent on several environmental and physical conditions which are easy to interpret for an ergonomist as having Task, User and Environmental implications. With reference to hand tools, examples of task related issues are velocity and forces in the friction interface, but also palm contact area and hand location. Examples of user related issues are skin conditions and size of the skin contact. Environmental issues are skin treatments, contaminants and temperature.

It was also observed in the literature search that few studies explored more than one independent variable and that few conditions were controlled. In order to draw more general conclusions from friction experiments involving palm skin as one friction partner, and textures and different material samples as the other, a series of experiments were initiated of which research on textured samples only is reported in this thesis. The focus was on such textures likely to be used in handles for hand tools and other hand held objects. In this respect the experiments had the same aim as the work by Bullinger et al (1979). By designing the experiments for subsequent multiple regression analysis (e.g. by carefully selecting specific textures and controlling for surface pressure, velocity, contamination's and skin treatments), more general conclusions were expected on which variables contribute to the generation of palm-texture friction and the degree of this contribution. According to the traditional law of friction, static friction should be higher than dynamic friction. However, the work by Bullinger (*ibid*), supported by Yamaguchi (1990), indicated that, in materials with properties like skin, dynamic friction is higher than static. A closer look at the velocity dependence of palm friction was therefore of concern as many hand held objects, such as tools, are used under both static and dynamic skin exposure, as described earlier in this thesis.

Another driving force to perform this research was that no studies were found that investigated the influence of contaminants on the palm-sample interface, being textured or non-textured. The closest reference was Buchholz et al (1988) who showed that porous material generated a higher coefficient of friction than non-porous under wet palm conditions. It was not clear, however, whether any other surface characteristics affected friction under the examined conditions.

No studies of palm friction were found concerned with perceived comfort, or discomfort sensations from such exposure, whether static or dynamic. The closest report (Taylor and Lederman 1975) assessed the perceived roughness as subjects touched textured tiles both in clean conditions and lubricated by soap. The design of the present series of experiments was, however, strongly influenced by Taylor and Lederman (*ibid*).

The present over arching strategy was to provide the industrial design community with guidance in these aspects and possibly add a new dimension in the choice of textures and materials. The variables are presented in Table 8.1 and are briefly described in Section 8.4 to 8.9.

8.2 Experimental studies reported in this thesis

The studies reported in this thesis address the following dependent variables:

- the coefficient of friction
- perceived discomfort when in static and dynamic palm contact

The following research issues were identified as being important independent variables contributing t to palm friction and discomfort, and were investigated in Experiments 1 to 3 and reported in Chapters 10 to 12 of this thesis.

The issues were:

- surface texture/topography
- the influence of velocity in the friction interface, i.e. static and dynamic friction
- surface pressure
- the influence of moist and wet palm skin conditions
- the influence of contamination in the friction interface

8.3 Dependent variables

Three dependent variables were recorded, namely friction force, normal force and perceived discomfort. The dependent variables investigated are shown in Table 8.1. These dependent variables will now be considered in detail.

Dependent variables	Comments
Friction force F_f	To establish μ
Normal force F_n	To establish μ
Perceived discomfort	Borg CR-10 scale

Table 8.1 Dependent variables

8.4 Friction forces and normal forces

The friction forces F_f and the normal forces F_n were recorded as they are the basic forces for calculation of the coefficient of friction according to the formulae referred to in Chapters 1 and 3 namely;

$$\mu = F_f/F_n, \text{ (or, expressed alternatively, } F_f=\mu * F_n \text{)}$$

The friction forces were recorded at the friction interface in a direction parallel to the surface of the researched samples and along their length.

The normal forces under examination were 1, 10 and 20 Newton.

All friction recordings started with subjects pressing the finger down on the sample to reach the requested normal force. To record static friction μ_S, each subject then pulled their finger for a short distance, approximately 5 to 10 mm, just enough to initiate a sliding motion in the skin- sample friction interface. This was repeated 5 to 6 times. Under these conditions finger velocity accelerated to in excess of 5 mm/s. To record dynamic friction μ_K, each subject pulled their finger at least 100 mm of the total 130 mm of the test sample 5 to 6 times. The velocity started at 0 mm/s and accelerated to in excess of 64 mm/s but did not exceed 130mm/s.

The coefficient of friction μ, being μ_S or μ_K were filed to a data log in six velocity categories (see Table 8.4 in Section 8.12, page 148).

The normal forces generated a nominal mean pressure, at the interface between skin and a non-textured sample, of approximately 6 kPa, 40 kPa and 80 kPa. When accounting for the effect that grooves in the sample surface will have, these pressures were expected to increase in relation to the duty cycle of the samples, at most by a factor of 4. The pressures will then include the range 50-150 kPa which according to Hall (1995) is common for many hand tools used in their typical work.

8.5 Surface load and palm pressure

Hand tools and controls are used with a wide variety of forces. Forces in precision work using the tip of the fingers are considerably lower than when the full hand is used in a power grip. Both the gripping forces and the area of friction interface may affect skin pressure. The relationship between such pressure and the coefficient of static and dynamic friction was investigated in Experiments 1 and 2. The forces acting between the skin on the digit pulp and the friction partner were in the range 1 to 20 Newton. The pressure was calculated based on the duty cycle of the examined machine cut samples, the applied force and the individual subjects' skin-to-sample contact area.

Hall (1995) found the mean perceived pain pressure (PPT) for males to be approximately 845kPa. Bullinger et al (1979) recommended grooves in textures in hand contact should not exceed 3 mm in width to avoid discomfort. Based on this, the coarsest of the researched samples were designed with ridges of 0.5 mm and grooves 1.5 mm wide and 0.1, 0.3 and 0.5 mm deep to generate skin pressure < 300 kPa and restrict the discomfort to 35% of PPT, with the aim of not exposing subjects to pain over the repeated friction exposures.

Certain materials and textures may be perceived as uncomfortable when in static or dynamic friction contact with the palm. In experiments 1 and 2, perceived discomfort was investigated under different loads and when exposed to different contaminants. The correlation between perceived discomfort and instrumentally recorded coefficient of friction was investigated.

The finger pad was dyed with ink, using a plain ink-pad, prior to making the contact print, samples (see Figure 8.1). The nominal finger contact area i.e. the 'fingerprint' area, was recorded on graph paper placed on the research equipment at the same location as the test samples (see Figure 8.2) whilst applying pressures of 1, 10 and 20 Newton's respectively as viewed on a CRT in front of the subject. This method enabled recording of the same skin area when exposed to friction in the friction test situation.

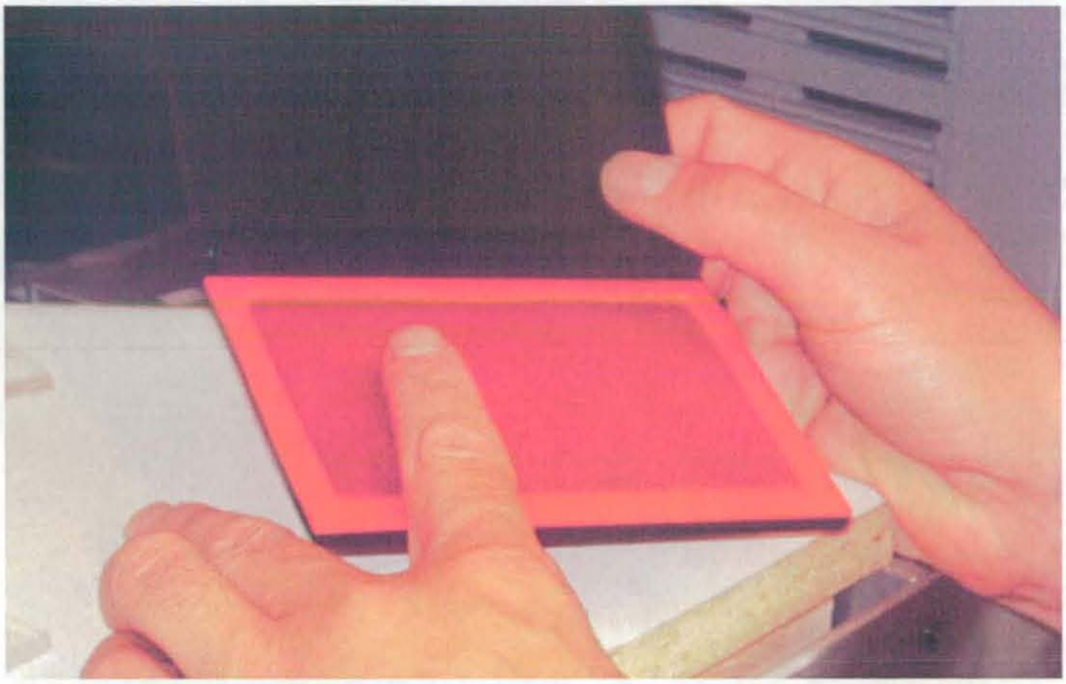


Figure 8.1 Inkpad

A mechanical instrument for recording areas, a planiometer, was used in the analysis of the fingerprint area after enlarging to 200%.

Figure 8.2 Ink prints were produced on paper placed at the same location as the researched samples

The area of the friction interface i.e. the fraction of the surface that is in skin contact, was calculated for the textured samples used in Experiment 1 and 2 using information on the duty cycle of the test sample. Thus on a texture with 50% grooves and 50% land, i.e.50% duty cycle, the area of the friction interface is half the 'fingerprint' area. The finger pressure, P, on the test sample was determined from information on the normal force and the duty cycle of the sample according to the formula

$$P = Fn/A/d$$

- where

Fn = normal force (Newton) acting from the finger against the test sample

'A' = nominal finger contact area (mm2)

'd', = duty cycle of the test sample (%)

8.6 Perception of discomfort

The subjects had a good opportunity to perceive the sensations of touch from the friction interface during the course of the friction experiments. They touched the sample rather than having the sample applied to them, as recommended by Lederman and Taylor (1972). Subjects' estimates of discomfort were reported verbally at the end of each sample- force-contamination treatment to the researcher after viewing the Borg CR-10 scale (Borg 1982). This scale was displayed vertically 1 metre in front of the subject throughout the experiment.

This routine was chosen as it allowed subjects to explore their perceived discomfort from each particular texture, during the 3-5 strokes they performed per level of normal force, in the friction data collection routines preceding the discomfort rating.

The subjects were trained in the estimation of discomfort and the use of the scale before the start of the data collection. The Borg scale was primarily developed for subjective estimations of physical workload. Other scales were considered but following advice from experts in the field (private communication with Professor Gunnar Borg and Dr. Sven-Erik Johansson) the benefits of the Borg CR-10 scale of ratio properties and easy to comprehend expressions were considered paramount. It was also considered that alternative methods would require reference surfaces, longer periods of subject training and more administration.

8.7 Independent variables

The independent variables are found in Table 8.2 below with details.

Independent variables	Comments
Textures	Surface topography expressed as width and depth of land and grooves, pitch, duty cycle and surface topography specifications are reported in Section 8.3.1 and in Appendix SURFACE TOPOGRAPHY.)
Contaminants and skin conditions	See 8.3.2 for details
Area of the friction interface and generated surface pressure	The area of the skin in sample contact considering the duty cycle of the friction interface. Methods for recording are presented in Section 8.3.4
Skin moisture	Recorded with an Evaporimeter. (Section 8.3.5)
Finger velocity	Registered in the unit mm/sec. (Section 8.3.6)

Table 8.2 Independent variables

8.8 Friction in coarse and fine textures

Engineering and industrial designers may choose amongst a variety of textures when developing handles that are to be produced by injection moulding techniques. Such textures are often used to give the surface a specific visual appearance. With handles, controls, caps, lids, etc., which are manipulated and controlled with the human hand, there are good reasons to choose specific textures based on the friction properties of specific textures in contact with the palm of the hand. Some textures may provide discomfort and pain, some may provide less friction than others, and may be unsafe with certain applications.

Twelve different samples were used to investigate which particular surface design elements influence the coefficient of friction. A brief verbal description of the samples is given in Table 8.3. Photos are available in Figure 8.3 and topographic specifications are available in Appendix 2. All samples were made from the same material to control material characteristics so that texture only is under examination. The selected material, Polycarbonate is commercially available in a wide spectrum of surface topographies but also in a non-textured, glossy condition. Such a glossy sample was selected to be the reference sample in the series of experiments. Six textures were purposely designed and machine cut and to provide grooves and lands of specific width, depth and spacing to allow conclusions to be made on their contribution to friction and discomfort. A further five textures were mass-produced commercially available samples produced in photo-etched casting techniques and injection moulded. These mass produced textures were selected on grounds of their visual appearance by five industrial designers, experienced in hand tool design, selected eight textures on the grounds that they were likely to be chosen over a spectrum from fine to coarse when designing handles. They were selected from a 3-dimensional sample catalogue of commercially available textures for injection moulding tools (Moldex AS Norway 1995).

Textured samples						Not textured sample	
Coarse				Fine		Glossy	
Machine cut	**Experi-ment**	**Mass-produced**	**Experi-ment**	**Mass-produced**	**Experiment**	**Mass-produced**	**Experi-ment**
No. 1 very fine grooves	1+2						
No. 2 fine grooves	1+2						
No. 3 wide grooves	1+2						
No. 202 wide striped 0.1 mm deep	3	No. 9004 wide striped	3	No. 9050 small dots	3	No. 5 "glossy"	1+2
No. 203 wide striped 0.3 mm deep	3	No. 9006 narrow striped striped	3	No. 9057 large dots	3		
No. 204/ No. 4 "coarse" wide striped 0.5 mm deep	1+3			No 9078 small dots and flat spots	3		

Table 8.3 Allocation of the 12 samples investigated in Experiments 1, 2 and 3.

The texture numbers are nominal and carry no information on texture properties.

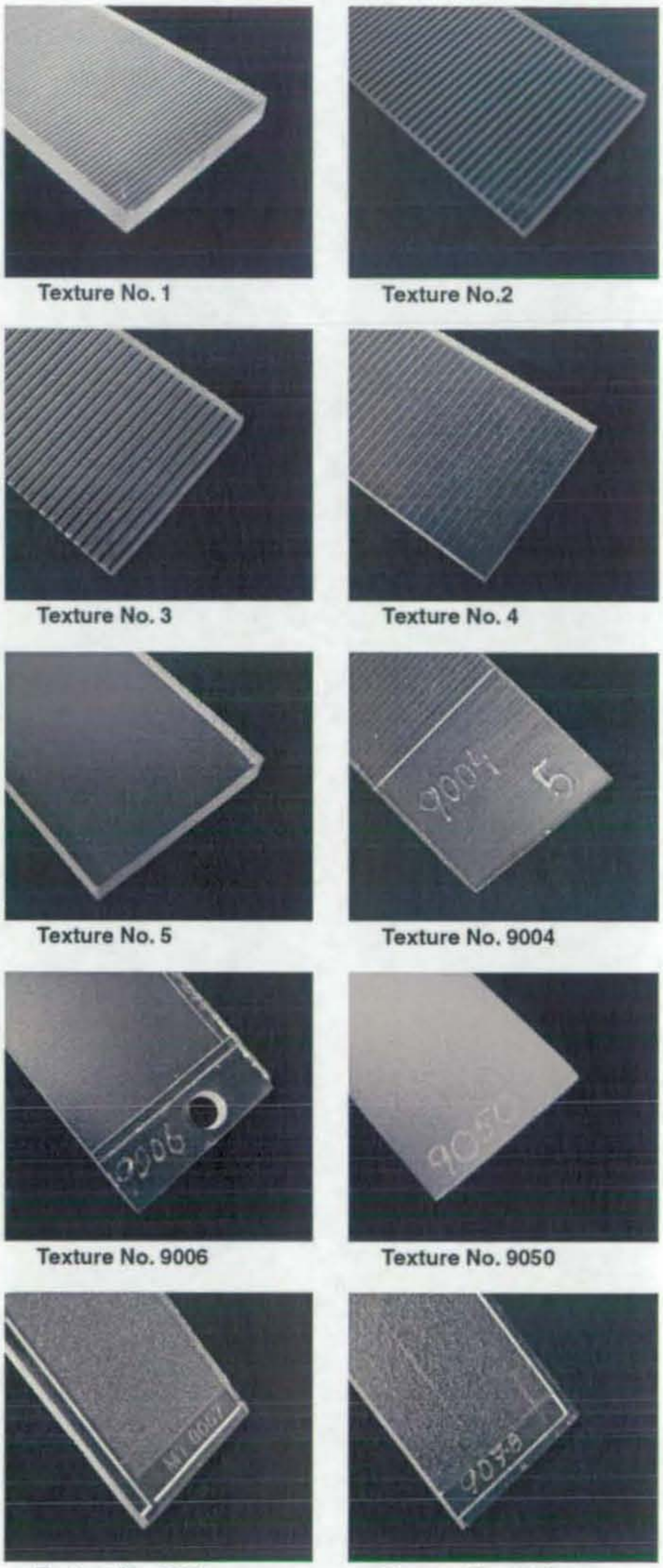


Figure 8.3 Photos showing ten samples investigated in experiments 1-3 of this thesis. Additionally two textures were examined; No. 202 and No. 203. These were similar to No.4 but cut to different depths, 0.1 and 0.3 mm. Details of the surface topographies are available in Appendix 2.

The five mass-produced textures had different grades of fine, coarse and flaked textures showing entirely random patterns with no direction. Two mass-produced textures had grooves and land similar to the machined textures described above. They were included in the research because of the differences between the two production methods i.e. machine cut and mass-produced. Friction on the grooved textures was recorded in the direction across the patterns

The textures were divided into two sets. The first set contained five machine cut samples that were used in Experiments 1 and 2. The second set contained eight mass produced textures and deeper machine cut samples were used in Experiment 3. The samples in concern were arranged by the experimenter in random order and stored in filing frames ready to be fitted on the test rig (by the experimenter) in that order.

8.9 Surface topography

Surface topography is one of the most dominant contributors to friction. In Experiments 1 and 2, the researched textures were specified as to the width of land and grooves but also depth of cut. In Experiment 3 samples were analysed for surface topography according to standard recordings in tribology. A regression model explaining the coefficient of friction and including surface topography variables was established in experiment 3. The details of the mass-produced textures that were of interest were the standardised and well published surface topography variables Ra, Rp, Del.q. S and Sm, explained in detail in Appendix 2 Two scientists, Thorvald Eriksson and Lennart Nilssonat the Royal University of Technology in Stockholm* recommended these parameters to the author as likely to represent friction when palm skin is one friction partner. In addition they suggested two new characteristics to be investigated which specify the upper part of the topographies only. These characteristics have not previously been published. In this thesis they are referred to as T5 and H5.

8.10 Effect of contamination and different skin conditions

Hand tools are rarely free from contaminants. For example, hydraulic oil and grease are commonly used in engineering workshops, lard in meat processing plants and glycerol is a common ingredient in hand lotion. Wet tools are not unusual in outdoor use and sweaty hands can wet tools in hot environments. Continuous exposure to H_2O will change the dynamics of palm skin dramatically.

It is a general perception that sweat in the hand increases friction. This has also been supported by several scientific reports. The expression to "spit into the hands" when attempting to carry out a task involving high forces, such as chopping wood, driving in a nail, lifting of heavy objects etc. is recorded in folk lore. In all experiments a "normal", not by any particular way manipulated, hand was researched as well as hands which had been exposed to 0.9 % NaCl in water to simulate sweat. In Experiments 1, 2 and 3 the researched part of the palm was additionally exposed to oil and grease. In Experiment 3 the palm was hydrated having been in luke-warm tap water for 40 minutes to simulate a truly sweaty, moist hand.

Five contaminants and three skin conditions were investigated. The contaminants were selected to represent the variety of contaminants that may be found on the friction interface between people's hands and the objects they handle in industry, offices and homes. The contaminants were glycerol and paraffin oil that are common ingredients in skin care products, lard, (the animal fat that affects tool handling in the food industry) engineering grease (also known as wheel bearing grease) and hydraulic fluid (commonly found in the automotive industry in transmission systems).

Contaminants
Contaminants were administered on the test samples in different ways depending on their inherent character and in an amount representative of what hands and hand tools may be exposed to in industry and in the home. The result of pilot trials, presented in Section 8.5, suggested the following methods:

- prior to each test, the subject dipped the pad of the distal phalange in the finger of concern gently into a shallow bowl, the bottom of which was covered with 3 mm of the liquid contaminants glycerol, paraffin oil and hydraulic oil respectively.

---

* Surface topography data were analysed at the KTH[4] Department of Machine elements under supervision of Professor Sören Andersson. Surface topography data for the textures are presented in Appendix SURFACE TOPOGRAPHY.

- a brush was used to spread a thin layer of lard or engineering grease respectively on the sample surface.

8.11 Skin moisture

Moisture and sweat in palm skin are often considered to be dominant factors affecting palm friction. The physiological mechanism for sweat generation was presented Section 2.6, page 40. It was shown that hydration of the skin follows two mechanisms, water eruption from the sweat glands and by insensible perspiration of water penetration through the skin. In humans, the latter mechanism, transepidermal water loss (TEWL) is the largest in the palm (Nilsson 1977). In the present series of experiments, TEWL was recorded on the exposed area of the palm using the same instrument as other skin friction researchers (Cua, et al 1990b), a dedicated evaporimeter (Nilsson 1977). The instrument requires 30 seconds for adaptation on the examined skin to reach steady state before monitoring which should be performed over 15 seconds. The probe, in the shape of a short but wide tube, was gently located at the area to be exposed to friction, see Figure 8.4, immediately prior to friction recordings with the subject seated on a stool in front of the equipment. Subjects were instructed and trained in this procedure prior to the onset of the experiment.

Figure 8.4 The probe for recording skin moisture applied on the researched skin location

8.12 Velocity in the skin-sample interface

When the hand is in contact with, and manipulates, handles and other objects, both static and dynamic friction may be involved. However, due to the elasticity of human skin there is a mixed condition in which only some sections of the friction interface turn to a dynamic state while others are still under static conditions. Eventually, the whole interface slides and genuine dynamic friction occurs. Bullinger et al (1979) suggested that friction forces generated while the finger of the subject moved at velocities ≤ 4 mm/s could be specified as static friction, and velocities >4 mm/s could be treated as dynamic.

Studies on static and dynamic friction respectively were based on information from the text book 'Tribology' (Bowden and Tabor 1976) and pilot studies presented in Section 8.5.

The velocity in the friction interface was automatically recorded using a red laser beam pointing at the finger tip just below the edge of the nail. Finger position and finger velocity were recorded at 10 Hz as the finger moved over a 100 mm distance along the tested sample in a direction towards the subject. This direction was decided on based on reports in the journal Forskning och Praktik[5] (1993). In those reports, it was stated that hand tools which had either been identified as hazardous, or problem tools, were operated in a direction along the fingers when using the power grip. Examples of such tools were screwdrivers and other hand rotated tools, but also in ratchets and wrenches. The pulling (proximal) direction was more convenient to the subject and frequent pushing is likely to cause discomfort from below and under the nail.

In the present series of experiments the subjects moved their index finger, at controlled sample contact and increasing velocity from 0 to more than 128 mm/s over the sample length of 100 mm. Peak velocity was estimated to be valid in hand tool use according to pilot studies presented in Section 8.5. Data were sampled at 10 Hz over the entire speed range 0 to 128 mm/s. These were filed to the data log in six velocity categories 2 to 4 m/s, 4 to 8 m/s, 8 to 16 m/s, 16 to 32 m/s, 32 to 64 m/s and 64 to 128 m/s (Table 8.4).

[5] Research and Practice (1993), Section 4.3.4

Velocity categories	Velocity range	Nominal velocities reported in this thesis
1	2 - 4 m/s	Static friction
2	4 - 8 m/s	6 m/s
3	8 - 16 m/s	12 m/s
4	16 - 32 m/s	24 m/s
5	32 - 64 m/s	48 m/s
6	64 – 128 m/s.	96 m/s

Table 8.4 Categories and mid-points of velocities examined in the present series of static and dynamic friction research.

8.13 Other variables

Other variables were manually filed in to the computer prior to research using codes representing each individual subject, along with predetermined research and environmental conditions (Table 8.5). Yet other variables, sample number, type of contaminant and nominal normal force levels were easily filed to the computer simply by setting either of three 9-digit knobs according to a predetermined code when conditions were changing in the research routine. Such changes took place on line during the course of the experiment.

Controlled variables	Comments
Subject number	Order of appearance in the laboratory
Date of research	Date of research session
Research number	Relating to the individual subject
Subjects sex	Filed in subject log
Age of subject	Filed in subject log
History of palm injury or exposure to chemicals or lubricants	Filed in subject log
Relative humidity in laboratory	Recorded with an Evaporimeter (Nilsson (1977)
Researched part of the palm	Digit pulp of index finger on dominant hand

Table 8.5 Variables manually filed to the computer.

8.14 Collection of skin friction data

The approach in the experimental work was to measure static and dynamic friction, but also perceived discomfort, when exposing fingers to differently textured surfaces under contaminated as well as different skin conditions.

The experimental equipment allowed the subjects to place their finger on a test sample with a specified force and then pull their finger towards the body. Three levels of force could be applied on the samples.

Subjects were introduced to the aim of the experiment and familiarised with the laboratory equipment. The samples were shown but not touched by the subject. The contaminants to be used were explained and the different ways they were to be applied to the samples illustrated, but not practised. This was in order to keep subjects hands free from contaminants prior to the first test. The function and use of the evaporimeter was demonstrated. The use of the Borg CR-10 scale was explained and practised until subject's felt comfortable with reporting their estimation perceived discomfort.

The three levels of force expected to be applied on to the samples while performing the test for friction were illustrated. The subjects practised applying these forces and how to keep the force within 10% of the recommended level. The moving belt was used to practise how the velocity was expected to increase from 0-150 mm/s. Ten trials were to be performed per force level. Subjects were instructed as follows:

- start by keeping the finger still and press it down on the far end of the test sample until one of three randomly selected normal force goal levels, F_n, 1, 10 or 20 Newton's is reached. This goal level is shown on the bar (A) and the current applied force (bar B) is seen in the shape of two bars on the nearby screen.

- pull your finger towards yourself, keeping the normal force within the ± 10 % limits as highlighted next to the bar (B) on the screen.

- repeat this routine 3-5 times.

- Give an estimate of perceived skin discomfort referring to the displayed Borg CR-10 scale.

Depending on the type of experiment the distance to be pulled was small, for static friction 5 to 10 mm, or large, for dynamic friction 100 to 120 mm. The velocity in the former case was in the range 0 - 10 mm/sec. In the latter case the velocity started at 0 and accelerated to at least 128 mm/s at the end of the 130 mm long specimen. The coefficient of friction, the normal force and the velocity were automatically logged to the computer.

8.15 Order of treatments and skin condition recordings.

Three skin conditions were investigated (also referred to as "non-contaminated conditions"). These were 1) "normal" clean, 2) sweat and 3) hydrated skin conditions. For the "normal" clean skin condition, subjects washed and dried their hands on a paper towel 15 minutes prior to the commencement of the research. No other skin treatment took place before or during the experiment. For the "sweat" condition, a pipette was used to place 0.05ml of a solution containing 0.9% NaCl in H_2O to simulate sweat at the starting position on the samples. In the hydrated condition, subjects kept their non-dominant hand in a surgical rubber glove, filled with luke warm tap water, for 30 minutes. The hand was then wiped dry gently with a paper towel a few minutes before the start of the experiment.

All tests started with the hands in "normal" clean conditions, this was followed by exposure to water at 22° C with 0.9 % NaCl (referred to as "sweat"). Depending on the experiment, this was followed by one of several exposures, in the following order of 'greasiness' 1) Glycerol, 2) paraffin oil, 3) hydraulic oil, 4) Lard, 5) engineering grease. A separate set of test samples was dedicated to each type of contaminant. A general graphic presentation of the experiment agenda is available in Figure 8.5. Details of the sample administrations and related hand washing, skin moisture recordings and discomfort ratings for the non-contaminated conditions are presented in Figure 8.6, and contaminated conditions in Figure 8.7. The allocation of variables to the experiments in this thesis is presented in Table 8.6.

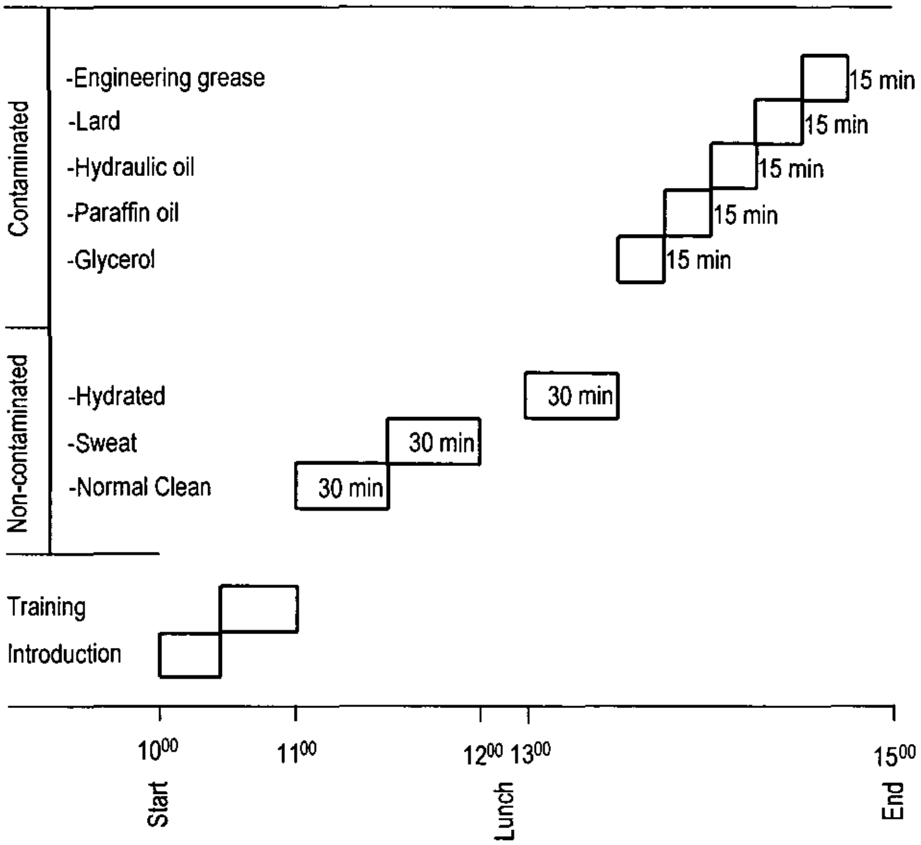


Figure 8.5 General graphic presentations for the experiment agenda at Experiments 1, 2 and 3

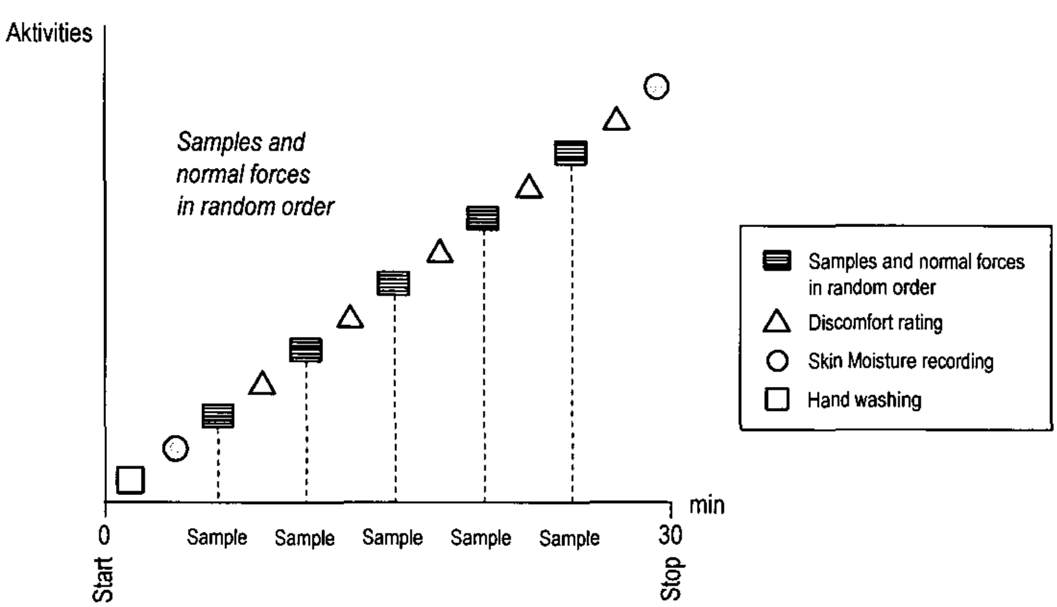


Figure 8.6 Details of the sample administration and related hand washing, skin moisture recordings and discomfort ratings for the non-contaminated conditions

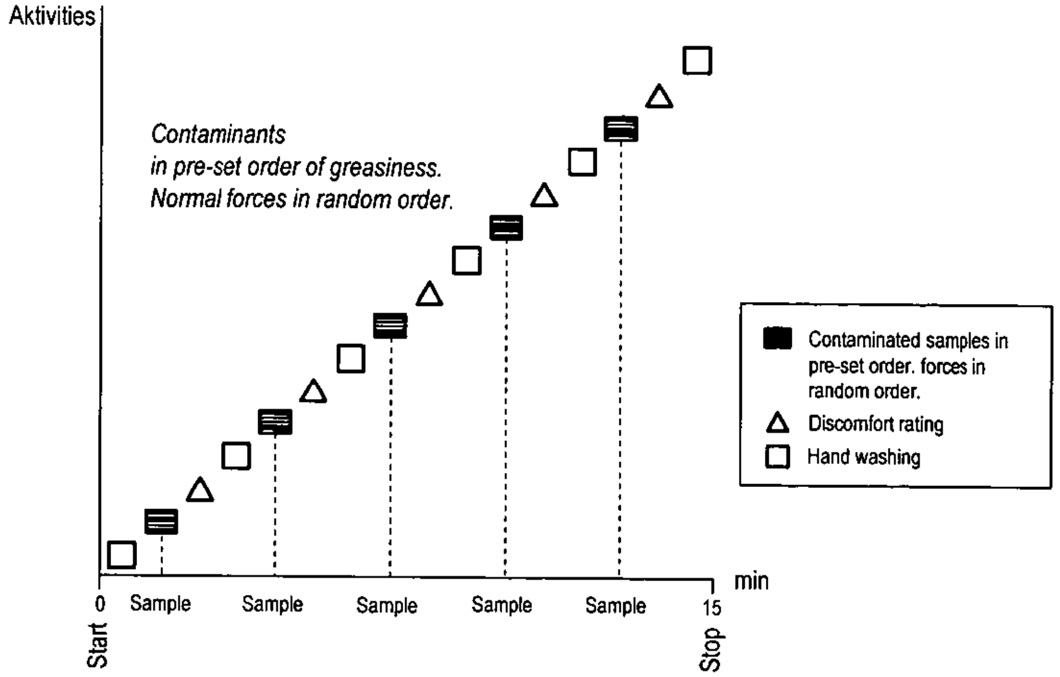


Figure 8.7 **Details of the sample administration and related hand washing, skin moisture recordings and discomfort ratings for the contaminated conditions**

Researched variables	**Experiment 1** Dynamic friction and perceived discomfort for textured and non-textured surfaces in palm contact under clean and contaminated conditions	**Experiment 2** Static friction and perceived discomfort for textured and non-textured surfaces in palm contact under clean and contaminated conditions	**Experiment 3** Palm friction on fine and coarse surfaces. Special attention to skin moisture, velocities, and contaminations in the friction interface
Dependent variables			
Coefficient of dynamic friction, μ_k	■	00000000000000000000000000	■
Coefficient of static friction, μ_s	000000000000000000000000	■	■
Perceived discomfort	■	■	00000000000000000000000000
Independent variables			
Textured	■	■	■
Material			
Polycarbonate	■	■	■
Skin conditions			
Normal	■	■	■
"Sweat"	■	■	■
Hydrated	000000000000000000000000	000000000000000000000000	■
Contaminants			
Lard	■	■	00000000000000000000000000
Glycerol	■	■	■
Engineering grease	000000000000000000000000	00000000000000000000000000	■
Paraffin oil	■	■	00000000000000000000000000
Hydraulic fluid	000000000000000000000000	00000000000000000000000000	■
Skin location			
Pad of distal phalanx on index finger	■	■	■
Velocities			
0 - 4 m/s	000000000000000000000000	■	■
32 - 64 m/s	■	00000000000000000000000000	■
0 - 128 m/s	000000000000000000000000	00000000000000000000000000	■
Normal force			
1N	■	■	■
10N	■	■	00000000000000000000000000
20N	■	■	■

Table 8.6 Allocation of variables to the experiments in this thesis.

Key: ■ **= variable investigated**

0000000000000000 = **variable not investigated**

Chapter 9 Experiment 1. Dynamic friction and perceived discomfort for textured and non-textured surfaces in palm contact under clean and contaminated conditions

The work described in this chapter was published in a condensed version in Bobjer, O., Johansson, S-E. and Piguet, S. (1993) Friction between hand and handle. Effects of oil and lard on non-textured surfaces; perception of discomfort. *Applied Ergonomics*, **24** (3), 190-202

9.1 Introduction

This experimmment concerns dynamic friction, μ_k, between palm skin and textured surfaces suitable for handles in hand tools and other objects manipulated by hand. Dynamic friction is the most common type of friction. The skin of the palm is elastic and drapes easily around objects and textures on surfaces. Dermal ridges contribute to these dynamics. Many tools are, however, used under static, μ_s and dynamic conditions depending on the task performed. Static conditions were specifically researched in Experiment 2 (see Chapter 10).

Industrial designers may select amongst numerous textures and patterns, both to highlight certain surfaces and to provide friction. The degree to which textures affect palm friction is reported in Experiment 1. However, objects as well as hands are rarely free from contaminants or sweat. The degree to which friction on textures is affected in the presence of sweat and contaminants is reported at three levels of load. The resulting pressure on palm skin is calculated.

The successful choice of a texture for a product in hand contact may depend on comfort or discomfort sensations. In this experiment the perceived discomfort sensation is evaluated both under clean and contaminated friction conditions. Other issues are whether uncomfortable textures provide more or less friction and whether contamination will change this relationship.

9.2 Aim of Experiment 1

The aim of the present study was to identify the coefficient of dynamic friction, μ_k, perceived discomfort, and the effect of contaminants and sweat on textured and non textured surfaces at low, medium and high surface load.

9.3 Experimental procedure

The subjects were introduced to the aim of the experiment and trained to use the provided instruments as presented in Section 8.14. Subjects applied the requested normal force, 1 10 or 20 Newton, then they pulled the index finger at least 100 mm of the 130 mm long test sample. The velocity started at 0 mm/s and accelerated to in excess of 64 mm/s but did not exceed 130 mm/s. Instruments collected related data throughout the entire velocity range. The individual sample surfaces and the examined normal forces were tested in random order. The "normal" clean and the "sweat" conditions were examined in that order of skin hydration. These skin conditions preceded the contaminated conditions, which were administered in a set order due to the type of lubricant starting with glycerol followed by paraffin oil and finally the greasiest, lard, as described in Section 9.5. Recording of skin moisture using a water evaporator (TEWL) was performed prior to the experimentation with the "normal" clean skin, the "sweat'" and the hydrated skin condition. The "normal forces" 1, 10 or 20 Newtons were randomly provided by the experimenter. The duration of the test was approximately two hours. None of the subjects experienced any fatigue or discomfort. No financial compensation or gifts were given. A general specification of researched samples and their treatments are described in detail in Chapter 8.

9.3.1 Subjects

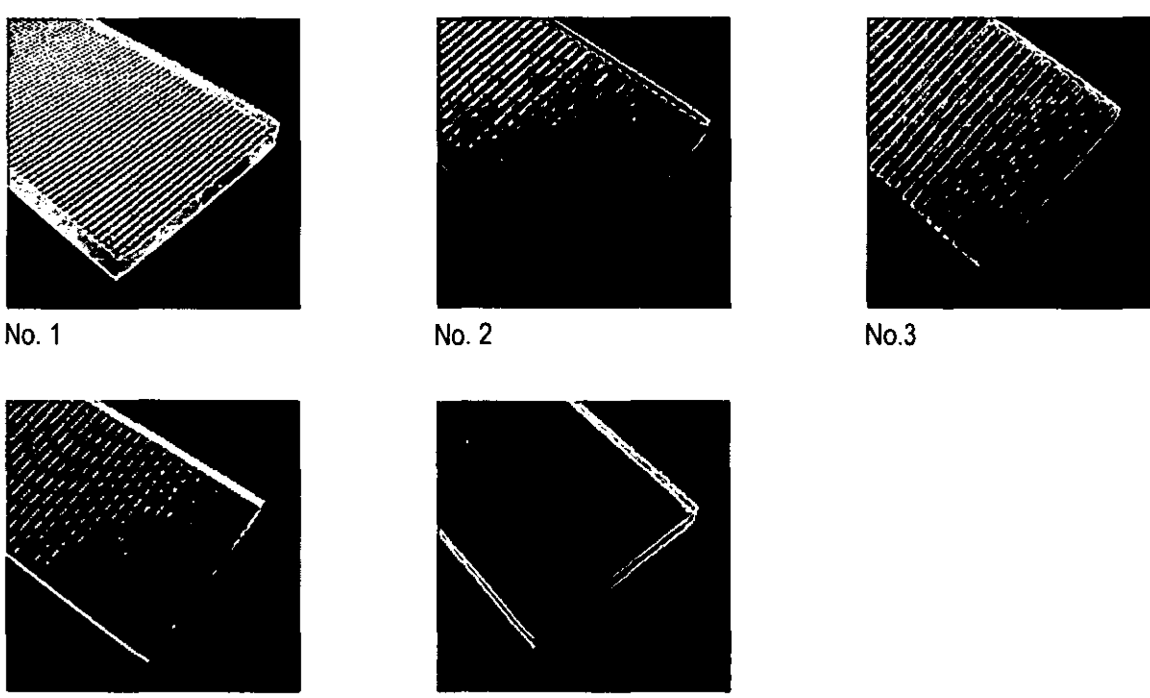
Fourteen subjects, all male, Caucasians, aged 25 to 57 years, took part in Experiment 1, (Table 9.1). Twelve of the subjects normally performed office jobs; the other two performed daily light industrial work in a model shop. None were exposed to chemicals in their professions.

No. of subjects:	14
Sex:	Male
Age:	25 - 57
Profession:	12 white collar workers
	2 light manual work

Table 9.1 Subjects in Experiment 1

9.3.2 Test samples

Four differently textured and one non-textured surface, all in polycarbonate material, were used. The material was machined to form the textures referred to in Table 9.2, on blocks 130 x 35 x 5 mm. The five samples in this experiment were chosen to reflect the influence of 25, 50, 75 and 100 % contact area with the skin (duty cycle). They are shown in Figure 9.1 and specified in Table 9.2. The samples were chosen so that No. 1 and No. 3 had the same duty cycle – the ratio of ridge area over total area expressed as a percentage. The grooves of No. 1 were half as wide, with twice as many ridges as No. 3. No. 2 was an inverted image of No. 4 with No. 2 having wider ridges and No. 4 wider grooves. The depth of all grooves was 0.3 mm. All samples were washed in a dishwasher prior to the study and cleaned with 96% alcohol using a paper tissue prior to each experimental session to reduce debris on the surfaces.



No. 1 No. 2 No.3

No. 4 (=No. 204) No. 5 "Glossy"

Figure 9.1. The five samples examined in Experiment 1.

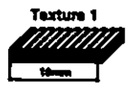
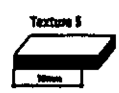
Sample No.	Sample	Pitch (mm)	Duty cycle ratio of ridge area of total area (%)	Groove area as a fraction of total area (%)	Width of ridges (mm)	Width of grooves (mm)
1		1	50	50	0.5	0.5
2		2	75	25	1.5	0.5
3		2	50	50	1.0	1.0
4		2	25	75	0.5	1.5
	Reference					
5			100			

Table 9.2 Surface character of the test samples. The depth of all grooves was 0.5 mm.

9.3.3 Treatments

In addition to a "normal" clean hand condition and the simulated sweat condition the presence of three contaminants, paraffin oil, lard and glycerol was also investigated. Section 8.15 "Order of treatments and skin condition recordings", describes in detail the conditions of the friction interface and the way the contaminants were applied. The number of treatments and test conditions are presented in Tables 9.3 and 9.4. For details on the conditions of the friction interface and the way contaminants were applied (Chapter 9).

Treatments:	Textured surfaces	4
	Non-textured surface	1
	Materials	1
	Loads	3
	Contaminations	3
	Non-contaminated	2
	Sum of treatments for 14 subjects	1050

Table 9.3 Treatments in Experiment 1

Location	Details
Normal force F_n	1, 10 and 20 N
Surface pressure (averaged)*	6.3 - 288.6 kPa
Velocity v	32 - 64 mm/sec
Direction of movement	Finger pulled (towards the subject)
Skin moisture	One recording for each subject prior to each "Normal" clean skin exposure.
Number of samples	Five. Four were textured with 25 %, 50 % (two samples), or 75 % contact area with the skin. One was not textured with100 % contact area with the skin.
Number of contaminants	Three. Paraffin oil (1), lard (1) and glycerol (1)
Non-contaminated surface treatments	Two. 0.9 % NaCl in H_2O (simulated sweat), and the "normal" clean hand.

N.B. * Based on adopted normal force F_n, and calculated friction interface area per subject

Table 9.4 Test conditions in Experiment 1

9.4 Experimental procedure

The general test and data collection procedure is described in Chapter 8.

In this dynamic friction experiment, the task was to pull the hand towards the body over at least 100 of the 130 mm long test sample. The velocity started at 0 mm/s and accelerated to in excess of 64 mm/s but did not exceed 130 mm/s. Data were sampled while the speed of the finger was in the range 32 - 64 mm/s. The individual sample surfaces and the examined normal forces were tested in random order. Two skin conditions, the clean condition and "sweat" preceded the contaminated conditions which were administered in a set order due to the type of lubricant starting with glycerol followed by paraffin oil and lard, as described in Section 8.14. Subjects performed 5 to 6 strokes on the sample while instruments collected related forces and velocities. Subjects were instructed, and trained, to consider the perceived discomfort while performing these set of strokes and report their subjective assessment to the experimenter immediately after these strokes. The duration of the test was approximately three hours with breaks to wash their hands between the contaminated sets. No financial compensation or gifts were given.

The dependent variables were:

- Coefficient of dynamic friction, μ_k,
- Perceived discomfort.

The independent variables were:

- Texture of test samples; i.e., pitch, duty cycle and number of ridges.
- Contaminants, Paraffin oil, Lard, Glycerol
- Skin condition (Normal and "Sweat")
- Normal force F_n.

9.4.1 Statistical analysis

Data were analysed statistically using the SAS package version 6.03 (SAS 1987). Simultaneous tests for differences between means were determined using the Bonferroni's t-test with alfa = 0.05 (Morrison 1983) with a modification suggested by Holm (1979) taken into consideration. This test adjusts for the large number of comparisons and is also valid for dependence between groups.

9.5 Results

9.5.1 Coefficient of dynamic friction μ_k

Subjects started to apply their friction exposure from a static position on each of the samples. Due to the elasticity of palm skin there is a gradually rising strain observed in the epidermal tissue before minor spots (patches of skin) at first and then larger ones start to slide. The results of μ_k and perceived discomfort CR-10_k, including means and standard deviations for three force levels, two skin conditions and three environmental conditions and five samples are shown in Table 9.5. The reported surface pressures took in to account the duty cycle of the respective researched textures as described in Section 8.5.1 "Surface load and palm pressure".

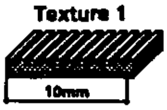
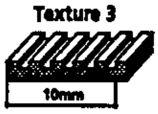
Texture	Skin conditions and contaminants	Coefficient of dynamic friction μ_k		Perceived discomfort CR-10_k		Normal force F_n		Surface pressure kPa	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
4	"Normal" clean skin	0.79	0.11	0.7	0.4	1.04	0.01	22.4	5.3
Texture 4		0.76	0.03	1.5	0.5	10.00	0.17	151.0	23.3
		0.70	0.07	2.5	0.2	19.77	0.43	288.5	61.2
	"Sweat"	0.91	0.05	1.2	0.6	1.05	0.06		
		0.76	0.05	2.6	1.3	10.32	0.19		
		0.70	0.04	4.4	2.2	19.77	1.03		
	Glycerol	0.67	0.15	1.3	0.7	1.05	0.04		
		0.62	0.05	2.1	1.0	10.16	0.32		
		0.57	0.05	3.0	0.8	19.34	0.41		
	Paraffin oil	0.82	0.21	1.2	0.5	1.09	0.08		
		0.73	0.03	2.3	0.9	10.28	0.25		
		0.62	0.04	3.4	1.6	19.42	0.50		
	Lard	0.59	0.14	0.6	0.2	1.06	0.05		
		0.59	0.05	1.2	0.5	10.29	0.43		
		0.54	0.05	2.2	0.5	19.92	1.05		
1	"Normal" clean skin	0.92	0.63	0.2	0.2	1.02	0.06	12.5	4.1
		0.62	0.17	0.8	0.2	9.91	0.19	87.4	30.0
Texture 1		0.56	0.13	1.5	0.9	19.41	0.50	162.5	63.5
	"Sweat"	1.20	0.16	0.7	0.7	1.02	0.05		
		0.77	0.11	1.5	1.1	10.13	0.19		
		0.63	0.13	2.5	1.3	19.46	0.40		
	Glycerol	0.65	0.10	0.8	0.6	1.03	0.06		
		0.54	0.07	1.4	0.9	10.23	0.24		
		0.47	0.04	2.0	0.9	19.50	0.37		
	Paraffin oil	0.66	0.13	0.8	0.6	1.02	0.04		
		0.50	0.08	1.8	0.8	10.14	0.25		
		0.46	0.03	2.7	1.2	19.63	0.49		
	Lard	0.97	0.19	0.6	0.4	1.02	0.06		
		0.48	0.10	1.3	0.8	10.18	0.38		
		0.42	0.03	1.8	0.9	19.60	0.70		
3	"Normal" clean skin	0.75	0.30	0.7	0.5	1.02	0.03	12.8	4.2
Texture 3		0.74	0.17	1.2	0.7	10.03	0.21	87.2	30.1
		0.72	0.13	2.1	1.1	19.33	0.44	163.2	64.1
	"Sweat"	1.11	0.13	1.3	0.6	1.04	0.04		
		0.87	0.07	2.9	1.4	10.10	0.20		
		0.74	0.11	3.8	1.7	19.51	0.46		
	Glycerol	0.70	0.15	1.1	0.6	1.06	0.04		
		0.65	0.08	2.3	1.1	10.07	0.31		
		0.57	0.07	3.6	1.6	19.35	0.65		
	Paraffin oil	0.76	0.26	1.4	0.8	1.03	0.04		
		0.71	0.07	2.7	1.6	10.06	0.20		
		0.62	0.07	3.7	1.9	19.54	0.51		
	Lard	0.68	0.19	1.0	0.9	1.06	0.06		
		0.62	0.08	2.4	1.1	10.17	0.40		
		0.57	0.06	3.2	1.3	19.69	0.90		
2	"Normal" clean skin	1.44	0.68	0.3	0.2	1.02	0.05	8.4	2.8
Texture 2		0.85	0.19	0.6	0.2	10.10	0.21	58.1	19.8
		0.72	0.20	1.4	1.0	19.75	0.49	108.1	42.5
	"Sweat"	1.55	0.26	0.8	0.4	1.02	0.05		
		0.99	0.27	2.1	1.0	10.13	0.19		
		0.78	0.25	3.1	1.1	19.37	0.58		
	Glycerol	0.67	0.13	0.8	0.3	1.01	0.04		
		0.56	0.14	1.8	0.6	10.09	0.23		
		0.51	0.10	2.8	1.3	19.51	0.44		
	Paraffin oil	0.64	0.14	0.5	0.3	1.03	0.05		
		0.47	0.14	1.8	1.0	10.32	0.29		
		0.42	0.07	2.5	1.4	19.76	0.69		
	Lard	0.86	0.25	0.5	0.4	1.03	0.06		
		0.44	0.11	1.1	0.6	10.10	0.34		
		0.38	0.09	2.0	1.0	19.79	1.36		

Table 9.5 Cont'd. overleaf

Texture	Skin conditions and contaminants	Coefficient of dynamic friction μ_k		Perceived discomfort CR-10$_k$		Normal force F_n		Surface pressure kPa	
5	"Normal" clean skin	2.22	1.12	0.7	0.9	1.03	0.03	6.3	2.1
Texture 5		1.01	0.35	0.6	0.6	10.12	0.21	43.5	14.9
		0.85	0.30	1.2	1.0	19.50	0.48	81.4	31.0
	"Sweat"	1.21	0.20	0.5	0.6	1.02	0.04		
		0.82	0.17	1.0	0.9	10.08	0.27		
		0.61	0.15	1.7	1.0	19.61	0.48		
	Glycerol	0.30	0.14	0.3	0.4	1.01	0.05		
		0.13	0.06	0.5	0.4	10.11	0.39		
		0.11	0.04	0.7	0.5	19.76	0.45		
	Paraffin oil	0.28	0.08	0.2	0.5	1.01	0.04		
		0.10	0.02	0.5	0.4	10.02	0.28		
		0.09	0.02	0.6	0.5	19.47	0.54		
	Lard	0.72	0.32	0.4	0.4	1.04	0.05		
		0.16	0.06	0.8	0.8	10.23	0.41		
		0.10	0.04	0.9	0.8	19.77	0.63		

Table 9.5 Means and standard deviations for μk and perceived discomfort CR-10 $_k$ for recorded forces and the corresponding surface pressure given, five environmental conditions and five samples. Surface pressure data consider the duty cycle of the researched sample and the recorded normal force (n =14).

This experiment was dedicated to dynamic friction (in the velocity range 32-64 mm/s); as μ_k generally is more common than static friction, and provided more insights in the parameters that determine the friction of skin (Suh 1986). Subjects however started to apply their friction exposure from a static position on the samples. In the process of data analysis, which covered velocities from zero mm/s, it was observed that μ_s was considerably smaller than μ_k. Too few data were however recorded in this lower velocity range in order that reliable data could be obtained to compare μ_s with μ_k. A repeat series of experiments was therefore performed to focus on static conditions. These are reported, and compared with the present results on μ_k, in Experiment 2 (Chapter 10).

9.5.2 Effect of load and contamination

The coefficients of dynamic friction presented in Figure 9.2 clearly show the effect that normal forces Fn at 1, 10 and 20 Newton's had on μ_k. Data were extracted from Table 9.5 in which standard deviations are also presented. The highest coefficient of dynamic friction μ_k i.e. 2.22 (SD=1.12) is observed for a "normal", i.e. clean hand, in partnership with the non-textured reference surface (No. 5, Table 9.5) and at the same time when the force of approximately 1 Newton was being applied to the distal pad of the index finger of the subjects. Under such forces the mean surface pressure is 6.3 kPa (SD=2.1).

When the pressure increases to 81.4 kPa (19.5 N on the fingertip), the coefficient of friction is reduced to 0.85 (SD=0.30). The reduction of μ_k with increased surface pressure is noticed on most textures and contaminants in Experiment 1. There is a negative correlation between μ_k and surface pressure, ranging from -0.12 to -0.62 over all the clean and contaminated conditions investigated. Significant differences are presented in Table 9.6.

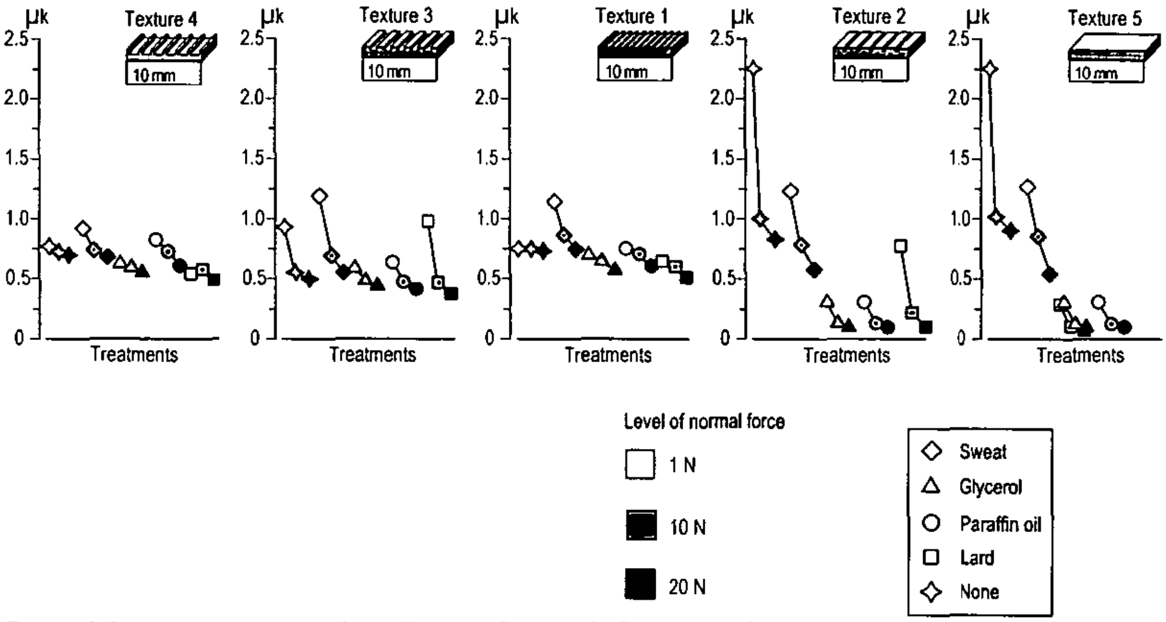


Figure 9.2 **Mean recorded coefficient of dynamic friction μ_k for digit pulp in dynamic friction contact with four textured and one non-textured surface under clean and contaminated conditions (n=14). Normal forces are 1, 10 and 20 N, respectively. Data and standard deviations are available in Table 9.5.**

9.5.3 Area of digit pulp under pressure

The area of the fingertip in contact with a plain non-textured surface was recorded during the process of data collection, as described in Section 8.5 "Surface load and palm pressure". From these readings an average nominal surface pressure was calculated considering the duty cycle for each material and subject combination. The expression "nominal" is used because the actual (molecular) contact area is much less than this owing to the shape and function of the dermal ridges on the finger pads. The results of Experiment 1 show that friction is related to these normal forces. For the practitioner e.g. the industrial designer, more appropriate information would be friction data based on surface pressure, as it can more easily be applied to handles and controls. Forces are however easy to measure and apply under experimental conditions. The method for recording the area of palm skin in this experimentation was closely related to the method published by Taylor and Lederman (1975). The means and 95 % confidence intervals for the fingertip area, with reference to normal forces, are shown on Figure 9.3. These demonstrate that hand forces affect the contacts between palm skin and contact surfaces. The ratio is 7.5 mm^2 /N and 1.5 mm^2 /N in the lower and higher range respectively.

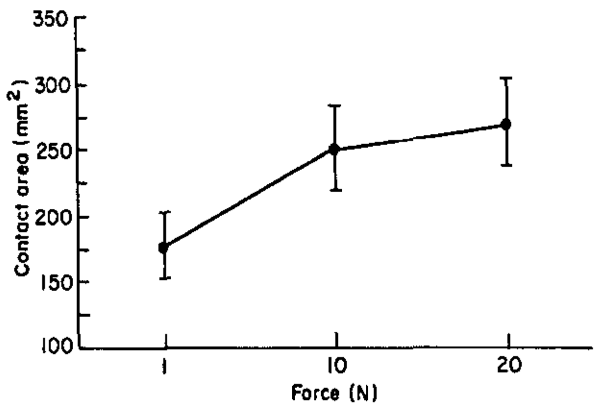


Figure 9.3 Mean nominal contact area from the pad of the index finger. Three force levels. 95 % confidence intervals (n = 14)

9.5.4 Effect of textures and contamination

The different textures used in this experiment have a considerable influence on the coefficient of dynamic friction μ_k. In Figure 9.4 the textures are ordered on the abscissa in terms of least to most duty cycle (contact area). For textured samples, the "normal " clean and "sweat" skin conditions show the highest μ_k while the contaminants paraffin oil, lard, glycerol presented lower readings. Amongst the samples in Experiment 1, texture No. 2 resulted in high μ_k when "sweat" was present on the friction interface. While texture No's. 3 and 4 with typically wide grooves had a positive effect on friction when oil was present. The non-textured surface No. 5 gives the highest μ_k under "normal" skin conditions but the lowest coefficient of friction occurs under contaminated conditions.

Additional information is given in Figure 9.4 which shows the coefficient of dynamic friction with reference to the type of texture and contamination considering all contaminants and all surface treatments and the mean of all forces applied:

:

- μ_k for the non-textured surface = 0.58

- μ_k for the textured surfaces = 0.71

- μ_k for textured and non-textured surfaces = 0.68.

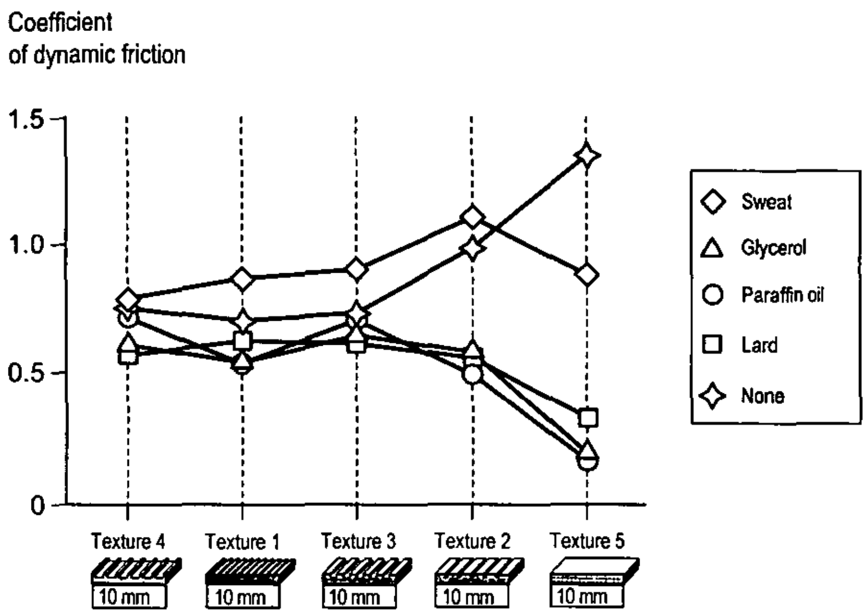


Figure 9.4 **The coefficient of dynamic friction μk with reference to textures duty cycle, skin conditions and contaminants. Surface numbers and related duty cycles are indicated below each point. Average of 1, 10 and 20 Newton Normal force (n=14).**

9.5.5 Contaminations and skin conditions

Figure 9.4 above shows that when the hand was not contaminated, a large duty cycle increased μ_k but decreasing effects were generally noticed when the friction interface was contaminated with paraffin oil and lard. When "sweat" (in the shape of 0.9% NaCl in H_2O) was present on the samples a different pattern was noticed. The slight increase in μ_k with 25, 50 and 75% duty cycle was broken and a decreasing effect at 100% duty cycle was shown, indicating the importance of textures to the generation of friction when lubricants and H_2O are present on the friction interface.

Figure 9.5 shows dynamic friction, μ_k, with reference to type of texture and contamination at 1 N normal force. For significances see Table 9.5 on page 161.

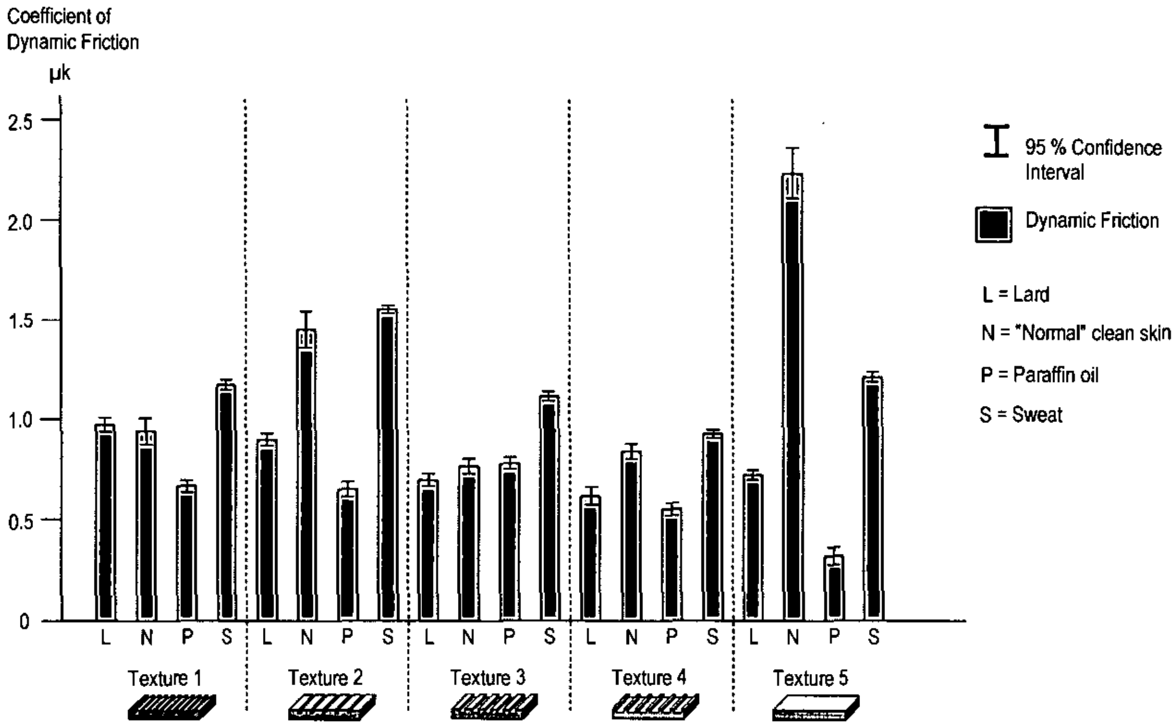


Figure 9.5 Recorded mean coefficient of dynamic friction μ_k and 95 % confidence interval with reference to type of texture and contamination at 1 N normal force

The control condition "normal", i.e. clean skin, results in a high μ_k in friction partnership with the non-textured sample. The correlation between μ_k and surface contact area under such clean conditions was 0.44. When paraffin oil, glycerol and lard are present on the friction interface the correlation with surface contact area is dramatically different and changes sign to -0.54, (Table 9.7).

A conspicuous effect of the different textures in Experiment 1 can be seen in Figure 9.6 when paraffin oil was present on the friction interface. The textured surfaces No's. 3 and 4 gave a 41 - 49 % increase in μ_k compared with the textures Nos. 1 and 2 in the range 10 - 20 N.

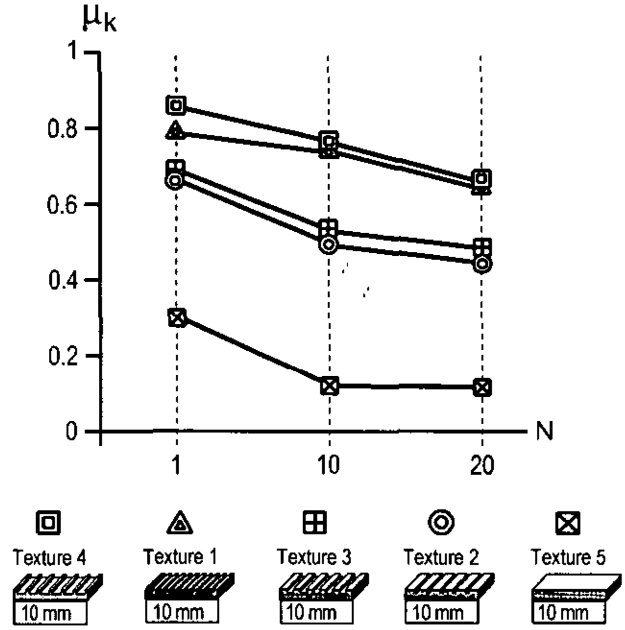


Figure 9.6 **The effect of paraffin oil on surfaces at a load of 1, 10 and 20 N on the tip of a finger. All the differences except those between those between level 2, 3 and 4 are significant at 10 and 20 N, p < 0.05.**

9.5.6 Discomfort from dynamic friction exposure

The means and standard deviations of perceived discomfort are presented in Table 9.5. Mean discomfort estimates among all subjects, samples and environmental conditions range from 0.5 (just noticeable) to 4 (fairly strong), but the variance is large for this variable. The width of the grooves dominated discomfort sensations. The non-textured surface was the most comfortable regardless of load, contamination or skin treatment. The finest of the textures (Nos. 2 and 1) were rated 1.5 (SD=1.0) and 2.7 (SD=1.2) respectively (weak and moderate discomfort respectively, while the coarsest of the textures, No. 3 and No. 4, were rated as 3.8 (SD=1.7) and 4.4 (SD=2.2) (fairly to strong discomfort) respectively.

In the "normal" and "sweat' conditions, no significant differences in perceived discomfort were demonstrated between any of the textured samples. The two coarsest textures, No. 3 and No. 4, which express large pitch with small duty cycle, are however significantly ($p< 0.05$) more uncomfortable than the non-textured reference surface No. 5 under some contaminated conditions (glycerol, paraffin oil) when the load was medium and high, see Table 9.6. The differences between the textured surfaces Nos. 1, 2, 3 and 4 were not statistically significant, $p>0.05$.

Figure 9.7 shows the order of discomfort ratings, ranked from least to most discomfort, when a 20 N normal force acts on the fingertip. The different combinations of textures and contaminations are indicated in the graph. The texture that ranked as the most uncomfortable, texture No. 4, gave rise to a mean 325.6 kPa surface load (when the duty cycle of 25% is considered). Lower normal forces and less coarse texture resulted in lower surface load and less discomfort.

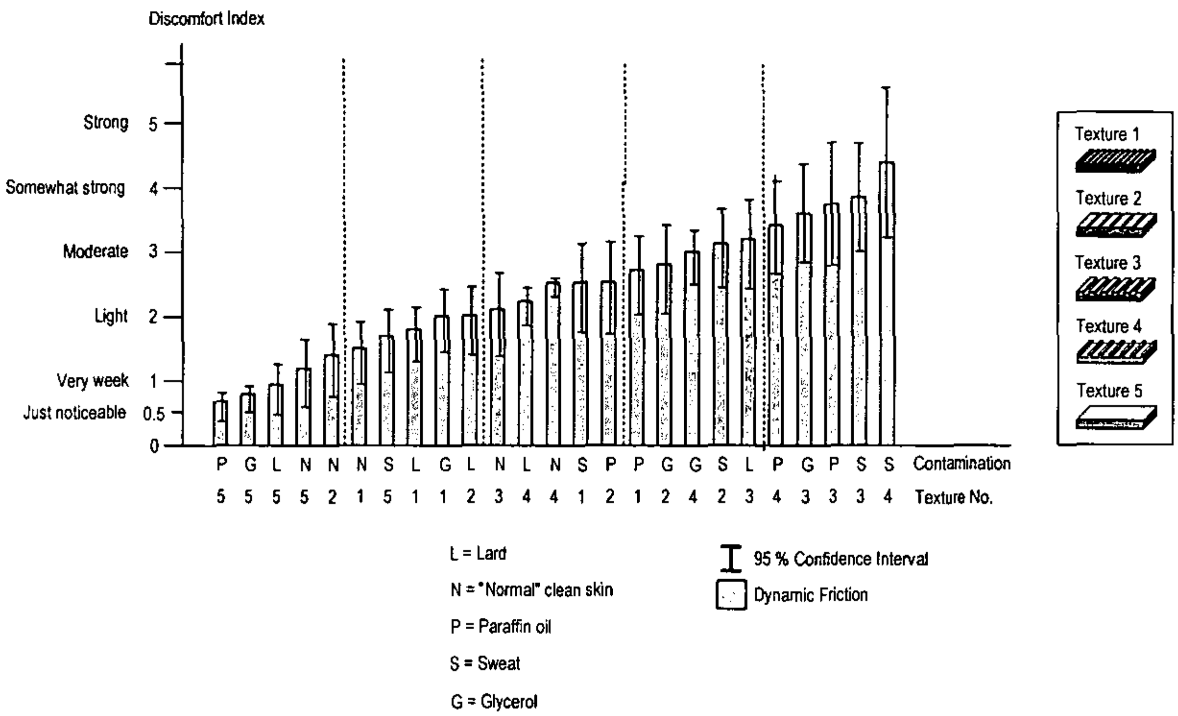


Figure 9.7 Recorded mean discomfort index from Borg CR-10 scale and 95 % confidence interval at 20 N normal force, ranked in order of mean discomfort. The individual sample numbers and contaminant/skin conditions are indicated below each bar.

9.5.7 Significant differences

Significant differences in μ_k, and perceived discomfort, expressed as Borg CR-10, between the textures and contaminants in this experiment are shown in Table 9.6.

Coefficient of dynamic friction

For a "normal" hand, the type of texture has no significant effect on μ_k. For "sweat", significant differences are noticed in the low (1N) force range. For this condition, texture No. 2 with a 75% duty cycle shows significantly different (and higher) friction, while texture No. 4, with 25% duty cycle, shows significant (and lower) μ_k than the other textures in the experiment. For contaminated conditions, texture No. 4 generated significantly higher μ_k than the non-textured sample No. 5. It was not statistically possible to discriminate texture No. 1 from No. 2 and No. 3 from No. 4 for μ_k under any contaminated condition.

Discomfort

Only a few significant differences in discomfort were noticed under normal and "sweat" conditions depending on type of texture. Under contaminated conditions, the non-textured surface No. 5 was generally significantly more comfortable than any of the textured surfaces.

Comparison between	"Normal" clean skin		"Sweat"		Glycerol		Paraffin oil		Lard	
texture No.	μ_k	CR-10	μ_k	CR-10	μ_k	CR-10	μ_k	CR-10	μ_k	CR-10
1/2	ns	ns	1	ns	ns	ns	ns	ns	ns	ns
1/3	ns	ns	ns	ns	20	ns	10-20	ns	A	ns
1/4	ns	ns	1	ns	ns	ns	10-20	ns	1-20	ns
1/5	ns	ns	ns	ns	A	20	A	10-20	10-20	ns
2/3	ns	ns	1	ns	ns	ns	10-20	ns	10-20	ns
2/4	ns	10	1	ns	ns	ns	10-20	ns	20	ns
2/5	ns	ns	1	ns	A	10-20	A	10-20	10-20	ns
3/4	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
3/5	ns	ns	ns	10.20	A	A	A	A	10-20	10-20
4/5	ns	20	1	ns	A	A	A	10-20	10-20	ns

A = Significant at all forces $p < 0.05$

ns = Not significant at any force
Specific number = significant at these forces $p < 0.05$

Table 9.6 Significant differences in μ_k and significant differences in perceived discomfort (CR-10) between the five samples evaluated in Experiment 1, with reference to contamination (n=14)

9.5.8 Correlations

Correlations between μ_k and perceived discomfort index CR-10_k on the one hand, and normal force, surface pressure, pitch, area of friction interface and number of ridges on the other, was calculated as Pearson's *r* (Table 9.7).

This shows low but significant correlations ($p<0.05$) between perceived discomfort index CR-10_k and μ_k ($r = \leq - 0.31$). When "sweat" is present on the surface, the correlation between normal force and μ_k shows its strongest and negative correlation ($r = -0.71$).

There is however a positive correlation between surface pressure and discomfort (in the range 0.48 to 0.68) depending on contamination ($p<0.05$).

	Correlation coefficients, r					
	μ_k			CR-10_k		
	Contaminants			Contaminants		
	"Normal" clean skin	"Sweat"	Paraffin oil, glycerol and lard	"Normal" clean skin	"Sweat"	Paraffin oil, glycerol and lard
Normal force	-0.36	-0.71	-0.40	0.55	0.56	0.48
Surface pressure	-0.37	-0.62	-0.12	0.68	0.53	0.48
Pitch	-0.29	0.10	0.54	0.19	0.37	0.40
Area of friction interface	0.44	0.15	-0.54	-0.30	-0.28	-0.40
Number of ridges	-0.42	-0.03	0.44	-0.03	0.09	0.40
μ_k - CR10_k index	-0.14	-0.31	0.13			

Table 9.7 **Correlation coefficients, r, between load, surface characteristics and coefficient of dynamic friction μ_k and discomfort expressed as CR-10k index. Note that the sign frequently changes. All correlations are significant ($p<0.05$)**

9.6 Discussion

9.6.1 Traditional laws of friction and palm friction

With reference to the traditional "laws" of friction, as described by Amonton (1699) and Coulomb (1785), we can conclude that the frictional characteristics of human palm skin do not conform in the following respects:

- The coefficient of friction is <u>not</u> directly proportional to the normal force (load) F_n. The coefficient of palm friction is inversely related to the load, regardless of whether the skin is in a normal condition, sweaty or exposed to oil or lard and regardless of the texture of the surface.

- The coefficient of friction is dependent on the size of the surface area in contact with the skin.

- Preliminary data from this experiment also indicates that palm skin <u>is</u> velocity dependent, and shows positive correlations with the velocity in the friction interface, i.e. μ_s appear to be smaller than μ_k.

9.6.2 Effect of normal force on friction and discomfort

From this experiment we can confirm the findings of other reports (Comaish and Bottoms 1971; Buchholz et al (1988) that human palm skin decreases its coefficient of friction as the normal force increases. For a clean hand, a 20-fold increase in normal force on a none textured surface yields only a 7.7-fold increase in the frictional force. There is more reduction in the lower normal force range, 1-10 N, than in the higher range 10-20 N. This is well illustrated in Figure 9.2 (page 157) where the reduction of μ_k with increased load under both clean and contaminated conditions is easy to see. Apparently, the fundamental frictional characteristics of the skin have an influence on the coefficient of friction even when lubricants such as paraffin oil, glycerol or lard are present. Not only do high surface loads, and the related higher pressure, reduce μ_k, such conditions are also perceived as more uncomfortable. This is illustrated in Figure 9.8 where the coefficient of friction μ_k is shown on the upper part and perceived discomfort CR 10 is shown on the lower part. The data refer to texture No. 2, which is the finest (least coarse) of the textures included in this experiment. Other textures examined in Experiment 1 showed the same friction and discomfort pattern.

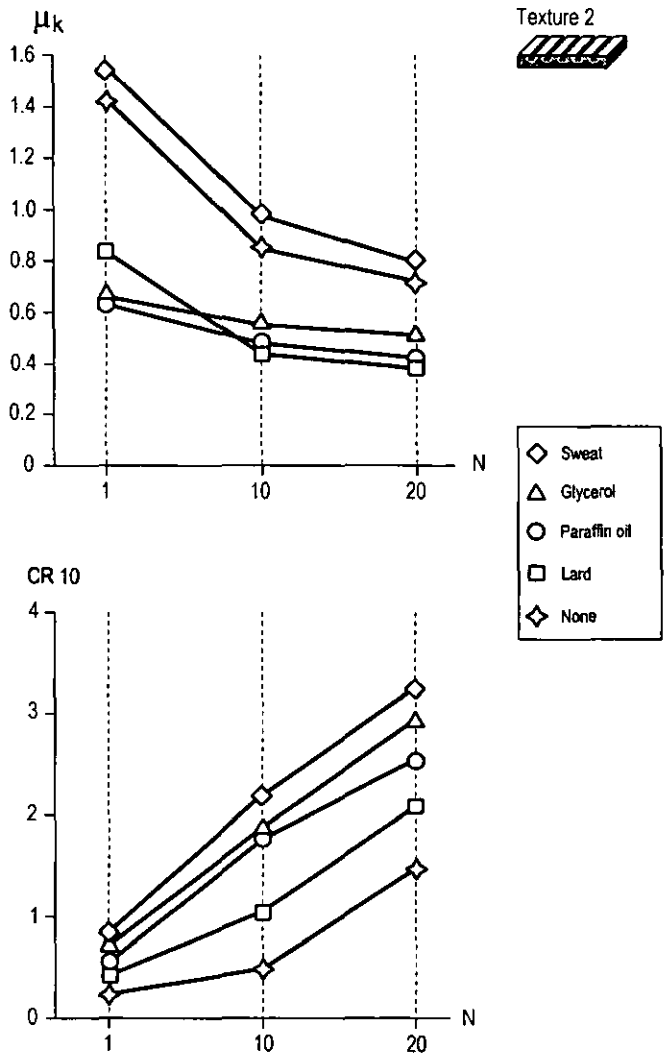


Figure 9. 8 Influence of the labelled contaminants on μ_k upper graph, and perceived discomfort lower graph, at three force levels. Texture No 2 with 0.5 mm wide grooves and 1.5 mm wide ridges (n=14)

The mean pressure on the finger pads in common use of hand tools in manufacturing industry was shown by Hall (1995) to be within the range 20 –100 kPa, with nippers, drills and writing pen at the lower end and saws and metal shears at the higher end. Many hand tools are used under low pressure conditions where friction is the highest and the influence of μ_k from pressure is the strongest. According to the findings presented in this experiment, a large contact area will increase the coefficient of friction and accordingly high forces in the direction along the skin-surface interface area will be generated, than had the contact area been smaller. When hands are used in prehension, e.g. to turn a door knob or a screwdriver, more prehensile muscle involvement is required when these are designed with a smaller contact area rather than a larger. Larger contact area reduces fatigue and the handling is more comfortable.

In the author's opinion the skin's reaction to reduce friction with higher loads may be functional in the way that it reduces the shear force that would otherwise generate a blister or an oedema, and allow for a callus to build up. The conclusion above refers to clean skin conditions only. For lubricated conditions, the recommendation on how to achieve high friction is radically different and in favour of textured surfaces - unfortunately at the cost of more discomfort. For the normal clean skin condition, no significant difference in μ_k was noticed between the five textures at any of the three applied forces ($p>0.05$). For the "sweat" condition, significant differences at this level were observed for six of the ten paired samples at 1 N. With contaminants present on the interface, the friction generating properties of the textures were more pronounced. For paraffin oil and lard, the coarser textures No.3 and 4, with 1.0 mm and 1.5 mm wide grooves respectively, generated significant and higher coefficient of friction than finer textures No. 1 and 2, both with 0.5 mm wide grooves. These differences were observed at all forces and particularly at medium and high forces.

Significant differences in perceived discomfort were predominantly seen in the higher force range but only when the textured samples were compared with the non-textured sample No. 5. The reason appears to be the large inter individual differences in the recorded discomfort variable. Each individual subject seems to have chosen their own "subscale" i.e. they tended to generally score low or high utilising the entire scale. This is discussed in detail in Section 9.6.5.

9.6.3 Textures with many ridges

Industrial designers sometimes claim that textures with many ridges that interact with the dermal ridges and "hook" on to the skin will provide higher frictional forces and thus increase coefficient of friction. Among the researched textures in this experiment, texture No. 1 had twice as many ridges as texture Nos. 2, 3, and 4 (the pitch of texture No. 1 was 1 mm, and the pitch of the other textures is 2 mm, see Table 9.2 on page 157). The presented data show a positive correlation with the number of ridges ($r = 0.44$) under contaminated conditions, see Table 9.7. Under "normal clean conditions the correlation, however, shows a negative sign, ($r = - 0.42$) see table 9.7. The mechanism being that the grooves between the many ridges provide volume for the skin and underlying tissue to enter. Friction forces are generated as this volume is deformed in the direction of the friction force. Under normal clean conditions another mechanism seems to act in favour of high friction namely that of large skin-sample contact area, rather than many ridges, which under clean conditions provide larger adhesion forces.

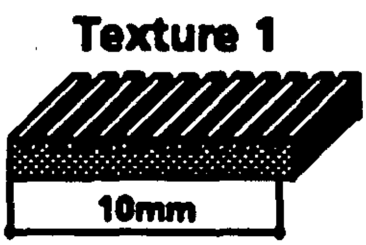
9.6.4 Effect of moisture of the skin on friction

The mean recorded humidity of the palm skin at the location on the exposed finger digit pulp was 63 g/m²/h (range 40 to 86). This is reported to be normal according to Nilsson (1977). Within this range no effect on coefficient of friction μ_k was found. The relationship between the humidity of the skin and the coefficient of friction is further investigated in Experiment 3 (Chapter 12) of this thesis.

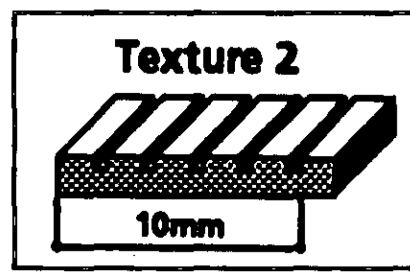
9.6.5 Perceived discomfort

The frictional characteristics of the glabrous skin of the palm were at a location on the pad of the distant phalanx. As far as friction is concerned, the entire glabrous tissue at the palm is basically the same (Bullinger et al 1979), but the density of the tactile sensory units is 7 times as high in these pads as is found centrally in the palm (Johansson and Vallbo 1979). This higher density reflects people's capacity to detect details by touch but this does not mean, however, that the fingertip is more sensitive to pressure sensations. On the contrary, research by Fransson-Hall and Kilbom (1993) showed that the average perceived pain threshold (PPT) for the pad of the third phalanx of the index finger on men was 845 kPa. This value is above the average for the whole palm. The subjects in the experiment were exposed to a mean of 81.4 kPa (SD=31.0) on the non-textured surface No. 5 when they applied the highest force (20 N) by the pad of the index finger. Such a pressure is 9.6% of the perceived pain threshold, PPT, on this location. The present experiment shows that the verbal expression for discomfort sensation, when no lubricants are present on the friction was "very weak" 1.2 (SD 1.0) with reference to the Borg CR10-scale. To examine the effects of the different duty cycle on the textured surfaces (No's. 1-4), pressures ranging from 8.4 kPa (SD=2.8) at 1N to 288.5 kPa (SD=61.2) at 20N were generated. The highest pressure was generated in contact with texture No.4 was found to be 34.1 % of the perceived pain threshold, PPT (Fransson-Hall and Kilbom *ibid*). The same texture generated the highest mean discomfort sensation in this series of experiments. Mean CR-10=4.4 (SD=2.29), which is close to the verbal expression 'fairly strong' on the Borg CR-10 scale. This discomfort sensation was generated when "sweat" was present on the friction interface.

In accordance with the findings by Lederman and Taylor (1972), it was found that discomfort was primarily associated with the width of the grooves and to a much lesser extent to the narrowness of the ridges. It was found that a 100 % increase in groove width from 0.5 to 1.0 mm gave rise to a 155 % increased discomfort sensation at loads of 87 kPa when textures Nos. 1 and 3 were used. These textures are illustrated in Figure 9.9.



Pitch 1 mm, duty cycle 50%



Pitch 2 mm, duty cycle 50%

Figure 9.9 Texture No. 2 has twice the pitch but the same duty cycle (area in contact with the skin) as Texture No.1. They were used to investigate the effect of discomfort.

Taylor and Lederman (1975) suggested that the volume of the skin and the underlying tissue compressed in the grooves relate well to the perception of roughness. They suggested as a "crude generalisation" that perceived roughness is a power function of groove width and of applied finger force. As a tentative equation they suggest that the power function for groove width is approximately four. They presented the equation

- perceived roughness = $F*G^4$

to explain this relationship of Force (as F) and Groove width (as G). The samples used by Taylor and Lederman *(ibid)* had narrower grooves (0.125 to 1.0 mm), narrower ridges (0.25 mm) and generally smaller pitch (0.375 to 1.25 mm) than those used in this experiment. The subjects used the three middle fingers and the tip, just below the nail, as the site of exposure. They applied forces in the range 2.75 to 6.88 N in relation to the 1 to 20 N in this experiment. Applying the same type of power function to the results in this experiment, in which twice the width of the grooves generated an increased perceived discomfort of 155%, would require the exponent of 1.25 as below.

- $F*G^{1.25}$

This is in poor agreement with the power of 4 as suggested by Taylor and Lederman *ibid.* One explanation for this major discrepancy may be that in this experiment, the concern was with discomfort and not roughness, as with Taylor and Lederman *ibid.* It seems from this comparison that roughness is easier to perceive and express than discomfort. Perception of discomfort is a difficult matter. Lederman and Taylor (1972) used a subjective scale of magnitude estimation where subjects selected a figure in a range of their own choice, normally 1-100, to express the roughness that they perceived. The Borg CR-10 scale used in this experiment was suggested to the author (private communication - Professor Gunnar Borg) while planning these series of research to include subjective estimations of discomfort. The Borg CR-10 scale is intended to measure human sensations when one can expect a subjectively defined maximum, e.g. worst imaginable. On reflection it seems, however, that the sensation of discomfort from finger pad contact had no stringent maximum that is easily defined for most people. The results showed that each individual seems to have chosen their own "subscale" i.e. they tended to generally score low, or high utilising the entire scale. This has led to large standard deviations and only few significant differences.

9.6.6 Relationship between friction and discomfort

There is a low correlation between coefficient of friction μ_k and perceived discomfort in these results ($r = \leq 0.3$). Figure 9.10 show the relationship between μ_k and perceived discomfort for all textures and contaminations in this investigation. It is obvious that the nicely ranked μ_k data lack any good correlation to discomfort. Intuitively, most people like to believe that a coarse and uncomfortable texture such as No. 4 (which has 0.5 mm ridges and 1.5 mm grooves) should generate the highest coefficient of friction against palm skin. However, this is not the case under normal clean skin condition according to these results. Palm skin friction is reasonably correlated ($r = 0.44$) to the size of the friction interface area (duty cycle) when the hand is clean. A small duty cycle i.e. a coarse texture, such as texture No. 4, acts in favour of μ_k under contaminated conditions. This is at the cost of increased discomfort.

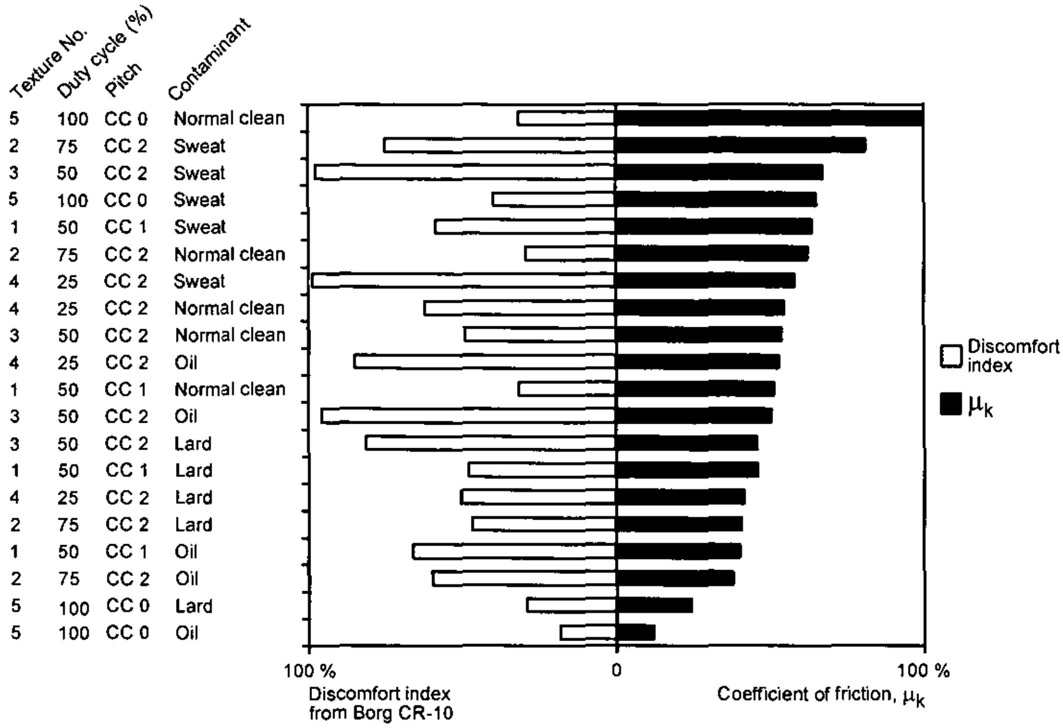


Figure 9.10 **The relation between coefficient of dynamic friction μ_k and the related discomfort rating derived from Borg CR-10 scale. Coefficient of friction μ_k and discomfort index are fractions of related maximum readings. 100 % μ_k refer to 1.36. 100 % discomfort index refers to 2.8 units according to Borg CR-10. Data in this graph are average from 1, 10 and 20 Newton normal force (n=14)**

Macro effects of texture upon palm skin appear to dominate the perception of discomfort but not the actual friction. Lederman and Taylor (1972) also made such observations. Perception of sensations from textures is an intricate matter and indeed a specialist area in itself beyond the scope of this thesis. It appears important that active participation (e.g. stroking the sample) by the subject in these tests for tactile sensations was preferred to having the subject touched by a specimen that is moved by the researcher. According to Lederman and Taylor *ibid,* an object felt actively with the finger feels like an object, while felt passively it feels like a touch, filtering out most of the subtle haptic sensations.

9.6.7 Effects of contaminants on friction

The lubricants in Experiment 1 had considerable effect on dynamic friction on non-textured surfaces. Both oil and 'sweat' reduced μ_k, the latter probably because of a lack of drainage on surfaces without grooves. On all textured surfaces the presence of "sweat" generally increased μ_k in relation to a "normal" hand while oil and lard reduced it. Table 9.8 shows the influence of "sweat" and oil in relation to a "normal" hand. At an absolute level the "normal" and the "sweat" hand generate high μ_k, (in the range 0.74 to 1.36), but contaminants generate low friction, (in the range 0.16 to 0.72). Textures that provide high friction under normal and sweat conditions generate low friction under contaminated conditions, and vice versa. This information is highly relevant to the designer, and it has been discussed earlier that high friction may reduce the muscle engagement while operating an object.

At the relative level, changes in friction due to the environmental conditions (e.g. water or contaminants on the surface) may however pose a risk of an accident, if the change is large. As shown in Table 9.8, the non-textured surface No.5 is particularly hazardous in this respect as the presence of "sweat" in relationship to the "normal" hand reduced μ_k by 35% from 1.36 to 0.88. When contaminants were present, the mean drop in relation to the "normal" clean condition was 84% to 0.22. Under contaminated conditions, some of the textured surfaces (No. 3, No. 4, and No.1, can be a safer alternative as the mean drops were 12%, 15% and 19% but texture No. 2 generated a drop of 45%. It is interesting to note that, when "sweat" is present on all of the textured samples μ_k increased, in relation to the normal hand. The increase was in the range 5-24%, see column 8 in Table 9.8.

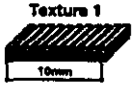
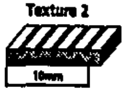
	No contaminants			Contaminants				Difference between conditions	
	"Normal" clean hand	"Sweat"	Mean for no contaminants	Glycerol	Paraffin oil	Lard	Mean for contaminants	"Normal" hand and "sweat"	"Normal" hand and mean contaminants
Texture 1 	0.70	0.87	0.79	0.55	0.54	0.62	0.57	0.17 (24%)	-0.13(19%)
Texture 2 	1.00	1.11	1.06	0.58	0.51	0.55	0.55	0.11(11%)	-0.45(45%)
Texture 3 	0.74	0.91	0.83	0.64	0.70	0.62	0.65	0.17(23%)	-0.09(12%)
Texture 4 	0.75	0.79	0.77	0.62	0.72	0.57	0.64	0.04(5%)	-0.11(15%)
Texture 5 	1.36	0.88	1.12	0.18	0.16	0.33	0.22	-0.48(35%)	-1.14(84%)

Table 9.8 Coefficient of dynamic friction and differences in μ_k depending on contaminants and skin conditions. Mean of 1, 10 and 20N normal force.

In this experiment a solution of 0.9 % NaCl in H_2O was used to simulate human sweat which according to Rothman (1954) is a composition of 99% H_2O, 0.5% Sodium Chloride and 0.5% inorganic salt. 0.05ml of this solution was applied to the sample before the subjects placed their finger on the wetted sample. The intention was that this small amount of liquid should spread on the friction interface the same way as would palm sweat generated in the eccrine sweat glands. From the exercise and the analysis, this scenario appeared to have taken place. No excess water was observed on the samples. The major difference in μ_k between the "sweat" and the "normal" hand conditions reported above, indicate however that some hydrodynamic (water planing) effect was introduced by the presence of the water solution. Such a scenario is likely to take place also when the sweat glands produce sweat. As a consequence of prolonged sweat generation the viscoelastic properties of the glabrous, and hydrophilic, skin is likely to increase. This produces a more flexible skin that more effectively drapes over surface irregularities and generates more friction, as described in Section 5.3. It is unclear to what extent such hydration of the palm took place in this experiment. Friction under hydrated conditions will be researched in some depth in Experiment 3 (Chapter 12).

9.6.8 Effect of contaminants and skin conditions on discomfort

The environmental condition in the friction interface that contributed most to discomfort sensations on textured surfaces was "sweat". This was generally the case for all textured samples and all loads (see Figure 9.10 and Table 9.5). Least discomfort, on textured samples, was reported when the hand is in its normal, non contaminated condition. Figure 9.6 may also act as an illustration to this situation. The higher friction forces which act in shear on the highly innervated palm tissue may explain why textured samples and "sweat" skin conditions are the most uncomfortable. This could explain why all the lubricants, which provide less friction, are perceived as more comfortable than "sweat". It is however difficult to understand why the normal non-contaminated hand, which also provides high friction, is the most comfortable of the treatments in textured samples. One explanation may be that any skin treatment, including 0.9 % NaCl in H_2O as "sweat" may add an element of discomfort to the laboratory situation. Another cause may lay with the fact that in order not to contaminate subjects' hands before the normal condition, this condition was administered first. Thus there may be a systematic error biasing the comfort ratings.

The final discussion and conclusions regarding the order effect of sample distribution is presented in Chapter 13, together with those for Experiments 2 and 3.

9.7 Conclusions

The friction of palm skin is not independent of the applied force, as suggested in the traditional law of friction published in the early history of mechanics, Amonton (1699) and Coulomb (1785). Rather the correlation is negative ($p<0.05$) both when considering the applied normal forces ($r = -0.71$) and the surface pressure in the friction interface ($r = -0.62$). In addition, the dynamic friction of skin exceeded the value 1.0 under normal clean conditions when the pressure was less than 43.5 kPa, such as when a force of 10 N act from the digit pulp on a non textured surface. When using tools under dynamic conditions, the high shearing friction forces, which then are generated are likely to contribute to the generation of blisters. Exposed to higher pressure the coefficient of dynamic friction was reduced and at 288.5 kPa it was 0.70 (SD=0.07).

Sweat and contaminants had a major influence on the dynamic friction. Figure 9.11 shows that by choosing different textures on surfaces, high or low friction readings can be gained depending largely on the skin condition (sweat) and environmental condition (glycerol). The ordinate presents a reference line to which a normal clean, not contaminated, skin-sample condition is related. Above and below this line higher and lower μ_k for palm skin in partnership with the samples on the abscissa can be compared when glycerol and "sweat" are present on the interface. The figure shows that these conditions only have a minor influence on the texture No.4. On textures 3, 1 and 2, Glycerol increases the friction in relation to the normal clean skin, while "Sweat" reduced it. The situation is different when palm is in contact with the non textured sample No.5 where both Glycerol and "Sweat" reduce friction by mean 0.5 and 1.2 units of μ_k respectively in relation to the normal clean skin.

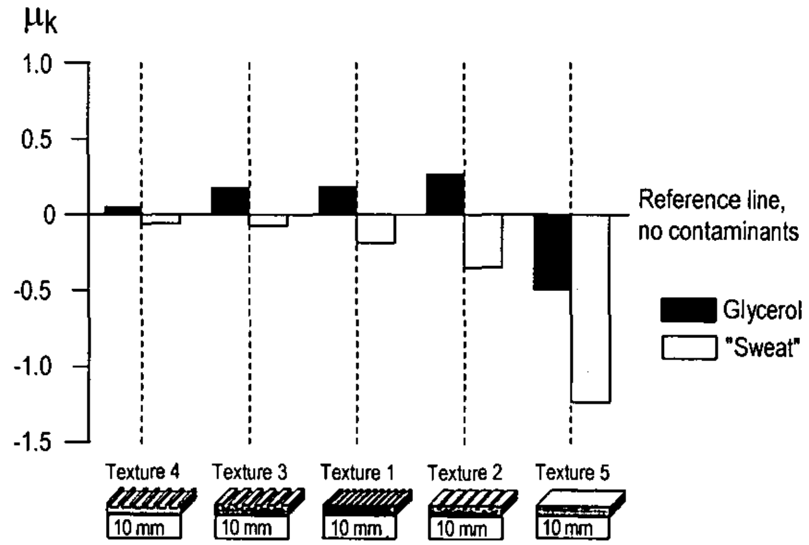


Figure 9.11 The coefficient of dynamic friction and how it is affected by sample surface characteristics, skin conditions ("sweat") and contaminants (glycerol). By choosing different textures on surfaces, high or low friction readings can be gained depending largely on the skin and environmental conditions.

The information in Figure 9.11 may also be seen as indicators of the suitability of these textures for use where the environmental conditions are likely to change. The non-textured sample No.5 may be an unsuitable choice due to the large deviations anticipated. Textures 1, 2 and 3 may be a safer choice as the influence of different environmental conditions is less. Texture No.4 may be unsuitable due to the considerable discomfort this coarse texture will generate.

Not-contaminated conditions

- For "normal" clean skin conditions, a high μ_k is associated with a large skin contact area such as the reference (not textured) sample No. 5 and texture No. 2 and with 100% and 75 duty cycle respectively. This provides mean palm friction μ_k, of 2.22 (SD=1.12) and 1.44 (SD=0.68) respectively when the force acting on the interface was 1N. In the non-contaminated conditions ("normal" clean skin and "sweat", mean μ_k was 1.18 (SD=0.55) but very few significant differences between the five textures were identified (see Table 9.6).

- Lower μ_k was gained, under "normal" clean conditions, when the surface was designed with patterns that reduce the contact area with the skin i.e. small duty cycle. Texture No. 4 was such a surface, with 25% duty cycle, for which mean palm friction μ_k, was 0.79 (SD=0.11) when the force acting on the interface was 1N.

Contaminated conditions

To gain a high μ_k in a contaminated environment a coarse pattern is required i.e. texture No. 3, with 50% duty cycle and 1mm wide grooves. This texture generated a mean μ_k of 0.70 (SD=0.15) at normal forces of 1N.

- In a contaminated environment paraffin oil, glycerol and lard resulted in lower μ_k on textures with large duty cycle, and the lowest was the non-textured sample No.5. Examples are textures No. 2 with 75% duty cycle and No. 5 with 100% duty cycle which, being exposed to the three contaminants in this experiment at normal forces of 20N, generated μ_k in the range 0.38 - 0.58 and 0.09-0.11 respectively.

- There was a negative correlation between μ_k and normal force, r = -0.71 The reduction of μ_k with increased load was noticed on most textures and contaminations in this experiment. The coefficient of friction was as high as 2.22 (SD=1.12) for a normal clean hand in partnership with a non-textured surface (No. 5) when a normal force of 1 N was acting on the fingertip. When the force increased to 20 N the coefficient to friction was reduced to 0.85.

- There was a low correlation between coefficient of friction μ_k and perceived discomfort ($r = \leq 0.3$). Most people like to believe that a coarse and uncomfortable texture should generate a high coefficient of friction against palm skin. This appears not to be the case under "normal" clean skin conditions, but under contaminated conditions a small duty cycle, such as on the coarse texture No. 4, acts in favour of high friction. This is at the cost of increased discomfort. Macro effects of texture upon palm skin appear to dominate the perception of discomfort but not the actual friction.

A model is presented in Figure 9.12 showing a chain of decisions leading to recommendations on the selection of coarse or fine textures considering environmental conditions and the desired coefficient of dynamic friction. In this model "No contaminants" represent "Normal" clean skin and "Sweat", while contaminated represents glycerol, paraffin oil and lard.

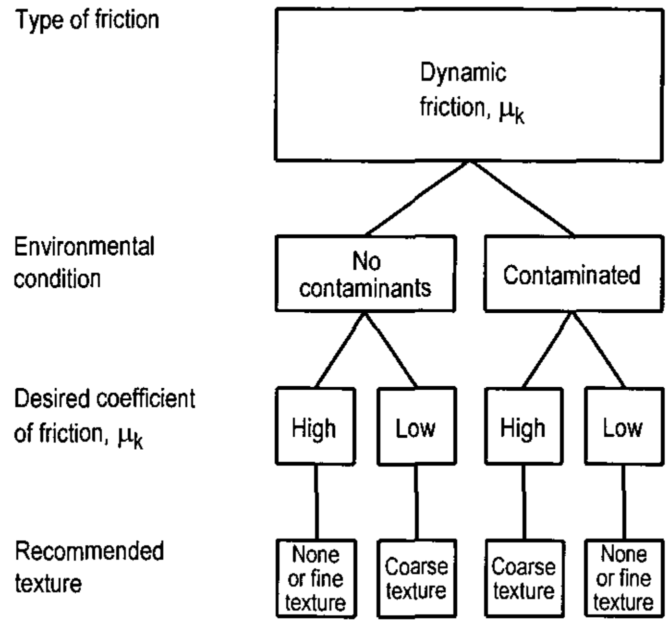


Figure 9.12 A model as a basis for recommendations on textures for different environmental conditions. Dynamic friction μ_k.

9.8 Summary and conclusions

This chapter discusses coefficient of dynamic friction, μ_k, at velocities 32-64 mm/s and perceived discomfort for different textured surfaces when touched by a "normal" clean hand, a "sweat" hand or a hand that was contaminated with glycerol, paraffin oil and lard. Fourteen male subjects applied forces of 1,10 or 20 Newton using the index finger of the dominant hand while stroking them, in the direction towards the body, along specimen of the same polycarbonate material with 100, 75, 50 or 25 % skin-contact area (by ridges). Surface pressures in the range 6.3 to 288.6 kPa were recorded. Grooves in textures reduced μ_k under normal and sweaty conditions, but grooves increased μ_k when contaminants were present. Textures providing large skin-contact area showed *either* a high *or* low coefficient of friction depending on the environmental conditions. Sweat increased μ_k in relation to a normal clean hand but oil and lard reduced μ_k.

Palm skin showed sticky characteristics and μ_k frequently exceeded 1.0 when the surface pressure was low. When the normal force increased a considerable reduction in μ_k was noticed. A 20-fold increase in normal force, from 1 to 20 Newton (an increase in surface pressure from 6.3 to 81.4 kPa), resulted in only a 7.7-fold increase in friction force as mean μ_k dropped from 2.22 (SD=1.12) to 0.85(SD=0.30) when palm was in friction partnership with a non-textured, glossy, surface of polycarbonate. This is in contradiction to the traditional "law" of friction, according to which coefficient of friction should be unaffected by the normal force. This trend has earlier been shown by Comaish and Bottoms (1971). In the present experiment a decrease was noticed for all tested surfaces and during most of the five tested environmental conditions, "normal" clean skin, "sweat", paraffin oil, lard, glycerol.

Discomfort was associated with wide grooves and large pitch but not ($r = \leq 0.3$) with coefficient of friction μ_k ($p<0.05$). Under "normal" clean skin conditions and 20 N normal force the discomfort for dynamic friction contact with the coarsest of the textures, No.4, was rated as "moderate" and 2.5 (SD=0.2) on the Borg CR-10 scale. The finest of the textures No.2 were rated as "weak" and 1.4 (SD=1.0), and the non textured surface No.5 was rated somewhat less uncomfortable 1.2 (SD=1.0) under the same conditions.

Chapter 10. Experiment 2. Static friction and perceived discomfort for textured and non-textured surfaces in palm contact under clean and contaminated conditions

10.1 Introduction

Experiment 2 focuses on friction and discomfort under static conditions. Palm skin does not behave like most materials found in textbooks of mechanical engineering or tribology. It is both elastic and plastic and is dense with receptors and free nerve endings. Static pressures of 845 kPa may be applied before pain is perceived. Experiment 1 (Chapter 10) indicated that static friction, μ_S, might be smaller than dynamic friction, μ_k, which would be in contradiction to the classic "law" of friction. When using a common pen, handles on a saw or a spade, the palm to skin contact is frequently static. When designing tools and equipment for static use in industry or homes, the designer needs insights in to what friction can be expected in palm contact. If the traditional "law" of friction applies then the static situation would generate high friction, which would suggest certain design solutions to the designer. However, if μ_S is smaller than μ_k then other measures such as mechanical slip stop may be required (e.g. to achieve a safe grip on tool handles). Experiment 2 was performed within two months of Experiment 1 and involved the same subjects.

10.2 Aim of Experiment 2

The aim of this experiment was to investigate the coefficient of static friction, μ_S, perceived discomfort and the effect of contaminants and non-contaminated skin conditions on textured and non-textured surfaces. An objective was to compare these results with friction and discomfort data collected under dynamic conditions in Experiment 1. This would involve a comparison of the same samples at low, medium and high surface load. A further aim was to develop a multiple regression model by which friction and discomfort could be estimated based on environmental, texture and contamination characteristics.

10.3 Experimental procedure

The subjects were introduced to the aim of the experiment and trained to use the provided instruments for static friction studies, and in the use of subjective scales, as presented in Section 8. Initially, each subject applied the requested normal force and pulled the finger toward themselves just a few millimetres (5-10 mm), enough to initiate a sliding motion on all parts of the skin in friction contact with the sample. The individual sample surfaces and the examined normal forces were tested in random order. The "normal" clean, the "sweat" and the hydrated conditions were examined in that order of skin hydration. These skin conditions preceded the contaminated conditions, which were administered in a set order due to the type of lubricant starting with glycerol followed by hydraulic oil and, finally, the most greasy, engineering grease, as described in Section 9.5. Subjective estimates of discomfort were assessed by the subject's with reference to the Borg CR10 scale immediately after each static treatment. A general specification of researched samples and their treatments are described in detail in Chapter 8

10.3.1 Subjects

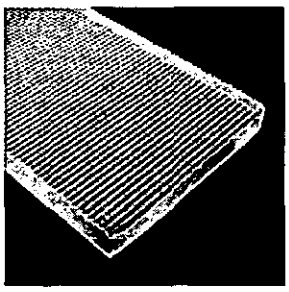
The fourteen male subjects in this experiment were the same as those who participated in Experiment 1 (Table 10.1). Twelve of the subjects performed office jobs; the other two performed daily light industrial work in a model shop. None were exposed to chemicals in their professions.

No. of subjects:	14
Sex:	Male
Age:	25 - 57
Profession:	12 white collar workers
	2 light manual work

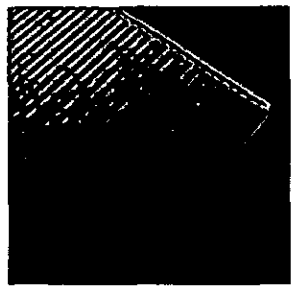
Table 10.1 Subjects in Experiment 2

10.3.2 Test samples

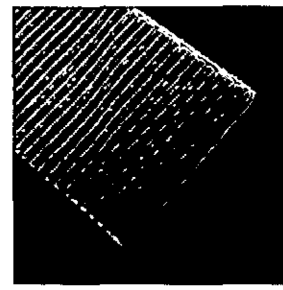
The same series of test samples were used as in Experiment 1, namely four differently textured and one non-textured surface of polycarbonate. They are shown in Figure 10.1 and specified in Table 10.2.



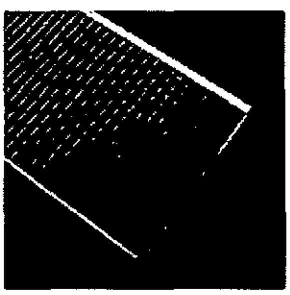
No. 1



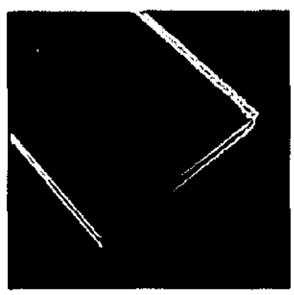
No. 2



No.3



No. 4



No. 5

Figure 10.1. The five samples examined in Experiment 2.

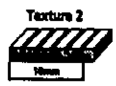
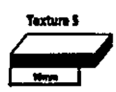
Sample No	Sample	Pitch (mm)	Duty cycle ratio of ridge area to total area (%)	Groove area as a fraction of total area (%)	Width of ridges (mm)	Width of grooves (mm)
1		1	50	50	0.5	0.5
2		2	75	25	1.5	0.5
3		2	50	50	1.0	1.0
4		2	25	75	0.5	1.5
5	Reference 		100			

Table 10.2 Surface character of the test samples. The depth of all grooves was 0.5 mm.

10.3.3 Treatments

Two contaminants on the friction interface were researched, paraffin oil and lard and two non-contaminated conditions, "normal" clean skin and "sweat" (Table 10.3). Section 8.15"Order of treatments and skin condition recordings", describes the details of the conditions at the friction interface and the way the contaminants were applied. The conditions used are presented in Table 10.3.

Textures	5
Materials	1
Loads	3
Contaminations	2
Not contaminated surface treatments	2
Subjects	14
Sum of treatments	840

Table 10.3 Treatments in Experiment 2

The test conditions are presented in Table 10.4. The only difference from Experiment 1 was that 5 to 6 strokes of approximately 5 to 10 mm length were performed per test condition to research static friction.

Location	Details
Normal force F_n	1, 10 and 20 N
Surface pressure (averaged)*	6.3 - 288.6 kPa
Velocity v	0-4 mm/sec
Direction of movement	Finger pulled (towards the subject)
Skin moisture	One recording for each subject prior to each "Normal" clean skin exposure.
Number of samples	Five. Four were textured with 25 %, 50 % (two samples), or 75 % contact area with the skin. One was not textured with100 % contact area with the skin.
Number of contaminants	Two. Paraffin oil (1), lard (1)
Non-contaminated surface treatments	Two. 0.9 % NaCl inH_2O (simulated sweat), and the "normal" clean hand.

*** Based on adopted Normal force F_n, and calculated friction interface area per subject**

Table 10.4 Test conditions in Experiment 2

10.3.4 Contaminants

Four friction conditions were investigated namely a "normal" clean hand condition "sweat", and with two contaminants, paraffin oil and lard.

For the "normal" hand condition, the subjects washed their hands 15 minutes prior to the experiment and, in addition, before and between exposures to the contaminated series of samples. For the "sweat" condition, a solution of 0.9 % NaCl in H_2O was applied to the samples.

The contaminants used under the contaminated conditions were:

- paraffin oil, 100 % of a purified mineral oil.
- lard, the animal fat, used in a condition like butter.

A separate set of test samples was dedicated to each type of contaminant. All tests started with "normal" clean conditions and "sweat", followed by paraffin oil and lard.

10.4 Experimental procedure

The general test and data collection procedure is described in Chapter 8.

In this experiment static friction μ_s was examined. The task was to press the finger on the sample until the requested normal force was reached and then pull the hand towards the body just 5 to 10 mm then release the finger from the sample, repeating this exercise 5 to 6 times. The velocity of the finger was measured at the tip of the finger, just below the nail. The experiment started at 0 mm/s and reached just over 4 mm/s. Data were sampled while the speed of the finger was in the range 0 to 4 mm/s. The individual sample surfaces and the examined normal forces were tested in random order as described in Sections 814. Two skin conditions, the clean condition and "sweat", preceded the contaminated conditions which were administered in a set order due to the type of lubricant starting with glycerol followed by paraffin oil and lard, (as described in Section 8.15). Subjects performed 5 to 6 strokes on the sample while instruments collected related forces and velocities. Subjects were instructed, and trained, to consider the perceived discomfort while performing these set of strokes and report their subjective assessment to the experimenter immediately after these strokes. The duration of the test was approximately three hours with breaks to wash their hands between the contaminated sets. No subjects complained of fatigue or discomfort. No financial compensation or gifts were given.

The dependent variables were:

- coefficient of static friction, μ_S,
- perceived discomfort.

The independent variables were:

- Texture of test samples; i.e., pitch, duty cycle and number of ridges.
- Contaminants, Paraffin oil, Lard, Glycerol
- Skin condition (Normal and "Sweat")
- Normal force F_n.

10.4.1 Statistical analysis

Data were analysed statistically using the SAS package version 6.03 (SAS 1987), and StatView version 4.1. Simultaneous tests for differences between means were determined using the Bonferroni's t-test with alfa = 0.05 (Morrison 1983) and a modification suggested by Holm (1979) was also taken into consideration. This test adjusts for the large number of comparisons and is also valid for dependence between groups.

The data were analysed by linear regression according to the equation:

$Y_i = B_0 + B_1 X_1 + B_2 X_2 + B_3 X_3 + E$ Where: Y_i = dependent variables μ_S,

B_0 = Intercept

B_1 to B_3 = regression coefficients

X_1 to X_3 = dummy coded variables

E = error term

The dependent variables (Y_i) were μ_s, and CR-10_s. Each texture was characterised by three variables, surface load, pitch and surface duty cycle (proportion of texture as ridges). All subjects performed the experiment on all levels but contaminations were presented in random order. Original variables and dummy coded variables are shown in Table 10.11 (page 206).

10.5 Results

10.5.1 Coefficient of static friction μ_S

This experiment was dedicated to investigating static friction (in the velocity range 2 to 4 mm/s). Subjects started to apply their friction exposure from a static position on each of the samples. Due to the elasticity of palm skin there is a gradually rising strain observed in the epidermal tissue before minor patches at first, and then larger patches of skin start to slide. Suh (1986) reported that under static conditions only a few of the mechanical, molecular and chemical activities μ_d, μ_p, μ_a (Chapter 5.3) are engaged in the generation of friction. The results of μ_S and perceived discomfort CR-10_S (including means and standard deviations for three force levels, two skin conditions, three environmental conditions and five samples) are shown in Table 10.5. The reported surface pressures took into account the duty cycle of the respective researched textures according to the formulae below.

$$SP = F_n / NFI*DC$$

Where:

SP = Surface pressure in kPa

F_n= Normal force being nominally 1, 10 or 20 Newtons

NFI = Recorded area of the finger friction interface in partnership with a non-textured sample

DC = The duty cycle of the respective sample (25, 50, 75 and 100%)

Data referring to coefficient of static friction per textured and non-textured surfaces are illustrated in Figure 10.2 and 10.3, showing means of the contaminants and skin treatments in Experiment 2.

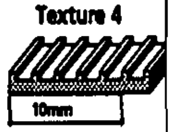
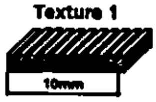
Texture	Skin conditions and contaminants	Coefficient of static friction μ_s		Perceived discomfort CR-10$_s$		Normal force F		Surface pressure kPa	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
4	"Normal" clean skin	0.70	0.25	0.58	0.38	1.02	0.02	22.4	5.3
Texture 4		0.84	0.11	1.58	0.74	10.02	0.24	151.0	23.3
		0.78	0.11	2.58	0.92	19.92	0.76	288.5	61.2
	"Sweat"	0.52	0.08	0.50	0.32	1.03	0.03		
		0.50	0.10	1.33	0.82	10.12	0.30		
		0.46	0.09	2.42	1.02	19.81	0.51		
	Paraffin oil	0.78	0.17	0.50	0.32	1.02	0.03		
		0.75	0.16	1.75	0.61	10.21	0.41		
		0.66	0.20	2.75	0.61	20.05	0.57		
	Lard	0.69	0.28	0.50	0.32	1.02	0.03		
		0.64	0.13	1.50	0.63	10.28	0.42		
		0.51	0.14	2.75	1.13	20.01	0.37		
1	"Normal" clean skin	0.81	0.39	0.17	0.26	1.01	0.03	12.5	4.1
		0.73	0.16	0.67	0.82	10.07	0.32	87.4	30.0
Texture 1		0.67	0.13	1.17	1.03	20.06	0.67	162.5	63.5
	"Sweat"	0.58	0.09	0.25	0.27	1.04	0.03		
		0.54	0.09	0.42	0.38	10.09	0.37		
		0.43	0.08	1.08	0.80	20.13	0.73		
	Paraffin oil	0.73	0.14	0.33	0.26	1.03	0.03		
		0.64	0.19	0.67	0.41	10.05	0.24		
		0.54	0.15	1.17	0.75	19.86	0.35		
	Lard	0.59	0.16	0.33	0.26	1.01	0.03		
		0.54	0.15	0.83	0.68	10.15	0.21		
		0.45	0.13	1.25	1.08	19.86	0.39		

Table 10.5 contd.

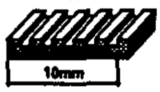
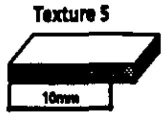
Texture	Skin conditions and contaminants	Coefficient of static friction μ_S		Perceived discomfort CR-10_S		Normal force F_n		Surface pressure kPa	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
3	"Normal" clean skin	0.77	0.27	0.33	0.41	1.02	0.02	12.8	4.2
Texture 3		0.83	0.21	1.30	1.00	10.16	0.33	87.2	30.1
		0.75	0.20	2.08	1.11	20.04	0.57	163.2	64.1
	"Sweat"	0.56	0.10	0.42	0.38	1.02	0.03		
		0.54	0.05	1.00	0.63	10.20	0.37		
		0.49	0.09	2.00	1.10	20.19	0.52		
	Paraffin oil	0.78	0.19	0.42	0.38	1.03	0.02		
		0.73	0.20	0.92	0.66	10.11	0.28		
		0.63	0.20	1.67	0.98	19.77	0.51		
	Lard	0.58	0.19	0.42	0.20	1.02	0.03		
		0.58	0.18	0.83	0.52	10.11	0.30		
		0.52	0.16	1.75	1.08	20.00	0.67		
2	"Normal" clean skin	1.00	0.53	0.08	0.20	1.02	0.02	8.4	2.8
Texture 2		0.75	0.26	0.58	0.80	10.24	0.30	58.1	19.8
		0.71	0.17	1.25	1.08	19.86	0.64	108.1	42.5
	"Sweat"	0.53	0.05	0.08	0.20	1.01	0.02		
		0.46	0.08	0.42	0.38	10.13	0.34		
		0.34	0.02	1.08	0.80	19.94	0.56		
	Paraffin oil	0.64	0.18	0.17	0.26	1.02	0.03		
		0.57	0.12	0.50	0.45	10.15	0.24		
		0.47	0.13	1.00	0.84	20.11	0.43		
	Lard	0.52	0.13	0.33	0.26	1.02	0.02		
		0.45	0.14	0.67	0.52	10.14	0.28		
		0.43	0.11	1.25	0.88	19.99	0.50		
5	"Normal" clean skin	1.32	0.59	0.17	0.26	1.01	0.01	6.3	2.1
Texture 5		0.91	0.21	0.42	0.20	10.04	0.25	43.5	14.9
		0.77	0.18	1.00	0.71	19.84	0.59	81.4	31.0
	"Sweat"	0.45	0.06	0.08	0.20	1.02	0.02		
		0.23	0.06	0.33	0.41	10.11	0.34		
		0.19	0.06	0.67	0.75	20.11	0.53		
	Paraffin oil	0.45	0.31	0.25	0.42	1.02	0.03		
		0.21	0.12	0.33	0.41	10.12	0.33		
		0.14	0.08	0.58	0.08	19.85	0.44		
	Lard	0.28	0.09	0.25	0.42	1.02	0.03		
		0.07	0.02	0.25	0.27	10.09	0.28		
		0.05	0.03	0.50	0.55	20.09	0.68		

Table 10.5 **Means and standard deviations for μ_S and perceived discomfort CR-10s for recorded forces and the corresponding surface pressure given, five environmental conditions and five samples. Surface pressure data consider the duty cycle of the researched sample and the recorded normal force. (n =14).**

10.5.2 Effect of load and contamination

The effect that forces of the levels 1, 10 and 20 Newton have on μ_S is shown in Figure 10.2 and 10.3. The forces are presented on the abscissa with reference to the investigated normal forces, contaminants and hand conditions. The coefficient of static friction, μ_S is presented on the ordinate. Data has been extracted from Table 10.5. The highest mean coefficient of static friction μ_S, 1.32 (SD=0.59) was observed for a "normal", clean hand in partnership with the non-textured reference surface (No. 5) and when the force of approximately one Newton was applied by the index finger. Under such forces the mean surface pressure was 6.3 kPa (SD=2.1). When the pressure increased to mean 81.4 kPa (19.5 N on the fingertip) the coefficient of friction was reduced to 0.77 (SD=0.18). The reduction of μ_S with increased surface pressure was noticed on most textures and contaminations in Experiment 2.). Significant differences between textures with reference to contaminants and skin conditions are presented in Table 10.9. There was a low but significant correlation ($p<0.05$) between μ_S and surface pressure ranging - 0.07 to - 0.15 over all the clean and contaminated conditions investigated (see Table 10.10).

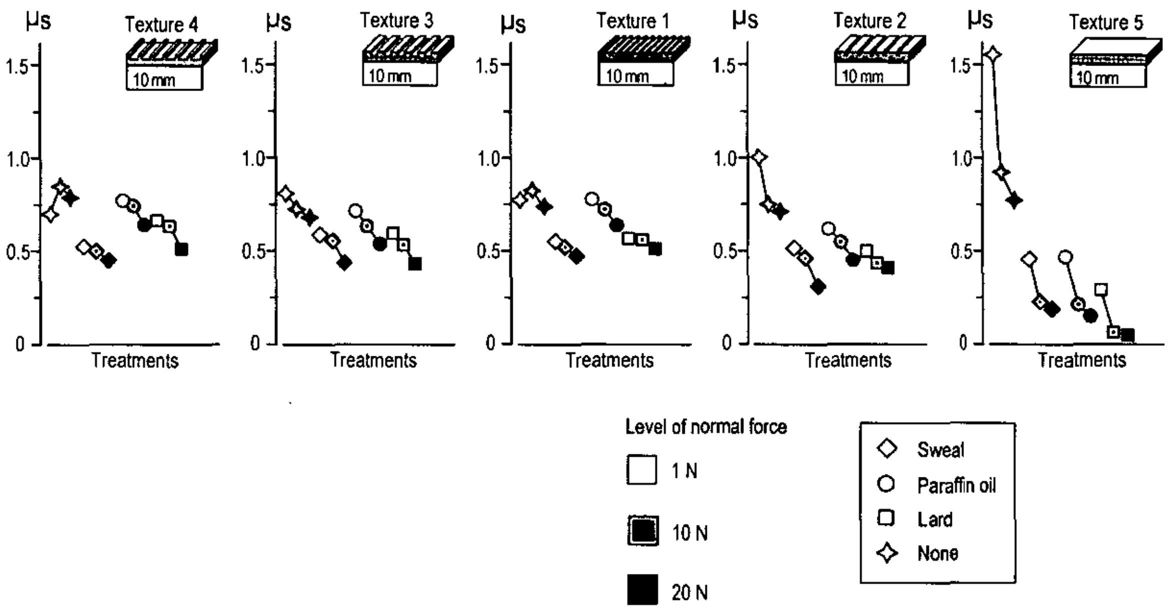


Figure 10.2 **Mean recorded coefficient of static friction μ_K for digit pulp in dynamic friction contact with four textured and one non-textured surface under clean and contaminated conditions. (n=14) Normal force are approximately 1, 10 and 20 N, respectively. Standard deviations are presented in Table 10.5.**

10.5.3 Effect of textures and contamination

The different textures, skin conditions and contaminations used in this experiment had a considerable influence on the coefficient of static friction μ_S. In Figure 10.2 the textures are ordered on the abscissa in terms of least to most duty cycle (contact area).

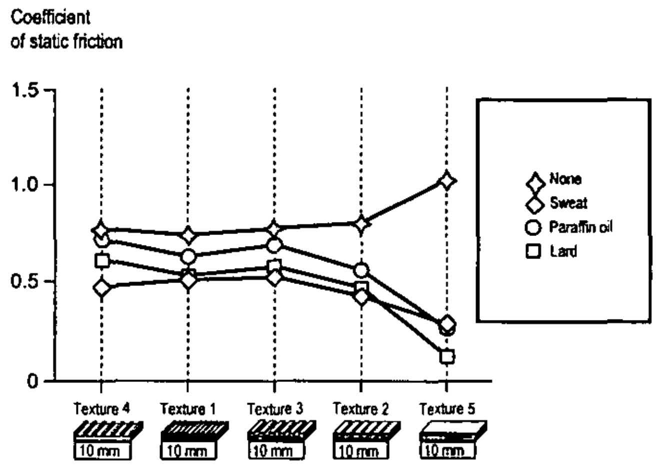


Figure 10.3 **Coefficient of static friction μ_S with reference to textures duty cycle, skin conditions and contaminants. Surfaces are specified in Table 10.2. Average of 1, 10 and 20 Newton normal force (n=14). p-values for differences between contaminants and textures respectively are presented in Tables 10.8 and 10.9.**

The highest recordings of friction were noticed for the non-textured surface No. 5. This is also seen in Figure 10.4, which presents coefficient of static friction and 95% confidence intervals for five samples, two contaminants and two skin conditions at 1 Newton normal force. In relation to a "normal" clean skin, all skin treatments and contaminants reduced static friction. The reduction was particularly large on the non-textured sample No. 5. "Sweat" generated <u>less</u> friction. Sweat" has a major and reducing effect on μ_S and generates the <u>lowest</u> readings regardless of the type of texture. This "sweat" situation is in strong contradiction to the findings under dynamic μ_k conditions in Experiment 1 where "sweat" on textured samples generated the <u>highest</u> coefficient of static friction.

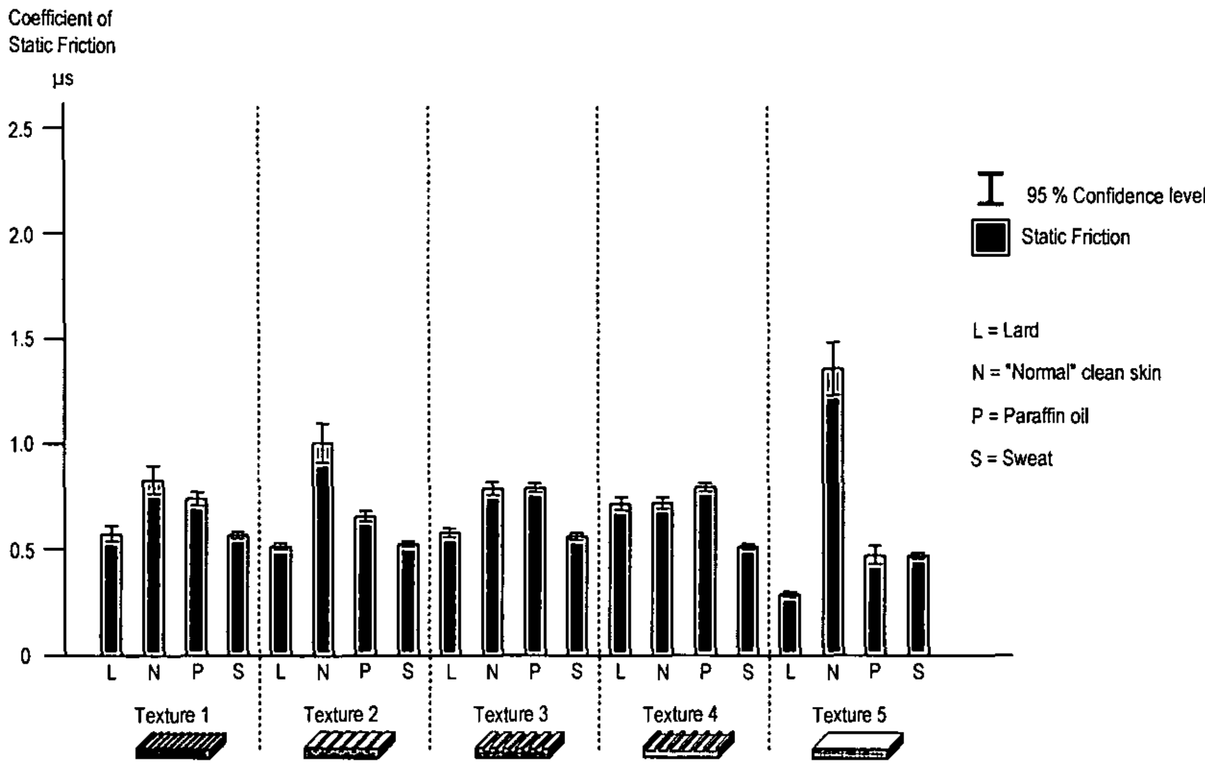


Figure 10.4 Coefficient of static friction and 95% confidence intervals for five samples, two contaminants and two skin conditions at 1 Newton normal force.

Textured and non-textured surfaces

The non-textured surface No. 5 gave the highest mean coefficient of static friction, μ_S = 1.32 (SD=0.59) in this experiment, under normal clean skin conditions and when the forces acting from the finger were low (1 N). The textured surfaces provided less friction under such conditions. The non-textured surface No. 5 also resulted in the lowest coefficient of static friction, μ_S= 0.05 (SD=0.03) with lard on the friction interface and the forces acting from the finger were high (20 N). Low friction was generally noticed for texture No. 5 when contaminants were present and also for "sweat" (Figure 10.4). Both Experiments 1 and 2 show that coefficient of friction under "normal" clean conditions had a positive and significant ($p<0.05$) correlation (Pearson's r) with the area of the duty cycle, for μ_k 0.44 and for μ_s 0.52, see Table 10.10 in Section 10.5.7. Table 10.6 show mean μ_s for non-textured, textured and of both kind of samples, in partnership with palm skin grouped under examined skin conditions, contaminants and all conditions. Contaminants decrease μ_S considerably on non textured samples, but on textured surfaces the reduction is marginal.

	Skin conditions "Normal" clean skin and "Sweat"	Contaminations Paraffin oil and Lard	All skin conditions and Contaminations
μ_S for the non-textured surface	0.65	0.20	= 0.42.
μ_S for the textured surfaces only	0.64	0.60	= 0.62.
μ_S for textured and non-textured surfaces	0.64	0.40	= 0.58.

Table 10.6 **Mean μ_S for non-textured, textured and of both kind of samples, in partnership with palm skin grouped under examined skin conditions, contaminants and all conditions.**

10.5.4 Relationship between static and dynamic friction

The mean coefficient of static and dynamic friction for all samples, investigated forces, two contaminants (paraffin oil and lard) and two skin conditions (normal clean skin and "sweat") examined in Experiments 1 and 2 are presented in Table 10.7. The table shows that $\mu_S < \mu_k$. Static friction provided 80.9% of the dynamic friction. In real terms mean $\mu_S = 0.580$ and mean $\mu_k = 0.717$ (data derived from Tables 9.5 in Section 9.5.1 and 10.5 in Section 10.5.1).

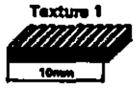
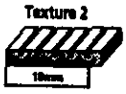
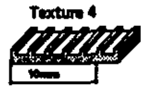
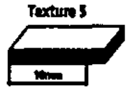
	No contamiants			Contaminants				
	"Normal clean skin	"Sweat"	Difference between "normal" clean skin and "sweat"	Glyerol	Paraffin oil	Lard	Mean for contaminant	Difference between 'normal' clean skin and mean contaminant
	μ_k μ_s	μ_k μ_s	μ_k μ_s	μ_k *	μ_k μ_s	μ_k μ_s	μ_k μ_s	μ_k μ_s
Texture 1 	0.70 0.74	0.87 0.52	0.17 (24%) - 0.23 (30%)	0.55 -	0.54 0.64	0.62 0.53	0.57 0.59	-0.13 (19%) - 0.15 (20%)
Texture 2 	1.00 0.82	1.11 0.44	0.11 (11%) - 0.38 (30%)	0.58 -	0.51 0.56	0.55 0.47	0.55 0.52	- 0.45 (45%) - 0.30 (37%)
Texture 3 	0.74 0.78	0.91 0.53	0.17 (23%) - 0.25 (32%)	0.64 -	0.70 0.71	0.62 0.56	0.65 0.64	- 0.09 (12%) - 0.14 (18%)
Texture 4 	0.75 0.77	0.79 0..53	0.04 (5%) - 0.24 (31%)	0.62 -	0.72 0.73	0.57 0.61	0.64 0.67	- 0.11 (15%) - 0.10 (13%)
Texture 5 	1.36 1.00	0.88 0.29	-0.48(35%) - 0.71 (71%)	0.18 -	0.16 0.27	0.33 0.13	0.22 0.20	-1.14 (84%) - 0.80 (80%)

Table 10.7 **Coefficient of dynamic as well as static friction for surfaces with reference to contaminant conditions and difference between conditions. Means of 1, 10 and 20 Newton "normal" force. *= Not investigated. (n=14)**

The differences between μ_k and μ_s at 20 N Normal force and the common contaminants and skin conditions in Experiments 1 and 2, are shown in Figure 10.5. This figure, showing all investigated environmental and texture combinations, illustrate that μ_k is frequently in excess of μ_s. These unique findings are in strong contradiction to the traditional "laws" of friction, which however were established based on material other than human palm skin.

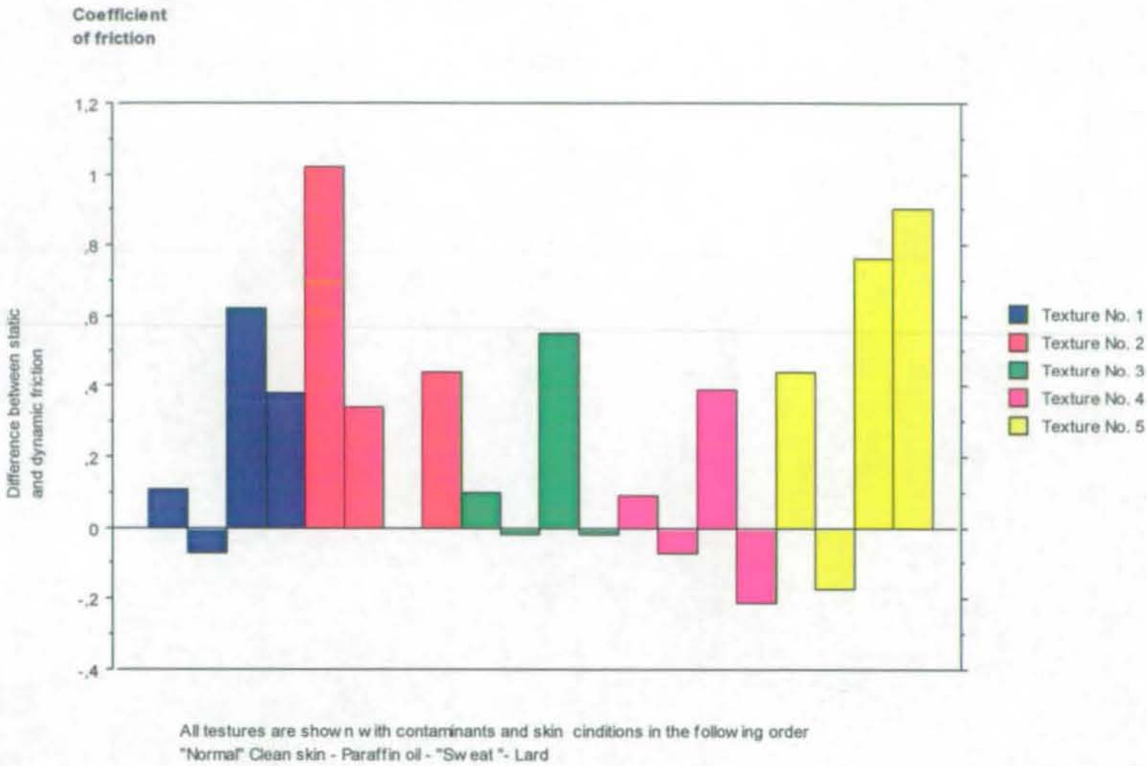


Figure 10.5 **Difference between coefficient of dynamic and static friction ($\mu_K - \mu_S$) at 1 N normal force with reference to texture number, contaminants and skin conditions. Data above the 0-line show μ_K to be in excess of μ_S. Data from Tables 9.5 and 10.5.**

10.5.5 Discomfort from static and dynamic friction exposure

The means and standard deviations of perceived discomfort CR-10_S are presented in Table 10.5 for all samples, skin conditions and contaminations in this experiment. Under static conditions the non-textured surface No.5 was the most comfortable regardless of load, contamination or skin treatment, with mean discomfort 0.40(SD=0.39) *(just noticeable)*. The finest of the textures, No. 1 and No. 2, were rated 0.69(SD=0.58) and 0.62(SD=0.56) respectively *(noticeable)* while the coarsest of the textures, No. 3 and No. 4, were rated as 1.1(SD=0.7) *(very weak)* and 1.56(SD=0.65). The single most uncomfortable texture under static conditions was texture No.4 under exposure to paraffin oil and lard. Discomfort ratings were 2.75 (SD=0.61/1.13) *(moderate discomfort).* The width of the grooves appears to dominate discomfort sensations, as was the case under the dynamic conditions reported in Experiment 1.

Comparison of static and dynamic conditions

When comparing the same samples and normal forces (1, 10 and 20 N) from Experiments 1 and 2, static friction generated the least discomfort. Static mean CR_{10} index was 0.40

(SD=0.5), *just noticeable discomfort*, while dynamic CR10 index was 2.36 (SD=1.13), *light discomfort* (Figure 10.6). As the Borg CR10 scale has ratio properties the relative perceived discomfort between the static and dynamic conditions are 5.9-fold.

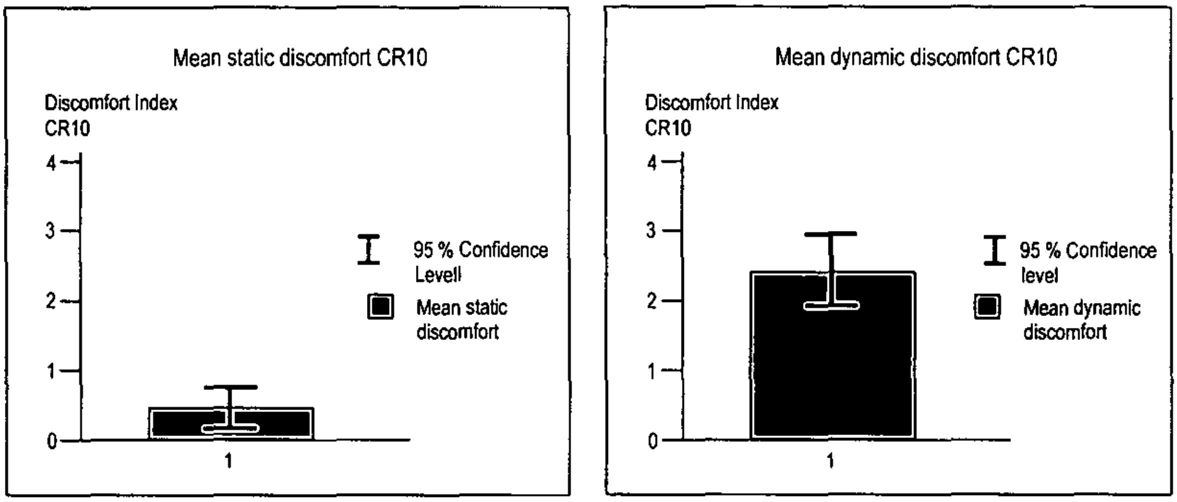


Figure 10.6 Mean discomfort index (Borg 1982) under static and dynamic friction exposure at normal forces 1, 10 and 20 Newton. (n=14)

Dynamic conditions, as presented in Section 10.5.5, also show surface No. 5 (non-textured) to be the most comfortable regardless of load, contamination or skin treatment, with mean discomfort 0.76 (SD=0.70) *very weak.* The finest of the textured samples, No. 1 and No. 2 were rated 1.35 (SD=0.76) and 1.39(SD=0.72) (*very weak*) respectively while the coarsest of the textures, No. 3 and No. 4 were rated as 2.20 (SD=1.13) and 1.98 (SD=0.78) (*light discomfort*), see Figure 10.7.

The single most uncomfortable texture-contamination combination under dynamic conditions was texture No.4 - sweat. The mean discomfort rating was 4.4 (SD=2.2) (*strong*). As under static conditions, the width of the grooves appears to dominate discomfort sensations.

The differences in discomfort between the static and dynamic conditions range 195 to 225% with the coarsest textures showing more discomfort than the fine (data from Tables 9.5 and 10.5 in Sections 9.5.1 and 10.5.1 respectivly).

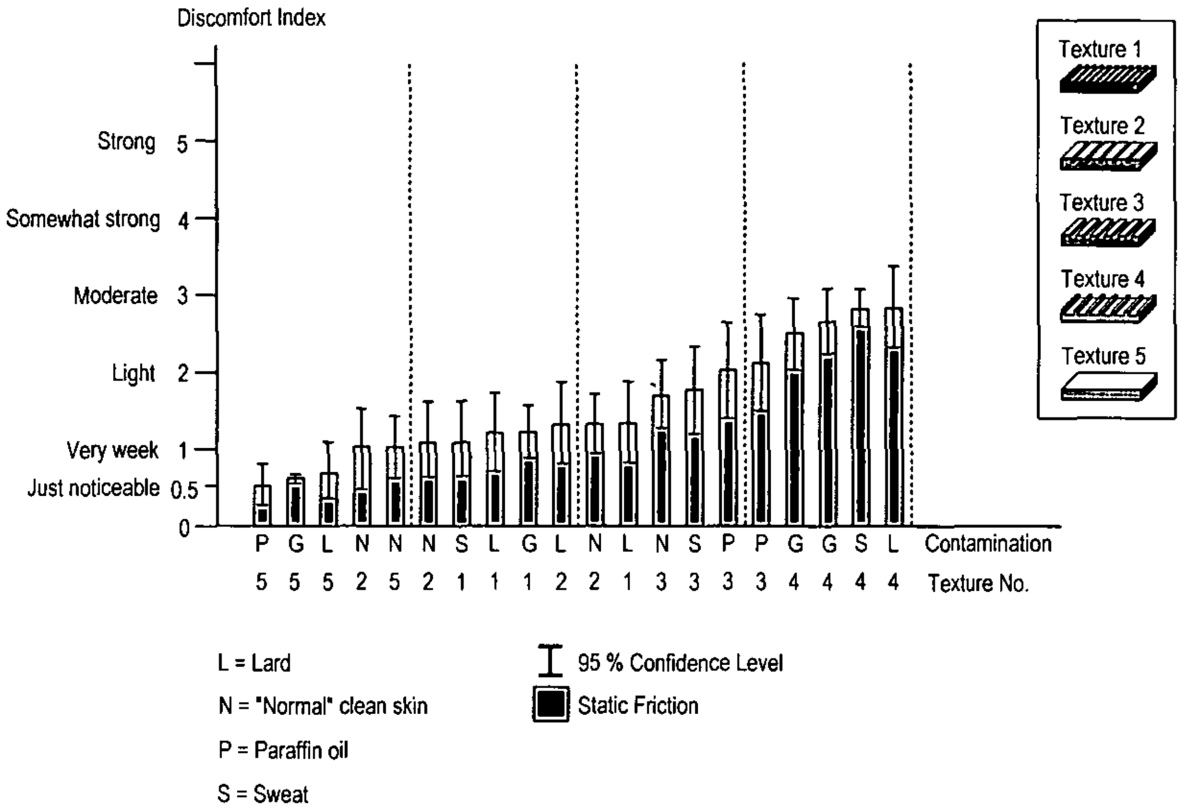


Figure 10.7 **Recorded mean discomfort index CR-10 (Borg 1982) scale and 95 % confidence interval under static friction conditions at 20 N "normal" force, ranked in order of mean discomfort. The individual surface numbers and contaminant/skin conditions are indicated below each bar.**

10.5.6 Significant differences

Coefficients of static friction and discomfort

Significant differences for coefficients of friction and perceived discomfort under static conditions are shown as p-values in Table10.8. Non-significant differences are marked (ns). The pair of samples evaluated is presented in the first column. The top of each two rows shows μ_S, below this the discomfort index CR-10_S is presented. The conditions of the friction interface, ("sweat", paraffin oil, lard, the "normal" clean skin condition, and the three nominal levels of load 1, 10 and 20 Newton) are presented in the other columns.

Pair of textures	"Normal" clean skin			"Sweat"			Paraffin oil			Lard		
	Normal force			Normal force			Normal force			Normal force		
	1 N	10 N	20 N	1 N	10 N	20 N	1 N	10 N	20 N	1 N	10 N	20 N
1/2μ_S	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
CR-10$_S$	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
1/3μ_S	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
CR-10$_S$	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
1/4μ_S	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
CR-10$_S$	.049	.031	ns	ns	0.03	0.03	ns	.005	.0025	ns	.04	ns
1/5μ_S	ns	ns	ns	.020	.0005	.0003	ns	.0015	.0002	.005	.00003	.00003
CR-10$_S$	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
2/3μ_S	ns	ns	ns	ns	ns	.024	ns	ns	ns	ns	ns	ns
CR-10$_S$	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
2/4μ_S	ns	ns	ns	ns	ns	.044	ns	.037	ns	ns	.031	ns
CR-10$_S$	.013	.041	.037	.017	.026	.025	ns	.0012	.0010	ns	.025	.022
2/5μ_S	ns	ns	ns	.041	.0002	.00001	ns	.0007	.0001	.006	.0001	.00000
CR-10$_S$	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
3/4μ_S	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
CR-10$_S$	ns	ns	ns	ns	ns	ns	ns	.040	.038	ns	ns	ns
3/5μ_S	ns	ns	ns	.035	.00000	.00006	.049	.0005	.0001	.0044	.0008	.00007
CR-10$_S$	ns	ns	ns	ns	.034	ns	ns	ns	ns	ns	.035	.031
4/5μ_S	ns	ns	ns	ns	.0006	.00004	ns	.0001	.0002	.0007	.00000	.00003
CR-10$_S$	.049	.0038	.0074	.022	.023	.007	ns	.0008	.0004	ns	.0012	.0014

Table 10.8 Test of differences (p-values if significant, otherwise ns) in coefficients of static friction μs but also and perceived discomfort CR-10s between textures with respect to environmental conditions. Surface characteristics of the test samples are available in Table 10.2, page 188

Sample No. 5 (non-textured) generated μ_S that were significantly different ($p < 0.05$) to the other (textured) samples. These differences were present when "sweat", paraffin oil and lard were present on the friction interface and for most levels of load. No significant differences were observed for the "normal" hand. Differences ($p < 0.05$) in perceived discomfort CR-10 for the static conditions were mainly noticed for pairs involving the coarsest texture, No. 4.

Effect of different interface conditions on dynamic friction

Significant differences in μ_S between the examined skin conditions and contaminants, given the four textured and one not-textured sample in Experiment 2, are presented in Table 10.9. The respective pairs of interface conditions are presented in the first column with the related levels of normal forces specified in the second column. The next five columns refer to the different sample types. The table shows whether significant differences in μ_S can be expected depending on type of change in interface conditions. This information shows that "sweat" generates significant different, and lower, friction than to "normal" clean skin, when medium and high forces are applied from the palm. The non-textured samples No.5 are more sensitive to the presence of different skin conditions and contaminants.

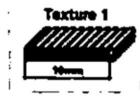
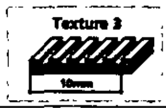
Pair of contaminants	Normal force, nominal	Texture 1 	Texture 2 	Texture 3 	Texture 4 	Texture 5 
Sweat vs. paraffin oil	1	0.048	ns	.029	.0075	ns
	10	ns	ns	ns	.0064	ns
	20	ns	.038	ns	.040	ns
Sweat vs. lard	1	ns	ns	ns	ns	.0032
	10	ns	ns	ns	ns	.00014
	20	ns	ns	ns	ns	.00026
Sweat vs. "normal"	1	ns	ns	ns	ns	.0048
clean skin	10	.027	.024	.009	.00017	.00002
	20	.0029	.00029	.016	.00021	.00002
Paraffin oil vs. lard	1	ns	ns	ns	ns	ns
	10	ns	ns	ns	ns	.021
	20	ns	ns	ns	ns	.027
Paraffin oil vs. "normal"	1	ns	ns	ns	ns	.0098
clean skin	10	ns	ns	ns	ns	.00003
	20	ns	.017	ns	ns	.00001
Grease vs. "normal"	1	ns	ns	ns	ns	.0016
clean skin	10	ns	.030	ns	.014	.00000
	20	.015	.0059	ns	.0044	.00000

Table 10.9 Test of differences in μ_S between contaminants. (p-values, otherwise ns). (n = 6)

10.5.7 Correlation coefficients

Table 10.10 shows the correlation coefficients (Pearson's r) for friction (μ_s and μ_k) and discomfort (CR-10_S and CR-10_k) from the present experiment and Experiment 1 respectively. The first column shows normal force, surface pressure, pitch, area of the friction interface and number of ridges on the samples. Correlation between static friction and discomfort are shown at the bottom left of the table.

	Correlation coefficients for static (μ_S) and dynamic (μ_K) friction						Correlation coefficients for static (CR-10_S) and dynamic (CR-10_K) discomfort					
	Contaminants and skin conditions						Contaminants and skin conditions					
	"Normal" clean skin		"Sweat"		Paraffin oil		"Normal" clean skin		Sweat		paraffin oil	
	μ_k	μ_s	μ_k	μ_s	μ_k	μ_s	CR-10_K	CR-10_S	CR-10_K	CR-10_S	CR-10_K	CR-10_S
Normal force	-0.36	-0.24	-0.71	-0.44	-0.40	-0.27	0.55	0.56	0.56	0.55	0.48	0.52
Surface pressure	-0.37	-0.15	-0.62	-0.07	-0.12	0.10	0.68	0.68	0.53	0.67	0.48	0.73
Pitch	-0.29	-0.22	0.10	0.51	0.54	0.59	0.19	0.27	0.37	0.52	0.40	0.32
Area of friction interface	0.44	0.52	0.15	-0.56	-0.54	-0.64	-0.30	-0.35	-0.28	-0.40	-0.40	-0.44
Numbers of ridges	-0.42	-0.27	-0.03	-0.54	0.44	0.49	-0.03	0.04	0.09	0.08	0.40	0.14
Friction / discomfort	-0.14	-0.10	-0.31	-0.09	-0.13	-0.11						

Table 10.10 Correlation coefficients (Pearson's r) for the independent and controlled variables (applied force, surface pressure, pitch, nominal surface area in skin contact, number of ridges on the samples) and the dependent friction variables (μk,, μs) and discomfort (CR-10_K, CR-10_S). Correlations between friction and discomfort for static and dynamic conditions, respectively, are shown at the bottom left of the table. All correlations are significant ($p<0.05$).

10.5.8 Regression analysis

The data were analysed by linear regression according to the equation:

$$Y_i = B_0 + B_1 X_1 + B_2 X_2 + B_3 X_3 + E$$

Where:

Y_i = dependent variables μ_S, μ_K

B_0 = intercept (Table 10.12)

B_1 to B_3 = regression coefficients (Table 10.12)

X_1 to X_3 = dummy coded variables (Table 10.11)

E = error term

The dependent variables (Y_i) were μ_S, μ_K, CR-10_S and CR-10_K. Each texture was characteristic by three variables, surface pressure, pitch and duty cycle (Table 10.11).

Original variable	Level	Dummy variable	Level
	15		-1
Surface pressure (kPa)	60	X_1	0
	120		1
	0		-1
Pitch (mm)	1	X_2	0
	2		1
	25		-1.5
Duty cycle %	50	X_3	-0.5
	75		0.5
	100		1.5

Table 10.11 Original variables (surface pressure, pitch, duty cycle) and dummy variables (X1, X2, X3).

Estimated regression coefficients and explained variances are shown in Table 10.11. All coefficients for μ_K and μ_S were significant ($p< 0.05$), but not for CR-10_S and CR-10_K. Predicted values for texture No's. 1 to 5 and for two estimated textures estimated according to the equation above are presented in Table 10.13.

Contamination	Variable	Regression coefficient for			
		μ_k	μ_k	CR-10$_s$	CR-10$_k$
Sweat	Intercept	0.37	0.88	0.75	1.80
	X_1	- 0.045	- 0.27	0.58	0.96
	X_2	0.036	0.13	ns	0.62
	X_3	- 0.053	0.05	ns	ns
Explained variance	R^2 %	42	57	43	38
Paraffin oil	Intercept	0.44	0.47	0.84	1.62
	X_1	- 0.048	- 0.09	0.57	0.80
	X_2	0.067	0.12	ns	0.49
	X_3	- 0.10 *	- 0.15 *	- 0.24 *	ns
Explained variance	R^2 %	47	75	48	41
Lard	Intercept	0.34	0.52	0.83	1.32
	X_1	- 0.039	- 0.19	0.60	0.66
	X_2	0.069	0.058	ns	0.35
	X_3	- 0.10	- 0.11	-ns	ns
Explained variance	R^2 %	54	45	45	33

Table 10.12 Regression coefficients for μ_S, μs CR-10$_S$ and CR-10$_K$ and contaminations. Explained variances (R2%) p-values if significant, otherwise ns.

Example

μ_S for texture No. 1, at 15 kPa surface pressure and "sweat" as hand condition, calculated as follows

Surface load 15 kPa $(X_1 = -1)$

Pitch = 1 mm $(X_2 = 0)$

Duty cycle = 50 % $(X_3 = -0.5)$

$$Y_i = B_0 + B_1 X_1 + B_2 X_2 + B_3 X_3 + E$$

$Y_i = \mu_S$

$B_0 = 0.37$

$B_1 = (-0.045)$

$X_1 = (-1)$

$B_2 = 0.036$

$X_2 = 0$

$B_3 = (-0.053)$

$X_3 = (-0.5)$

$\mu_S = 0.37 + (-0.045) * (-1) + 0.036 * 0 + (-0.053) * (-0.5) = 0.44$ (also found in Table 10.13.)

Predicted values for coefficient of friction, (μ_S, μ_k) and discomfort (CR-10_S, CR-10_k) according to the regression model in the equation presented above are presented in Table 10.13. Friction and discomfort relates to surface pressures of 15, 60, and 120 kPa, pitches of 0, 1 and 2 mm, duty cycles 25, 50, 75, and 100 %. The skin conditions and contaminants which fitted the regression model were "sweat", paraffin oil and lard respectively. In application of the regression model, friction and discomfort data can be established for not only the five examined samples but also for "virtual" textures having other, and combinations other texture measures, within the limitations of the original variables. Predicted friction and discomfort data for two virtual textures are presented in Table 10.13 along with such predictions of five examined samples. These samples are characterised by 1 mm pitch, 25 and 75% duty cycles, 15, 60, and 120 kPa surface pressures. These predictions are found within frames of double lines.

Duty cycle %		25%						50%						75%						100 %					
		Contamination								Contamination						Contamination				Contamination					
		"Sweat"		Paraffin oil		Lard		"Sweat"		Paraffin oil		Lard		"Sweat"		Paraffin oil		Lard		"Sweat"		Paraffin oil		Lard	
		μs	Cs	μs	Cs	μs	Cs	μs	Cs	μs	Cs	μs	Cs	μs	Cs	μs	Cs	μs	Cs	μs	Cs	μs	Cs	μs	Cs
		μk	Ck	μk	Ck	μk	Ck	μk	Ck	μk	Ck	μk	Ck	μk	Ck	μk	Ck	μk	Ck	μk	Ck	μk	Ck	μk	Ck
Pitch m.m	Pressure kPa																								
0	15																			0.30	0.0	0.27	0.00	0.15	0.00
																				1.09	0.33	0.22	0.00	0.48	0.29
	60																			0.25	0.45	0.22	0.48	0.11	0.50
																				0.83	1.30	0.13	0.76	0.29	0.95
	120																			0.21	1.03	0.17	1.05	0.08	1.10
																				0.56	2.26	0.04	1.56	0.11	1.61
1	15	0.49	0.36	0.65	0.62	0.53	0.47	0.44	0.23	0.54	0.39	0.43	0.31	0.39	0.10	0.44	0.15	0.33	0.16						
		1.06	0.72	0.78	1.19	0.88	0.67	1.12	0.79	0.64	0.94	0.77	0.66	1.17	0.87	0.49	0.70	0.65	0.65						
	60	0.45	0.94	0.60	1.19	0.50	1.06	0.40	0.81	0.49	0.96	0.34	0.91	0.34	0.68	0.39	0.72	0.29	0.76						
		0.80	1.68	0.69	1.99	0.70	1.33	0.85	1.76	0.55	1.74	0.58	1.32	0.90	1.84	0.40	1.49	0.47	1.31						
	120	0.40	1.52	0.55	1.76	0.46	1.66	0.35	1.39	0.45	1.53	0.35	1.51	0.30	1.26	0.34	1.29	0.25	1.36						
		0.53	2.64	0.60	2.79	0.51	1.99	0.58	2.72	0.46	2.54	0.40	1.98	0.63	2.80	0.31	2.29	0.28	1.98						
2	15	0.53	0.46	0.71	0.63	0.60	0.57	0.48	0.33	0.61	0.39	0.50	0.42	0.42	0.21	0.51	0.15	0.39	0.26						
		1.19	1.33	0.90	1.68	0.94	1.02	1.24	1.41	0.75	1.43	0.83	1.01	1.30	1.49	0.61	1.18	1.71	1.01						
	60	0.48	1.04	0.67	1.20	0.56	1.17	0.43	0.91	0.56	0.96	0.46	1.01	0.38	0.78	0.46	0.72	0.36	0.86						
		0.92	2.30	0.81	2.47	0.75	1.68	0.98	2.38	0.66	02.2	0.64	1.68	1.03	2.45	0.52	1.98	0.53	1.67						
	120	0.44	1.62	0.62	1.77	0.53	1.77	0.39	1.49	0.51	1.53	0.42	1.61	0.33	1.36	0.41	1.29	0.32	1.46						
		0.66	3.26	0.72	3.27	0.57	2.34	0.71	3.34	0.58	3.02	0.45	2.34	0.76	3.42	0.43	2.78	0.34	2.33						

Table 10.13 Predicted values for coefficient of friction, (μ_S, μ_k) and discomfort (CR-10_S, CR-10_k) according to the regression model in Equation (4). Friction and discomfort relates to surface pressure, pitch, duty cycle and skin-sample condition.

10.6 Discussion

This paper described the effect of static and dynamic coefficients of friction for different textures in friction partnership with palm skin, which was "normal" clean, and also with interface conditions involving "sweat", paraffin oil and lard. Subject's perceptions of discomfort when exposed to these conditions are also described. The results were compared with those from dynamic friction in Experiment 1 reported in Chapter 10.

Static and dynamic friction

The results from Experiments 1 and 2 show that the mean μ_S for the five textured samples exposed to two contaminants and two skin conditions is generally smaller than μ_K, (Table 10.14) where significance levels (t-tests) are presented. The relation between static and dynamic friction is also illustrated in Figures 10.5 on page 199 as well asFigure 10.8 and 10.9 below.

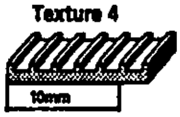
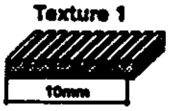
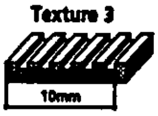
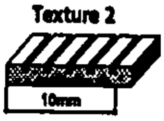
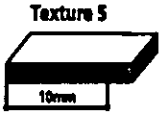
Texture	Coefficient of friction Mean; SD		Difference		p-levels
	μ_s; SD	μ_k; SD	μ_k - μ_s	%	p
Texture 4 	0.65 (0.15)	0.69 (0.07)	0.04	6.15	ns
Texture 1 	0.48 (0.26)	0.66 (0.14)	0.18	37.5	P<0.05
Texture 3 	0.68 (0.19)	0.72 (0.13)	0.04	5.9	ns
Texture 2 	0.57 (0.16)	0.75 (0.20)	0.18	31.6	P<0.01
Texture 5 	0.42 (0.15)	0.58 (0.20)	0.16	38.1	P<0.01

Table 10.14 Overall mean standard deviation of coefficient of static and dynamic friction and related standard deviations. Differences and significance levels for five samples exposed to contaminants and skin conditions at 1N normal force in experiments 1 and 2. p-values, otherwise ns. (n = 14)

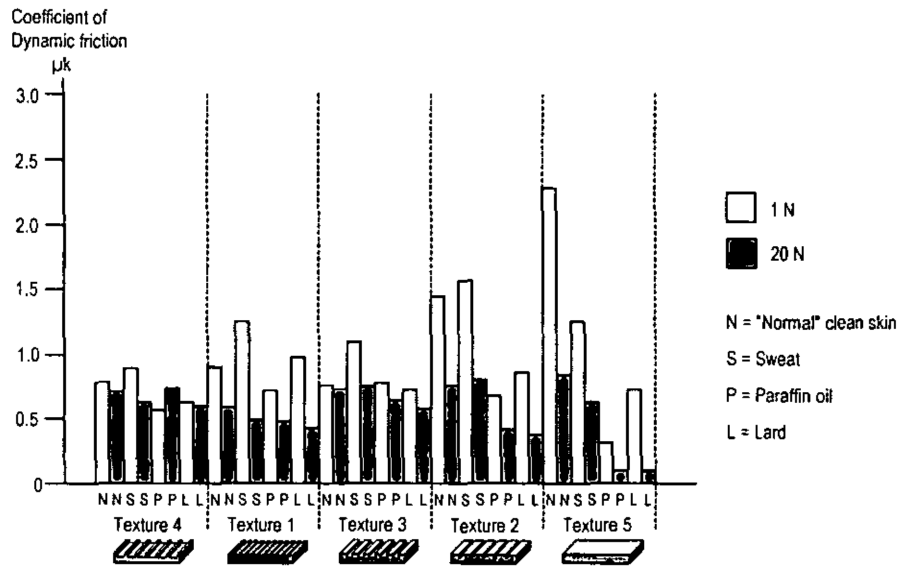


Figure 10.8 **Coefficient of dynamic friction and the influence of 1 and 20 Newton finger force interfacing four samples in Experiment 1. Contaminations and skin conditions are shown for the respective samples in order "Normal" clean hand, "Sweat", Paraffin oil and Lard.**

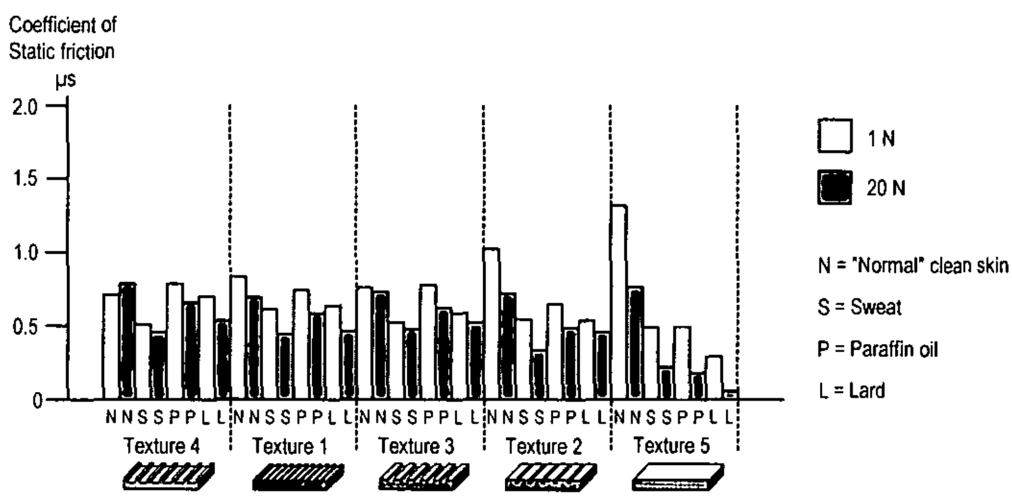


Figure 10.9 **Mean coefficient of Static friction and the influence of 1 and 20 Newton finger force interfacing four samples in Experiment 1. Contaminations and skin conditions are in set order. Contaminations and skin conditions are shown for the respective samples in order "Normal" clean hand, "Sweat", Paraffin oil, Lard.**

This influence of velocity and pressure is in contradiction to the generally accepted "law" of friction but not unlike the frictional behaviour of polymers (Suh 1986) and in agreement with the findings by Comaish and Bottoms (1971). The differences are significant under most environmental, surface and load conditions. The differences per combination of sample and contamination/skin condition are illustrated in Figure 10.5 and Section 10.5.4.

The normal force and surface pressure has a remarkable effect on human palm skin. A twenty-fold increase in the normal force, from 1 to 20 Newton would result in a 20-fold increase in the coefficient of friction if the traditional "Law of friction" would hold true. According to Experiments 1 and 2, however, dynamic friction μ_k is only increased (7.7-fold), while the static friction force μ_s is increased 12.9-fold.

The differences between μ_s and μ_k are particularly dominant in the <u>low</u> force range (one Newton) when the surface pressure (depending on the texture) is in the range approx. 6.3 to 25.2 kPa. Large differences were generally noticed for the "normal" clean and "sweat" condition. The difference between μ_s and μ_k is less marked in the higher force range (20 Newton) when the surface pressure is approx. 81.4 to 288.5 kPa.

The reduction of μ_s with increased normal force is considerable (r = - 0.44). In the dynamic situation μ_k the correlation is even stronger (r = - 0.71). Compression of palm skin and the underlying tissue will cause bulging and expansion of the interface area, as shown in Experiment 1 (Section 9.5.3).The 20-fold increase of the normal force, presented in this thesis, increase in the surface pressure (from 6.3 to 81.4 kPa while μ_s for a "normal" clean hand, was reduced to 58.3 % (from μ_s 1.32 to 0.77). The dynamic situation, $\mu_{k,}$ will reduce the coefficient of friction to 38 % (from μ_k 2.22 to 0.85) for the same "normal" clean hand condition. The correlation between μ_s and surface pressure is - 0.15, and between μ_k and surface pressure is - 0.37. Thus, it appear that palm skin is very efficient in transferring lateral forces at low surface pressure, with the effect that low forces may be transmitted with less muscular involvement. However, as seen in Table 10.15, these extreme friction values under low forces are reduced to below 1.00 under high surface loads. This skin reaction to reduce friction with higher loads may be functional too as it reduces the shear force that might otherwise generate a blister or an oedema. It will instead allow for a protective callous to build up.

Physical attribute	Condition 1 Newton	Condition 20 Newton	Increase	Decrease
Normal force Fn	**1 Newton**	**20 Newton**	**20-fold**	
Surface pressure. On not textured surface, 100% duty cycle	6.3 kPa	81.4 kPa	12.9 fold	
μ_s On not textured surface	1.32	0.77		Reduction to 58.3%
Friction force $F_f = \mu_s * F_n$	1.32	15.4	11.7-fold	
μ_k On not textured surface	2.22	0.85		Reduction to 38.5%
Friction force $F_f = \mu_k * F_n$	2.22	17.0	7.7-fold	

Table 10.15 Palm skin reaction to low and high pressure when in friction partnership with a non textured surface.

The correlation coefficient for μ_s and μ_k between surface pressure and "normal" clean skin conditions is -0.15 and -0.37 respectively (Table 10.10). One possible explanation for this is that the dermal ridges (which are unique to mammals who rely on palm friction, and not claws, for a safe grip) have specific dynamic qualities, which are active only under sliding conditions. A large duty cycle on textures acts in favour of higher friction under "normal" clean skin conditions (Pearson's r for the area of friction contact and μ_s and μ_k, are 0.52 and 0.44 respectively). The non-textured surface No. 5 increased μ_s considerably when the hand was "normal" but "sweat", paraffin oil and lard reduce this friction considerably (Figure 10.3). It appears that under static conditions "sweat" behaves as a lubricant but under dynamic conditions it behaves as normal clean skin.

Generators of friction

Suh (1986) describe the total coefficient of friction μ as the sum of μ_d, μ_p and μ_a, where

- μ_d is the asperity deformation is the deformation of microscopic protrusions on the surface, which is closely related to the module of elasticity (Young's modulus) for the material concerned.

- μ_p is the ploughing in the surface by protruding particles This component is expressed in terms of height, width and radius for protrusions on the surface and thus related to the surface topography.

- μ_a is the molecular adhesion between surfaces. In polymers, the adhesion is determined largely by its molecular structure.

For visco-elastic materials like skin, the three components μ_d, μ_p and μ_a contribute to friction to different degrees sequentially, as well as concurrently. According to the results from Experiments 1 and 2, the mechanisms appear to be that adhesion forces predominantly generate friction forces under "normal" clean conditions and these are reduced by the investigated contaminants. Under contaminated conditions the deformation component, μ_d, rather provides friction forces. It is suggested by the author that the grooves between the many ridges provide volume for the skin and underlying tissue to enter. Friction forces are generated as this volume is deformed in the direction of the friction force. This volume can be provided through few but wider grooves, or several more narrow ridges. This argument is supported by the correlation coefficients in Table 10.10 where both pitch, as an expression for wider grooves, and number of ridges, as an expression for narrow ridges show positive correlations ranging 0.44 to 0.59.

Palm friction may be attributed to the dermal and subcutaneous tissues' ability to deform and drape over surfaces during the sliding motion and provide high friction under lubricated conditions, but also to the ability of the friction engaging dermal cells to adhere to the corresponding surface under clean conditions. Thus palm skin is extremely efficient in transforming lateral forces at low surface loads, which means that such forces can be transmitted with only little muscular involvement. This may have been functional in the human evolution as it saves energy when holding on to items such as a weapon for long hours. These extremes turn to more common values during high surface loads, which also may be functional, as lower friction reduces the shear force that would otherwise generate a blister or an oedema. It will instead allow for a protective callous to build up.

Sweat

In the present series of experiments the "sweat" condition refers to a water solution with 0.9% NaCl, i.e. close to the composition of human sweat which consist of 99% water and 1% solids of which half is inorganic salt, e.g. sodium chloride and one half is organic, e.g. urea. (Rothman1954). A droplet (5 ml) of this solution was applied on the sample surface for the subject to put his finger on in the process of applying the required normal force and initiate a displacement. The aim being to provide a biochemical environment in the interface like that from sweat generated from the sweat glands. Under such true conditions, however, other mechanical changes in the skin are likely to take place as the visco-elastic properties may be affected. Such changes were not investigated or controlled for. Under "sweat" conditions, μ_S was found to be considerably lower than μ_K. The compression of the droplet on the sample, and the reduced drainage under static conditions, may be factors explaining the low μ_S figures.

Contamination

Significant differences in μ_s and μ_k due to contamination were mostly found in relation to the non-textured surface No. 5. No significant differences between textures were noticed for "normal" clean skin, largely depending on the large inter-individual variation with this variable. Differences between recorded means were considerable and Tables 10.5 and 10.13 may act as a guide to industrial designers in the choice of textures on surfaces that are touched and manipulated by hand.

Regression model

Based upon the regression model, a matrix is presented in Table10.13 showing predicted data for textures, surface pressures and environmental conditions ("sweat", paraffin oil and lard). The model is created for static as well as dynamic friction and the related perception of discomfort. The model considers "sweat", paraffin oil and lard and surface load, pitch and duty cycle. The mean explained variance, R^2, for μ_s and μ_k is 53.3% (range 42 to 75 %). The mean explained variance R^2 for the discomfort index CR-10_s and CR-10_k is 41.3% (range 33 to 48 %). It was however not possible to establish a regression model that satisfactorily explained the variation when the "normal" clean hand was engaged in static (or dynamic) friction due to variances under these conditions. Predicted data for μ_S, μ_K, CR-10_S and CR-10 $_K$ based on surface pressures and environmental conditions are found in Table 10.13. Due to the quality of the regression model, textures with other relations between grooves and ridges to those actually researched can be explored. The model is, however, not valid for predictions outside the measuring range of the researched textures and only for forces and displacements acting across the texture. The restricting levels are found in Tables 10.2 and 10.4 (in Section 10.3.2 and 10.3.3 respectively). Original and dummy variables are presented in Table 10.11 and regression coefficients in Table 10.12 (both in Section 10.5.8).

Discomfort

The large variance for the discomfort index CR-10 may be an effect of the subjective scale used (Borg 1982). This scale is intended to measure human sensations when one can expect a subjectively defined maximum, e.g. worst imaginable. On reflection it seems, however, that the sensation of discomfort from finger pad contact had no stringent maximum that is easily defined for most people. The results showed that each individual seems to have chosen their own "subscale" i.e. they tended to generally score low, or high or utilised the entire scale. This led to large standard deviations and only a few significant differences.

Most textures are perceived less uncomfortable under static than under dynamic conditions as seen in Table 10.16. The reason probably being the lower activity in the subcutaneous mechanoreceptors as there is less lateral displacement of the skin. The duty cycle has an obvious effect on discomfort, with the coarsest texture (No. 4) being the most uncomfortable. Figure 10.16 show the perceived discomfort rating CR-10_S at 20 Newton normal forces (The related surface pressure is 81.4 to 288.5 kPa). The correlation between perceived discomfort and μ_S is practically non existing and ≤ 0.09 (Table 10.10). The low correlation is in the same low region as for μ_K.

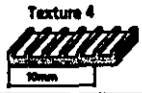
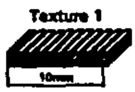
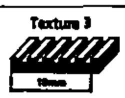
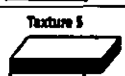
Texture	Perceived discomfort CR-10, Mean, SD		Significant Differences
	CR-10_S, SD	CR-10_K, SD	p
Texture 4 	1.19 (1.19)	2.01 (0.79)	$p < 0.05$
Texture 1 	0.48 (0.49)	1.36 (0.77)	$p < 0.001$
Texture 3 	1.05 (0.70)	2.23 (1.13)	ns
Texture 2 	0.62 (0.56)	1.47 (0.72)	ns
Texture 5 	0.40 (0.39)	0.71 (0.63)	ns

Table 10.16 Overall mean perceived discomfort expressed as CR-10 (Borg 1982) under static and dynamic frictin exposure, related standard deviations and signifficance levels for five samples exposed to contaminants and skin conditions in experiments 1 and 2. p-values, otherwise ns. (n = 14)

Most people like to believe that a coarse and uncomfortable texture such as No. 4 (which has 0.5 mm ridges and 1.5 mm grooves) should generate the highest friction against palm skin - regardless of contamination and skin condition. This was true under dynamic contaminated conditions but was not the case for "normal" clean skin conditions, for which coarse textures surprisingly reduced friction.

Thus there is a great risk of misinterpretation if the perceived discomfort sensation is used as a guide to estimate the coefficient of friction. However we do have the sensory mechanisms to determine very accurately, within milliseconds, if slips occur, to correct the normal force to prevent the slip and to establish a safety margin against slipping (Johansson and Westling 1984a). It appears that we lack the ability to mentally perceive this friction sensation in textures and discomfort will dominate the experience. Experiment 3 will explore a larger variety of textures commonly used for handles in tools and consumer products.

10.7 Summary and conclusions

Experiment 2 investigates coefficient of static friction μ_S and perceived discomfort for five surfaces when touched by a "normal" clean hand, a "sweat" hand and a hand contaminated with paraffin oil and lard. The experimental design, all subjects and most treatments were identical to Experiment 1 which examines only dynamic friction. Fourteen male subjects applied forces of 1, 10 or 20 Newton using the index finger of the dominant hand while touching and slightly stroking samples in the direction towards the body. The same polycarbonate material was designed to give 25, 50, 75, or 100% skin contact area by ridges (duty cycle).

Static and dynamic friction

μ_S is generally smaller than μ_k under clean as well as contaminated conditions and when the hand is in palm contact with non-textured, fine and coarse textures under low, medium and high pressure. μ_S rarely exceeds the value 1.00 which frequently was the case for μ_k at low interface pressure.

Type of texture

Coarse patterns reduce both μ_S and μ_K in friction contact with a "normal" clean palm, but a non-textured surface increase friction under such skin conditions. However, under contaminated conditions the situation is reversed and coarse surfaces increase μ_S and μ_K in relationship to the non-textured surface. This situation is reflected in the correlation coefficients. Under "normal" clean conditions there is positive correlation (mean 0.5) between the area of the friction interface and μ_S as well as μ_K , while under contaminated conditions negative correlation are found, (mean -0.59), $p<0.05$.

Surface pressure
Static as well as dynamic friction is reduced under high load. The loss of friction force, in relation to a situation according to the traditional "Law" of friction, is 41.5% and 61.7% for μ_S and μ_K respectively. The compression of palm skin and underlying tissue under applied load causes bulging and expansion of the interface area. The 20-fold increase of the normal force (from 1 to 20 Newton) will, on a non-textured sample, result in a 13-fold increase in the surface pressure (from 6.3 to 81.4 kPa).

Perceived discomfort
Coarse textures provide more discomfort than fine, and dynamic friction cause more discomfort than static friction. Normal force and width of grooves dominate the discomfort sensation. A 20-fold increase of the normal force will increase the discomfort CR-10 by a factor 4.87 for μ_s, and by a factor 3.07 for μ_k.

Regression model
As a result of a regression model a matrix is presented showing predicted static and dynamic friction data, for samples having different

- duty cycle
- pitch
- surface pressures ranging 15-120 kPa
- environment condition being "sweat", paraffin oil or lard

The mean explained variance, R^2, for μ_S and μ_K was 53.3%, and for the discomfort index CR-10_s and CR-10_k it was 41.3%.

Chapter 11 Experiment 3. Friction in fine and coarse textures with special attention to skin moisture and contamination

11.1 Introduction

Engineering and industrial designers have a variety of texture possibilities to choose between when developing handles made from metal but more so when made from polymers, resins and rubber products which can be provided with textures in a wide spectrum. Such textures can be achieved by means of moulding or casting, by industrially photo-etching or through spark-erosion in the surface. Textures are often used to provide a specific visual appearance. However, when it comes to handles, and similar items that are manipulated and controlled with the human hand, there may be good reasons to choose textures based on of the frictional properties of the hand-product interface. Some textures may provide discomfort or pain, others may provide less friction and some may be unsafe to use in certain applications.

11.2 Aims of Experiment 3

One aim of this experiment was to investigate mass-produced textures and also some machine cut textures with deeper profiles than in Experiments 1 and 2 for coefficient of friction over the velocity spectrum 0 to 128 mm/s. A second aim was to identify which elements of a texture contribute to friction, but also what contribution the external factors surface pressure, velocity, contamination and skin condition give coefficient of friction and present a multiple regression model by which friction could be predicted based on these variables.

A third aim was to investigate the relation between skin moisture and friction, and compare subjects with low and high skin moisture, and also to investigate the effect of natural diversity in palm skin moisture and coefficient of friction over many (16) weekdays.

11.3 Experimental procedure

The subjects were introduced to the aim of the experiment and trained to use the provided instruments as presented in Section 9. Subjects applied the requested normal force, 1 or 20 Newton, then at first pulled the finger toward themselves just a few (5-10) millimetres, 4 to 5 times. Then they pulled at least 100 of the 130 mm long test sample. The velocity started at 0 mm/s and accelerated to in excess of 128 mm/s but did not exceed 130 mm/s. Instruments collected related data throughout the entirely velocity range. The individual sample surfaces and the examined normal forces were tested in random order. The "normal" clean, the "sweat" and the hydrated conditions were examined in that order of skin hydration. These skin conditions preceded the contaminated conditions, which were administered in a set order starting with glycerol followed by hydraulic oil and finally the most greasy, engineering grease, as described in Section 8.15. The rate of skin moisture at the exposed part of the palm was recorded immediately prior to each "normal" clean skin friction exposure.

To specifically investigate the effect of skin hydration on friction, recordings of skin moisture (TEWL) was performed directly on the exposed part of the palm prior to friction recordings. In one experiment, seven subjects were recruited, who initially participated in Experiment 3 and were found belonging to two sub-groups. One having low moist skin and another having high moist skin. Their friction partners in this study were sandpaper 320 grit, leather, thermoplastic elastomer (Alcryn) and Polycarbonate. Subjects were examined prior to exposing their index, middle, ring and little finger to repeated experiments, using the same samples. The order of finger and sample exposure was randomised.

In another experiment, one subject performed friction and TEWL recordings at the same hour of the day, daily for sixteen consecutive weekdays using only the same non-textured sample (No.5).

11.3.1 Subjects

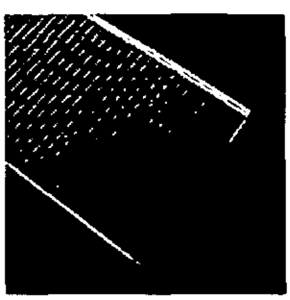
Thirteen male subjects took part in this experiment. Nine of these were the same as those who participated in Experiments 1 and 2 (Table 11.1). Four were new to this experiment. All subjects performed daily office work. The specifications of the subjects, materials and treatments used are described in detail in Chapter 9.

No. of subjects:	13
Sex:	Male
Age:	19 - 55
Profession:	All white collar workers

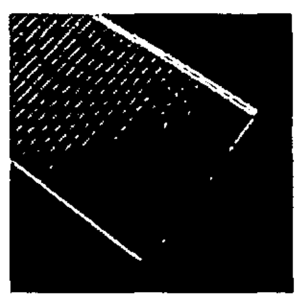
Table 11.1 Subjects in Experiment 3

11.3.2 Test samples

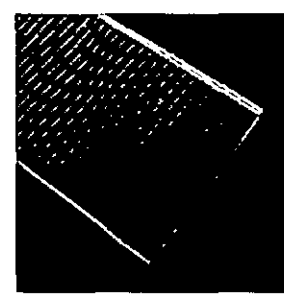
Eight differently textured samples, all in polycarbonate material, were examined. The textures were selected based on the character of their surface. They can generally be described as "coarse" and "fine", see photos in Figure 11.1. Coarse samples included machine cut and mass-produced textures. All "fine" textures were mass-produced. In addition, the non textured sample No.5 was used in the study of daily variations in friction and skin moisture.



No. 202 "coarse"
0.1 mm deep grooves

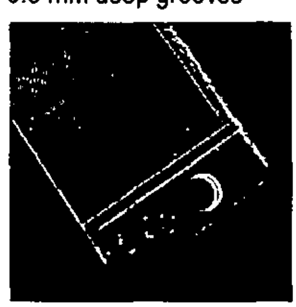


No. 203 "coarse"
0.3 mm deep grooves

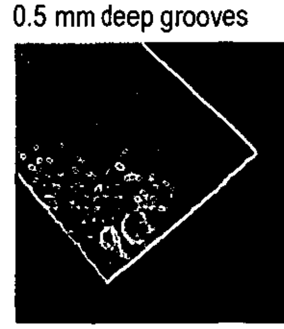


No. 204 "coarse"
0.5 mm deep grooves

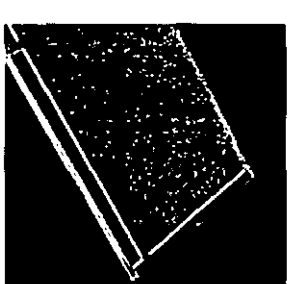
No. 9004 Wide striped



No. 9006 Narrow striped



No. 9050 Small dots



No. 9057 Large dots

No. 9078 Small dots and flat spots

No. 5 "Glossy

Figure 11.1 Eight textured and one non-textured sample examined in Experiment 12

The series of textures and their allocation to the respective categories are presented in Table 11.2 and described with their surface topographies in Table 11.3. Samples No. 202, No. 203, No. 204 were similar to Texture No. 4 (examined in Experiments 1 and 2) but in the present study the depths of their grooves were made to 0.1, 0.3 and 0.5 mm. respectively, see Table 11.4, in order to investigate the influence of groove depth on friction. (The grooves of Texture No. 4 were 0.5 mm) The method of machine cutting these grooves was the same as in Experiments 1 and 2. The other samples were mass-produced commercially available textures produced by Standex AS, Norway, and are presented with their catalogue number. All of the mass-produced textures were produced using injection moulding and photo-etched casting techniques.

Five surface topographic parameters were analysed with a standardised instrument, Talysurf, Taylor & Hobson, (R_p, R_a, Del.q, S, S_m). Two additional dedicated parameters, which were suggested by scientists at the Institution for Machine Science at the Royal University of Technology in Stockholm, were also investigated. These, referred to as T5 and H5, are presented in Appendix 3.

Texture		
Coarse		**Fine**
Machine cut	**Mass-produced**	**Mass-produced**
No. 202 "coarse" 0.1mm deep grooves	No. 9004 "wide striped"	No. 9050 "small dots"
No. 203 "coarse" 0.3 mm deep grooves	No. 9006 "narrow striped"	No. 9057 "large dots"
No. 204 (=No.4) "coarse" 0.5 mm deep grooves		No 9078 "small dots and flat spots"

Table 11. 2 The allocation samples in Experiment 3

No.	Sample No.	R_p (μm)	R_a (μm)	Del.q (degr.)	S (μm)	S_m (mm)	T5	H5
202	Coarse 0.1mm	76.27	18.96	24.18	170.27	1.538	14.00	43.00
203	Coarse 0.3mm	143.94	54.15	35.04	539.64	1.751	4.00	117.00
204	Coarse 0.5mm	178.80	79.64	43.40	398.162	1.683	13.00	95.00
9004	"wide striped"	28.75	21.18	11.09	244.01	1.40	4.50	9.50
9006	"fine striped"	33.29	22.71	15.56	276.11	0.65	12.50	6.25
9050	"small dots"	7.23	2.75	4.64	121.0	0.29	10.0	6.75
9057	"large dots"	31.43	11.23	12.32	264.52	0.413	6.50	27.5
9078	"small dots and flat spots"	16.77	6.55	6.00	157.44	0.512	3.75	8.5
	Range	7.23 - 178.80	2.75 –79.64	6.00 - 43.40	121.0-539.64	0.62-1.53	3.75-14.00	6.25-117.00

Table 11.3 Surface topography of the test samples

Sample No.	Sample	Pitch (mm)	Duty cycle ratio of ridge area of total area (%)	Groove area as a fraction of total area (%)	Width of ridges (mm)	Width of grooves (mm)
202, 203 and 204		2	25	75	0.5	1.5

Table 11.4 Surface character of the coarse machine cut test samples. The depth of the grooves in textures 202, 203 and 204 was 0.1, 0.3 and 0.5 mm respectvely

11.3.3 Treatments

Three contaminants on the friction interface were researched glycerol, hydraulic oil engineering grease and three non-contaminated conditions, "normal" clean skin and "sweat" and hydrated i.e. extremely moist skin. Section 8.15 "Order of treatments and skin condition recordings", describes the details of the conditions at the friction interface and the way the contaminants were applied. The contaminants and skin conditions unique to Experiment 3 were: Hydraulic fluid (Shell Tellarctic), a transmission fluid also used in automotive brake system, and Engineering grease (BP Energrease), also called wheel grease or ball bearing grease. A separate set of test samples was dedicated to each type of contaminant. The treatments and test conditions are presented in Table 11.5).

Conditions:	Samples	8
	Materials	1
	Loads	2
	Contaminants	3
	Non-contaminated skin conditions	3
	Treatments per subject	96
	Number of subjects	13
	Sum of treatments	1248

Table 11.5 Treatments in Experiment 3

11.4 Experimental procedure

The general test and data collection procedure is described in Chapter 8.

In this experiment coefficient of friction was recorded over a velocity spectrum from 0 to > 128 mm/s thus covering both static μ_s and dynamic μ_k friction. As in Experiments 1 and 2, static friction relates to hand movements of 0-4 mm/sec.and dynamic friction relate to 32 - 64 mm/sec. Coefficient of friction of the entire range 0 - > 128 mm/s. is referred to as μ_{mean}. The task for the subject was to press the finger on the sample until the requested normal force was reached and then pull the finger toward the body just a few millimetres 3 to 4 times. This was then repeated but with the finger pulling all along the sample until the velocity reached 128 mm/s.

The individual samples were tested in random order. As in Experiments 1and 2, all tests started with "normal" clean skin conditions, followed by glycerol, hydraulic fluid and then engineering grease to avoid the contamination of the clean samples. Recording of skin moisture using a water evaporator (TEWL) was performed prior to the experimentation with the "normal" clean skin, the "sweat"' and the hydrated skin condition.

Any of the "normal forces" 1 or 20 Newton's were randomly provided by the experimenter. The duration of the test was approximately two hours. None of the subjects experienced any fatigue or discomfort. No financial compensation or gifts were given.

Location	Finger pad of distal phalanx on the index finger, and in a sub study, four fingers (but not the thumb) of the dominant hand.
Normal force F_n	1 and 20 N
Surface pressure (averaged)*	6.3 to 288.6 kPa
Velocity v	To 0 > 128 mm/sec
Direction of finger movement	Towards the subject
Skin moisture	One recording for each subject prior to each "Normal" clean skin exposure.
Samples	Eight textures.
	Three machine cut textured with 25 duty cycle.
	Five mass-produced textures namely:
	No. 9004 "wide striped"
	No. 9006 "fine striped"
	No.9050 "small dots"
	No. 9057 "large dots"
	No. 9078 "small dots and flat spots"
	See illustrations in Figure 12.1 and Appendix 2 for topgrsphies.
	Four materials.namely:
	Polycarbonate
	Sandpaper 320 grit
	Leather
	Thermoplastic elastomer (Alcryn)
Number of contaminants	Three. Engineering grease, hydraulic fluid and glycerol
Not contaminated surface treatments	Three. "Normal", clean skin, "sweat"' and extremely hydrated skin

Based on adopted normal force F_n, and calculated friction interface area per subject

Table 11.6 Test conditions in Experiment 3

The dependent variables were:

Coefficient of friction, μ_k and μ_s

The independent variables were:

Texture of test samples; i.e. R_p, R_a, Del.q, S, S_m, H5, T5

Contaminations and hand conditions.

Normal force F_n.

Controlled variables were:

Skin moisture, TEWL

11.5 Results

11.5.1 All samples

Empiric results for the coefficient of friction for the eight samples in this experiment are presented in Table 11.7 and in Table 1 in Appendix 1. Table 11.7 present μ_{mean} and standard deviations for each sample with 1 and 20 Newton normal force for all contaminants and skin conditions respestivly, while Table 1 shows coefficients of friction at these conditions but as mean velocities over six velocity intervals ranging 0-128 mm/s. Predicted results according to the regression model are presented in Table 11 in Appendix 3..

Sample No.	Contaminant and skin conditions	Nominal "normal" force	μ Mean	sd
No. 202	"Normal" clean skin	1	0.652	0.294
		20	0.607	0.211
	"Sweat"	1	1.062	0.321
		20	0.811	0.261
	Skin hydration	1	0.879	0.370
		20	0.724	0.200
	Glycerol	1	0.645	0.204
		20	0.493	0.186
	Hydraulic oil	1	0.660	0.318
		20	0.575	0.280
	Engineering grease	1	0.518	0.179
		20	0.381	0.159

Table 11.7 Means and standard deviations for μ_{mean} for two force levels, six environmental condtions and eight samples. Mean velocities 0-128 mm/s (n =13). Table continues on three pages.

Sample No.	Contaminant and skin condition	Nominal "normal" force	μ Mean	sd
No. 203	"Normal" clean skin	1	0.577	0.273
		20	0.635	0.193
	"Sweat"	1	0.967	0.362
		20	0.710	0.236
	Skin hydration	1	0.820	0.389
		20	0.701	0.208
	Glycerol	1	0.573	0.175
		20	0.596	0.183
	Hydraulic oil	1	0.926	0.310
		20	0.699	0.239
	Engineering grease	1	0.644	0.187
		20	0.540	0.167
No. 204	"Normal" clean skin	1	0.552	0.277
		20	0.616	0.194
	"Sweat"	1	0.860	0.299
		20	0.605	0.197
	Skin hydration	1	0.936	0.551
		20	0.720	0.199
	Glycerol	1	0.500	0.160
		20	0.533	0.152
	Hydraulic oil	1	0.629	0.199
		20	0.555	0.227
	Engineering grease	1	0.594	0.199
		20	0.464	0.178
No. 9004	"Normal" clean skin	1	0.779	0.556
		20	0.607	0.247
	"Sweat"	1	0.729	0.315
		20	0.501	0.175
	Skin hydration	1	1.124	0.639
		20	0.915	0.400
	Glycerol	1	0.434	0.163
		20	0.315	0.153
	Hydraulic oil	1	0.383	0.190
		20	0.198	0.121
	Engineering grease	1	0.426	0.165
		20	0.098	0.044
No. 9006	"Normal" clean skin	1	0.740	0.572
		20	0.557	0.286
	"Sweat"	1	0.656	0.244
		20	0.415	0.161
	Skin hydration	1	1.096	0.582
		20	0.781	0.331
	Glycerol	1	0.374	0.138
		20	0.318	0.126
	Hydraulic oil	1	0.476	0.218
		20	0.297	0.138
	Engineering grease	1	0.506	0.168
		20	0.128	0.125

Contd.

Sample No.	Contaminant and skin condition	Nominal "normal" force	μ Mean	sd
No. 9006	"Normal" clean skin	1	0.740	0.572
		20	0.557	0.286
	"Sweat"	1	0.656	0.244
		20	0.415	0.161
	Skin hydration	1	1.096	0.582
		20	0.781	0.331
	Glycerol	1	0.374	0.138
		20	0.318	0.126
	Hydraulic oil	1	0.476	0.218
		20	0.297	0.138
	Engineering grease	1	0.506	0.168
		20	0.128	0.125
No. 9050	"Normal" clean skin	1	0.940	0.719
		20	0.635	0.275
	"Sweat"	1	0.734	0.318
		20	0.358	0.186
	Skin hydration	1	1.429	0.720
		20	1.056	0.500
	Glycerol	1	0.245	0.103
		20	0.107	0.049
	Hydraulic oil	1	0.184	0.130
		20	0.091	0.052
	Engineering grease	1	0.424	0.166
		20	0.062	0.028
No. 9057	"Normal" clean skin	1	0.660	0.408
		20	0.598	0.225
	"Sweat"	1	0.649	0.232
		20	0.398	0.150
	Skin hydration	1	0.967	0.492
		20	0.801	0.297
	Glycerol	1	0.378	0.149
		20	0.208	0.104
	Hydraulic oil	1	0.385	0.180
		20	0.180	0.089
	Engineering grease	1	0.466	0.196
		20	0.071	0.033
No. 9078	"Normal" clean skin	1	0.850	0.415
		20	0.595	0.239
	"Sweat"	1	0.725	0.273
		20	0.392	0.188
	Skin hydration	1	1.183	0.757
		20	0.968	0.503
	Glycerol	1	0.330	0.152
		20	0.138	0.063
	Hydraulic oil	1	0.337	0.185
		20	0.156	0.116
	Engineering grease	1	0.427	0.126
		20	0.072	0.032

Table 11.7 Means and standard deviations for μ_{mean} for two force levels, six environmental condtions and eight samples. Mean velocities 0-128 mm/s (n =13).

The results support the basic findings of Experiments 1 and 2. Namely, that when comparing the environmental impact on type of texture, coarse textures act in favour of higher friction under contaminated and "sweat'" conditions, whilst fine textures act in favour of higher friction under "normal" clean skin conditions (Table 11.8).

	Contamination and "sweat'"	"Normal" clean skin
Coarse	H	L
Fine	L	H

Where:

H = Combination act in favour of higher friction

L = Combination act in favour of lower friction

Table 11.8 The influence on friction from type of texture and environmental condition on friction

11.5.2 Non-contaminated skin conditions – all textures

Skin friction is affected by type of texture, skin condition, contaminants, normal force and velocity. Considering 20N normal force and mean velocity (0-128mm/s), the following results and relationships were found for the non-contaminant skin conditions.

Under "normal" clean skin condition, the μ_{mean} varied between 0.56 and 0.64, see (A) in Figure 11.2. μ_{mean} for the "sweat'" condition (B) is 0.68, which is close to that of "normal" clean skin. μ_{mean} for this "sweat" condition range 0.42 to 0.81, with coarse textures (No's. 202, 203, 204) providing more friction than fine textures (No's. 9004, 9006, 90509057 and 9078). Hydrated skin (C) gave a μ_{mean} of 0.83, which is considerably above the values for "normal" clean skin and "sweat". Depending on texture, the means for hydrated skin ranged from 0.70 and 1.05.

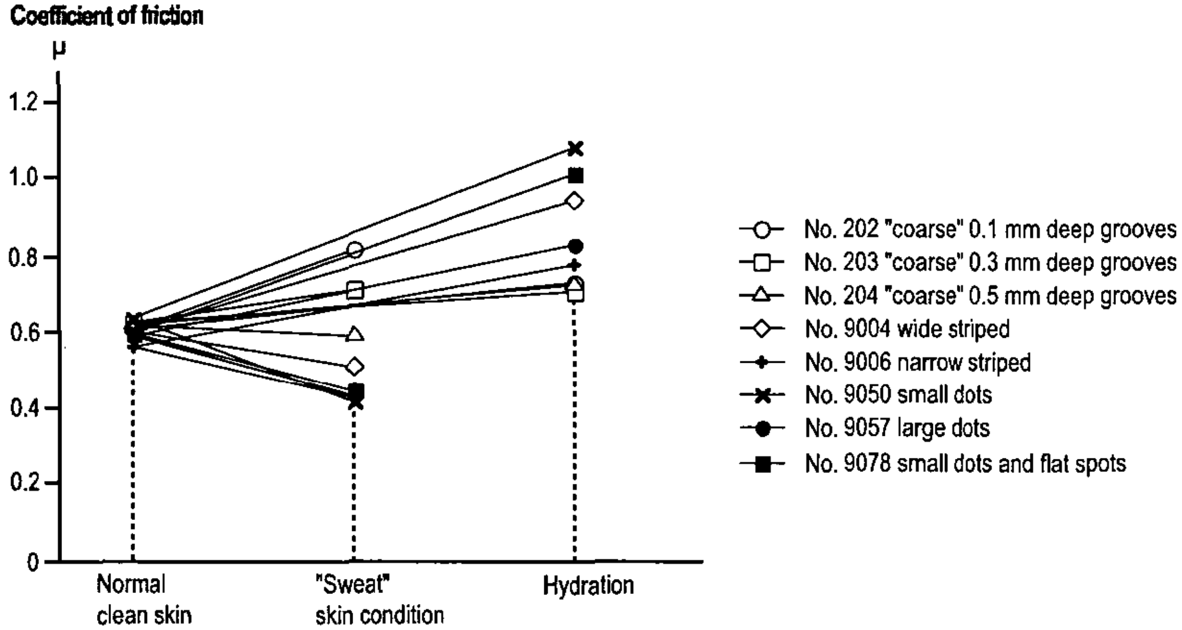


Figure 11.2 Coefficients of friction for eight textures under three non-contaminated skin conditions. Lines show the deviations from the normal clean condition. Mean of 20 N finger force. Mean velocity 0-128 mm/s.

11.5.3 Non-contaminated conditions - mass produced textures

Figure 11.2 shows that the highest friction was evident for hydrated skin on the fine mass-produced produced textures No. 9050 (small dots), No. 9078 (small dots and flat spots) and 9057 (large dots). The readings were observed for the same textures under "sweat" conditions, μ_{mean} =0.40.

11.5.4 Contaminated conditions - all textures

Under contaminated conditions, all mass-produced textures generated lower μ_{mean} than under non-contaminated skin conditions. Friction generated in partnership with coarse machine cut textures provided nearly the same friction under both conditions. Under contaminated conditions, the machine cut coarse textures (No. 202, 203, 204) generated the highest friction. Within the range of mass-produced textures, and contaminants used in this experiment, μ_{mean} at mean velocities 0-128mm/s and 20 N finger force varies from 0.062 (engineering grease, texture 9050 – fine dots) to 0.70 (hydraulic oil, texture 203 – coarse stripes), see Figure 11.3.

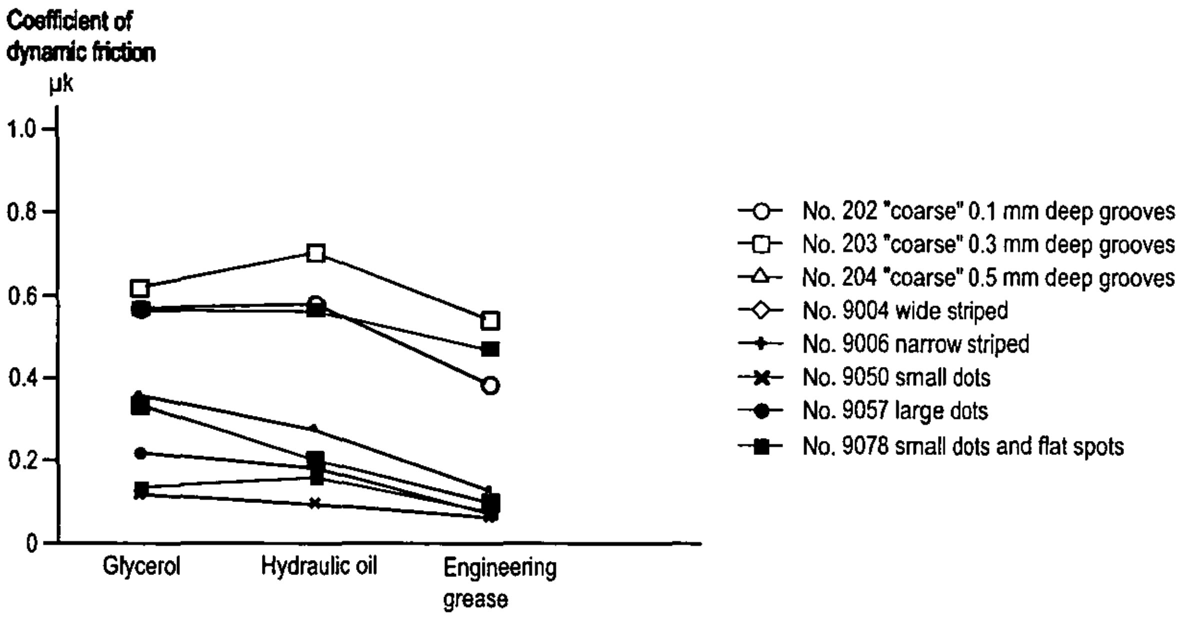


Figure 11.3 Mean coefficients of friction for coarse and fine textures under three contaminated conditions over the velocitiy spectrum 0-128 mm/s. Mean 70 kPa

11.5.5 Contaminated conditions - mass produced textures

Under contaminated conditions, see Figure 11.3, mass produced textures provided less friction than the coarse machine cut textures. Particularly the fine mass-produced textures (No. 9050, No. 9057, No. 9078) generated low friction under contaminated conditions. Major differences due to texture were, however, identified among the fine textures in this low range. Glycerol, with texture No. 9078, generated μ_{mean} of 0.138 but No. 9057 generated a μ_{mean} of 0.208, a reduction of 66.3%.

11.5.6 Daily differences in skin moisture and friction

For sixteen consecutive weekdays, a "normal" clean hand was subjected to skin moisture recordings and immediate friction measurements. The aim was to correlate coefficient of friction to palm moisture at the location of exposure (digit pulp on index finger on dominant hand). The friction partner was a non-textured sample (No.5). Moisture and friction data are presented in Table11.9. Palm skin moisture was recorded immediately prior to friction measurement. The velocity was recorded over 0-128 mm/s and split in velocity categories covering static friction μ_S (0-4mm/s) and dynamic friction μ_K (4-128 mm/s) and over the whole velocity range μ_{mean} (0-128 mm/s).

The study was limited to one subject. Over the16 days the skin moisture recordings varied in the range 40-70 g/m^2/h. The correlation (Pearson r) palm moisture *TEWL over these days was r = 0.40 ($p<0.05$). Skin friction μ_{mean} also varied (in the range 0.14-0.58) over the 16 days with μ_{mean}=0.45. μ_k varied in the range 0.12 - 0.32. Correlation with μ_{mean} over the 16 days was 0.45, while the correlation μ_s over the 16 days was 0.12. The covariation μ * TEWL was different if μ_s, μ_{mean} or μ_k was considered. The highest covariation was noticed for μs * TEWL, r=0.66, while the covariation for μ_{mean} TEWL was 0.28. See summary in Table 11.10.

Day	n.	TEWL pre exposure	μ mean 0-128 mm/s	μ_s 0- 4 mm/s
1	27	40	0.223	0.153
2	23	56	0.223	0.193
3	26	53	0.140	0.115
5	463	61	0.343	0.217
7	107	51	0.581	0.272
8	117	57	0.382	0.267
9	142	56	0.349	0.144
10	150	48	0.366	0.162
11	174	59	0.361	0.247
12	128	50	0.531	0.318
13	189	48	0.299	0.202
14	74	68	0.550	0.180
15	83	60	0.363	0.166
16	86	57	0.278	0.165

Table 11.9 Daily recordings of skin moisture TEWL, the related static friction μ_s and mean friction over the velocity range 0-128 mm/s on the same subject over 16 weekdays and identical "normal" skin conditions.

Correlation	Correlation Coefficient, r
TEWL *16 days	0.40
μ_s *16 days	0.12
μ_{mean} *16 days	0.45
μs * TEWL	0.66
μmean * TEWL	0.28

Table 11.10 Correlation's (Pearson r) between recordings of skin moisture (TEWL) μs and μmean over a period of 16 weekdays and Correlations (Pearson r) between skin moisture (TEWL), μ_s and μ_{mean} respectively. All correlations significant ($p< 0.05$).

11.5.7 Individual differences in skin moisture and friction

In Experiment 3, seven of the subjects in Experiment 3 performed additional friction exposure and skin moisture TEWL recordings while exposing the fingers on both hands and the thumb of the right (the equipment did not give room for the thumb on the left hand) to four materials with intrinsic coarse and fine textures. These were specifically selected from the group of 13 subjects in Experiment 3 on grounds that they, with reference to palm moisture, belong to either of two sub-groups, a low moist skin condition with a mean moisture value of 46.17 (5.37) $g/m^2/h$, and a high moist skin condition with a mean value of 109.48 (12.77) $g/m^2/h$. Their friction partners in this study were Sandpaper 320 grit, Leather, Thermoplastic elastomer (Alcryn) and Polycarbonate. Coefficient of friction was recorded as means over the velocity range 0-128 mm/s. Results are presented in Table 11.11. The correlation between friction data and skin moisture TEWL recordings are presented in Table 11.12. As far as skin moisture TEWL is concerned, these seven subjects were found to not belong to a homogenous group. When analysing these two sub-groups across the materials it was observed that the low moisture group had a negative correlation with μ, ($r = -0.32$) while the high moisture group had a positive correlation ($r = 0.21$), both significant ($p<0.05$).

	Coefficient of friction	
Material	**Mean μ**	**sd**
Polycarbonate	1.15	0.67
Leather	0.53	0.12
Alcryn	1.19	0.40
Sandpaper 320	0.97	0.21
All	0.95	0.49

Table 11.11 Coefficient of friction for palm skin in partnership with five coarse and fine textured materials.

	Skin moisture TEWL $g/m^2/h$			Coefficient of friction, μ		Correlation (Pearson r)
	Mean	**sd**	**Range**	**Mean**	**sd**	**μ * skin moisture**
High moist	109.48	12.77	82-128	1.26	0.69	0.21
Low moist	46.17	5.37	37-96	0.92	0.55	-0.32

Table 11.12 Means and standard deviations for recorded coefficient of friction and skin moisture TEWL for high and low moist population subgroups. Also the correlation skin moisture TEWL * recorded friction p< 0.05.

11.5.8 Influence of velocity in the friction interface

The changes in the coefficients of friction, as the velocity in the friction interface increases (from 0 to 128 mm/s), is presented as means over six intervals (3, 6, 12, 24, 48 and 96 mm/s) in tables and graphs with reference to different skin condition and contaminants and for fine and coarse textures (see Figures 11.4 to 11.9). Data is available in Appendix 1.

"Normal" clean skin

For "normal" clean skin the type of texture alone had little effect on friction over the investigated velocity range. The predominant trend was a continuous increase in the coefficient of friction over the increasing velocity span with some scatter. Peak recordings appear to be found at velocities > 96mm/s, (Figure 11.4).

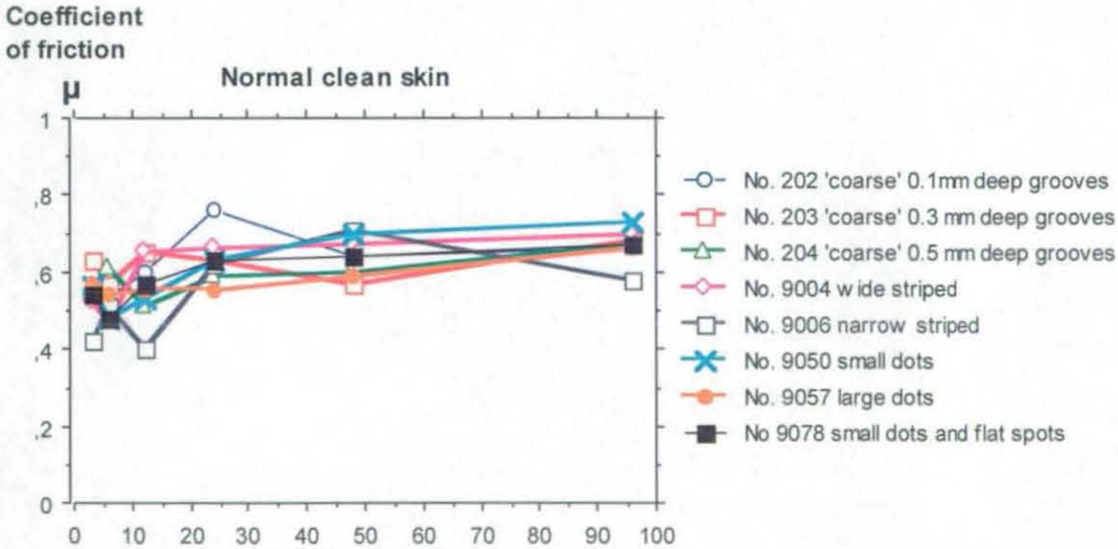


Figure 11.4 Coefficients of friction for coarse and fine textured samples in friction partnership with a "normal" clean hand

"Sweat"' skin conditions

For "sweat"' skin conditions the type of texture had a dominating effect on friction over the investigated velocity range. The predominant trend was a steep increase in coefficient of friction as the velocity increased in the range 0 to 24 mm/s (Figure 11.5). For some textures, peak recordings were observed at 48 mm/s while other peak recordings appear to be found at velocities > 96mm/s. "Sweat" on the friction interface appeared to reduce scatter but the coarse machine cut texture No. 202 showed some adverse data points for the lower of the velocities (see Figure 11.5).

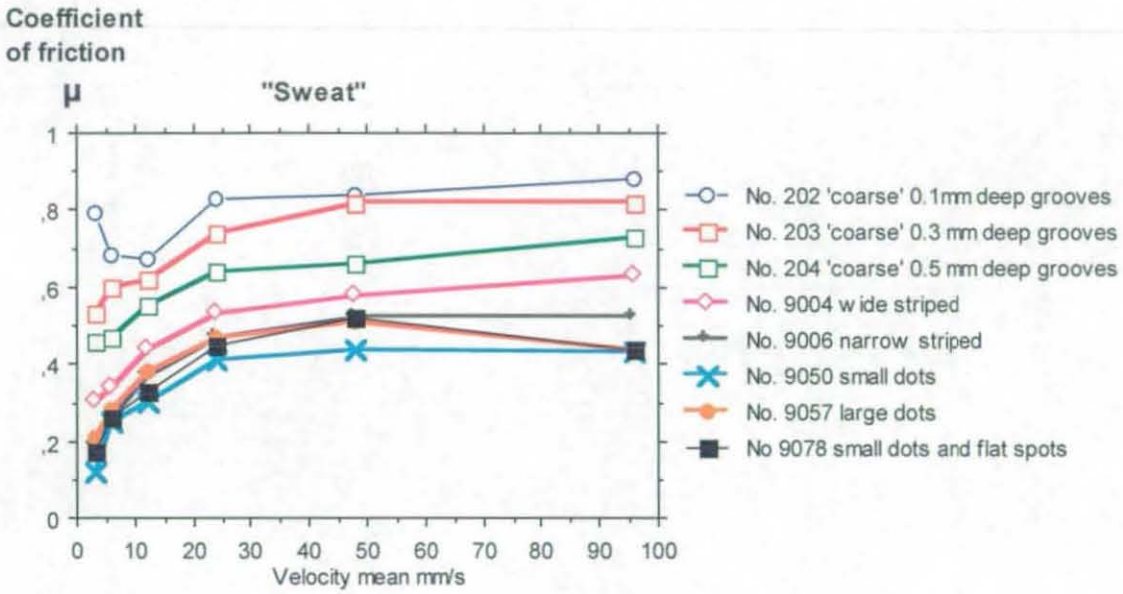


Figure 11.5 Coefficients of friction for all textures under "sweat" conditions and 70 kPa (20 N)

Hydrated skin

The hydrated hand showed strong velocity dependence in the range 0 –24 mm/s. Peaks are dominant at velocities 24 mm/s. At higher velocities the coefficient of friction is generally reduced or reached a steady value, see Table 11.5.

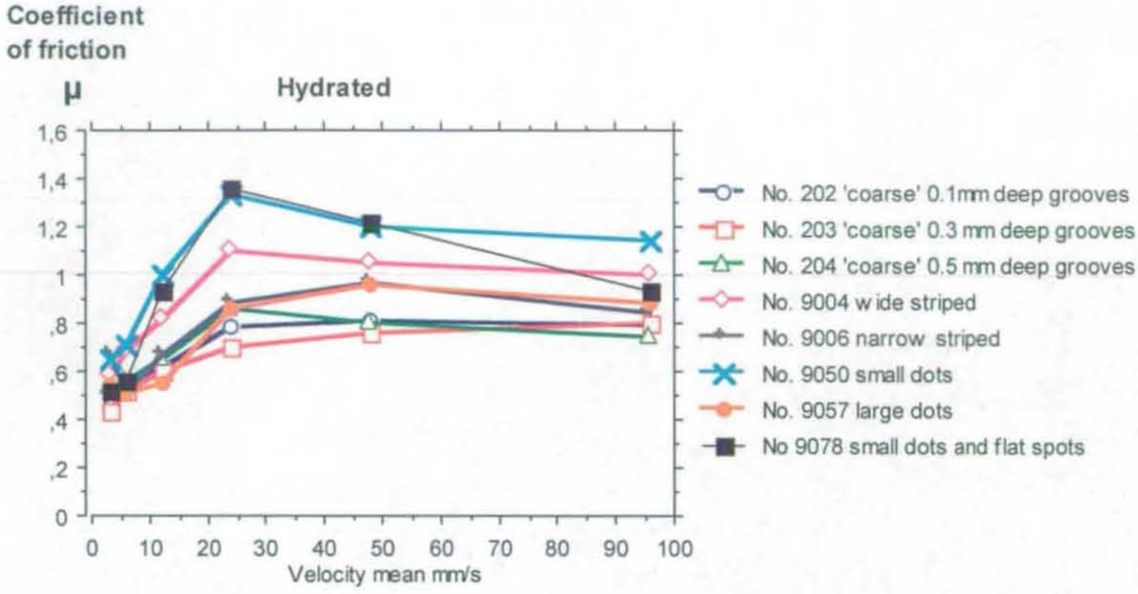


Figure 11.6 Coefficients of friction for all textures under hydrated conditions and 70 kPa

Glycerol

Glycerol on the friction interface generated characteristically different friction in coarse machine cut (No. 202-204) and mass-produced textures (No. 9004-9078). The former exceeded the latter by factors of 2 to 3. There was an increase in coefficient of friction until peak values were reached, generally at the velocity 24mm/s, after which slight reductions took place (Figure 11.7).

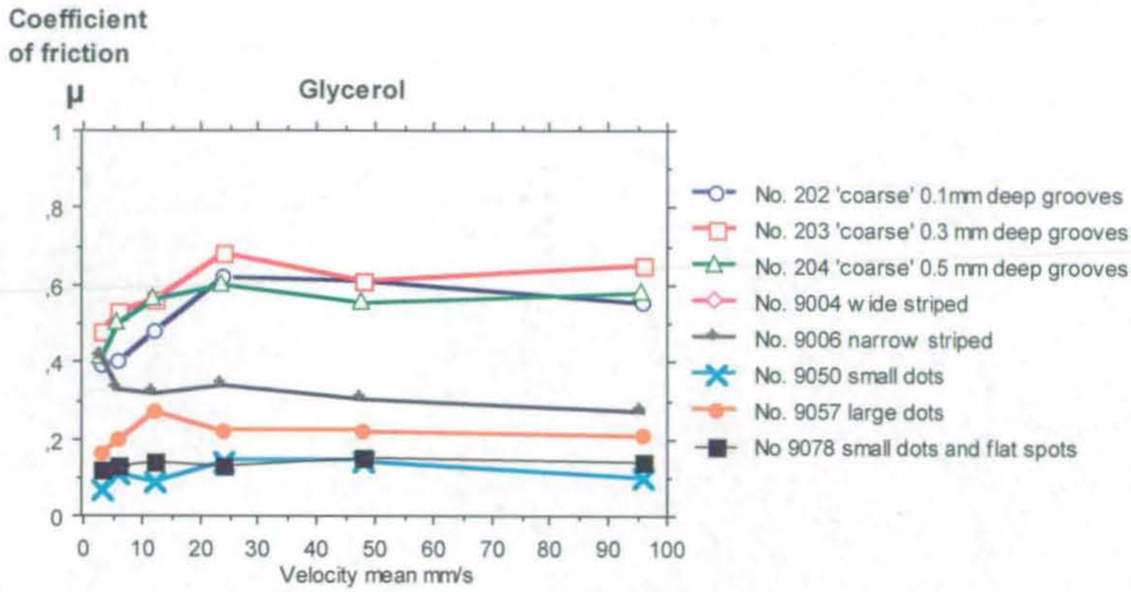


Figure 11.7 **Coefficients of friction for all textures with glycerol as a contaminant and 70 kPa**

Hydraulic oil

The velocity dependence with hydraulic oil present on the friction interface shows a similar pattern regardless of texture. A steady increase is followed by peaque at 25-50 mm/s, see Figure 11.8.

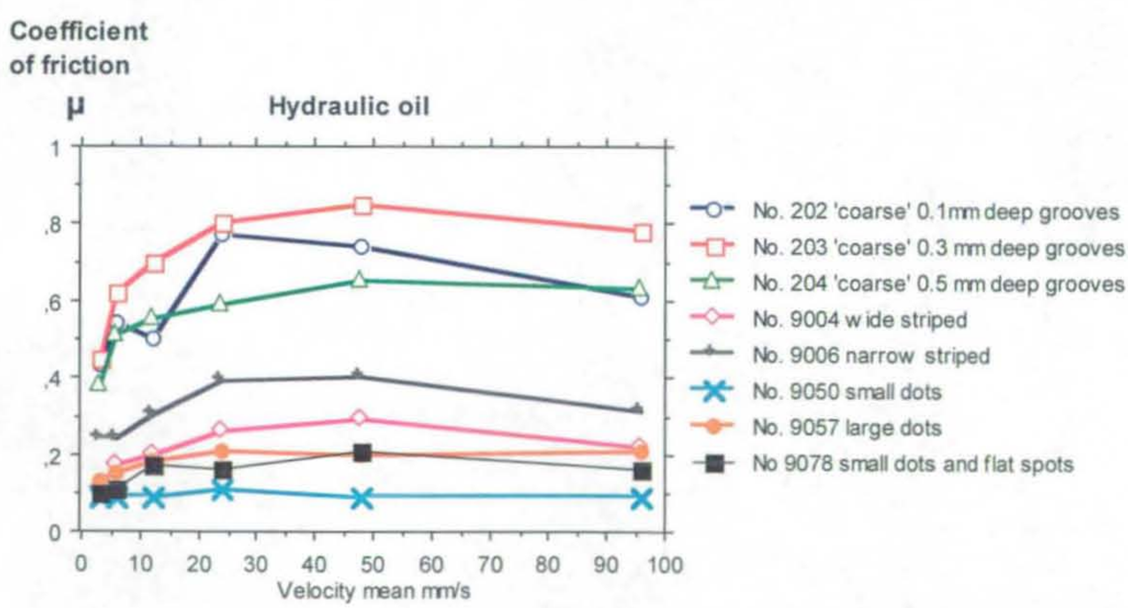


Figure 11.8 **Coefficients of friction for all textures with hydraulic oil as a contaminant and 70 kPa**

Engineering grease

Engineering grease behaved similarly to glycerol on the friction interface. The coefficient of friction was generally lower and the differences between coarse and fine textures were larger (Figure 11.9). That friction increased slightly with velocity over the investigated range.

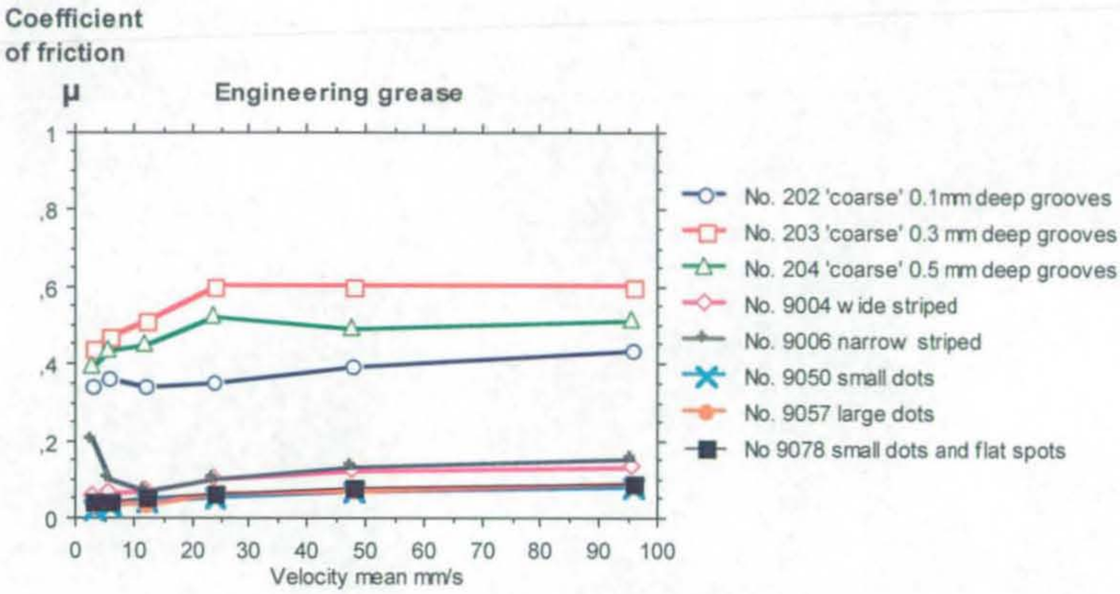


Figure 11.9 Coefficients of friction for all textures with engineering grease as a contaminant and 70 kPa

11.5.9 Static and dynamic friction

The friction due to velocity in the interface between palm and hand held objects will be relevant because in the use of tools, dynamic friction is frequently encountered. The changes in coefficient of friction as velocity increases were calculated over the velocities of 3 to 24mm/s and grouped in six categories as specified in Section 9.3.6. All friction/velocity gradients have positive sign, "sweat'" and hydrated skin present the highest gradients, 0.0257 and 0.0210 units of μ per mm/s respectively. The gradient for "normal" clean skin is considerably lower (0.0044). The friction – velocity gradient was based on empiric data in Table 1 in Appendix 1. Table 11.13 shows means, standard deviations and range based on that data with respect to skin conditions and contaminants.

The empirical data presented in Table 1 of Appendix 1 were also used to calculate significant differences between coefficients of friction recorded at velocities ranging 3 to 32 mm/s. See Table 11.14. When significant differences are observed, dynamic friction was higher than static friction, ($p < 0.001$ - 0.02). With coarse machine cut textures significant differences are frequently observed, but with the fine mass produced textures significances are only seen in partnership with the "sweat" hand condition. For the "normal" clean condition wery few significant differences could be calculated mainly due to large variances.

	Gradients Units of μ per mm/s		Range	
	Mean	sd	Minimum	Maximum
Skin condition				
"Normal" clean skin	0.0044	0.0039	0.00047	0.01095
"Sweat"	0.0257	0.0089	0.01204	0.036
Hydrated	0.021	0.01057	0.01	0.04
Contaminants				
Glycerol	0.0048	0.00433	0.00047	0.01095
Hydraulic oil	0.0081	0.00819	0.0019	0.02809
Engineering grease	0.0023	0.00266	0.00095	0.00762

Table 11.13. Increase in coefficient of dynamic friction (fricton-velocity gradient) per of 1 mm/s over the velocity range 3 to 24 mm/s for non-contaminated and contaminated conditions. Means of all textured samples in Experiment 3.

Skin conditions / Contaminants	Velocity mean mm/s	Machine cut textures						Mass produced textures									
		Coarse textures								Fine textures							
		No. 202		No. 203		No. 204		No. 9004		No. 9006		No. 9050		No. 9057		No. 9078	
"Normal" clean skin μ_s	3	0.53	**P<0.05**	0.63	ns	0.56	ns	0.52	ns	0.42	ns	0.56	ns	0.57	ns	0.54	ns
"Normal" clean skin μ_k	24	0.76		0.63		0.59		0.66		0.62		0.63		0.55		0.63	
"Sweat" μ_s	3	0.79	ns	0.53	ns	0.46	**P<0.05**	0.3	**P<0.02**	0.19	**P<0.01**	0.12	**P<0.02**	0.21	**P<0.02**	0.17	**P<0.02**
"Sweat" μ_k	24	0.83		0.74		0.64		0.53		0.47		0.41		0.47		0.45	
Hydrated μ_s	3	0.45	**P<0.01**	0.43	**P<0.02**	0.53	**P<0.01**	0.58	**P<0.02**	0.67	ns	0.65	ns	0.54	ns	0.52	**P<0.001**
Hydrated μ_k	24	0.78		0.7		0.86		1.1		0.88		1.33		0.86		1.36	
Glycerol μ_s	3	0.39	**P<0.02**	0.48	**P<0.05**	0.41	**P<0.02**	0	ns	0.41	ns	0.07	ns	0.16	ns	0.12	ns
Glycerol μ_k	24	0.62		0.68		0.6		0		0.34		0.14		0.22		0.13	
Hydraulic oil μ_s	3	0.43	**P<0.02**	0.45	**P<0.05**	0.38	**P<0.05**	0.11	ns	0.24	**P<0.02**	0.09	ns	0.13	ns	0.10	ns
Hydraulic oil μ_k	24	0.77		0.8		0.59		0.26		0.39		0.11		0.21		0.16	
Engineering grease μ_s	3	0.34	ns	0.44	**P<0.05**	0.39	ns	0.05	**P<0.02**	0.2	ns	0.02	ns	0.03	ns	0.04	ns
Engineering grease μ_k	24	0.35		0.6		0.52		0.1		0.1		0.05		0.06		0.06	

Table 11.14 Recorded coefficient of static and dynamic friction at 3 mm/s (μ_s) and 24 mm/s (μ_k) respectively. (p-values, otherwise ns). (n = 13)

11.5.10 Regression analysis

The linear regression model enables an estimation of the relative contribution of the independent variables to the dependent variables over the velocity range 0-12mm/s. The regression model in Experiment 3 is as follows:

Main effect:

$Yi = B_0 + B_1 * X_1$ (surface pressure) $+ B_2 * X_2$ (velocity) $+ B_{3\text{-}6} * X_{3\text{-}6}$ (surface topographies) $+ B_{7\text{-}12} * X_{7\text{-}12}$ (contaminants and skin conditions) + E

and the additional three interactions

- $B_{13\text{-}17}$*contaminations * X_2(velocity) + $B_{18\text{-}22}$*Contaminations * X_5 (surface topography T5)+ $B_{23\text{-}27}$ contaminations * X_6 (surface topography H5)+ E

- Where: Y_i = dependent variables μ_s, μ_k
- X_1 to X_{12} = original variables (Table 3 in Appendix 3)
- B_0 = intercept
- B_1 to B_6 , and one of B_7 to B_{12} = regression coefficients for main effects (Table 1 in Appendix 3)
- B_{13} to B_{27} = regression coefficients for interactions (Table 2 in Appendix 3)
- E = error term

Regression coefficients (Bi) and data (Xi) describing the original variables but also regression coefficients for the interactions are presented in Appendix 3.

The regression model demonstrates the following:

47% of the variance is explained by the regression model

20 % of the variance is due to individual factors

33% of the variance is due to error

The model is valid for:

- eight textured surfaces used in this experiment
- three contaminants
- three skin conditions
- surface pressures 7 to 70 kPa
- velocities of 0 to 12 mm/s
- surface topography variables Del.q, Sm, T5, and H5

The model identifies three interactions namely;

- contamination * velocity,
- contamination * T5
- contamination * H5.

11.5.11 Surface topographies

The characteristics of surface topographies in tribology are specified in the international standard ISO 4288: 1996 "Geometric Product Specification (GPS) - Surface texture: profile method - rules and procedures for the assessment of surface texture". The standard basically present how a well described stylus is traced a defined distance (the assessment length), frequently 5.6 mm, over different locations on the surface, normally 20 times. The recorded profile data is used in various specified algorithms (presented in figures A1-A5 below) to generate a range of topographic representations for different tribology purposes e.g. friction, lubrication and wear. The textures used in the present series of research were recorded with the instrument Talysurf Mk 1, and analysed according to Taylor and Hobson. The topographic representations for each of the eight coarse and fine textures investigated in Experiment 3 are presented in Appendix 2.

Five standard topographic representations were suggested by scientists[6] as suitable to include in investigations of friction generated when textured samples are in friction partnership with palm skin. These were:

Ra, the universally recognised, and most used international parameter of surface roughness. It is the arithmetic mean of the departures of the roughness profile from the mean line.

Rp, the maximum height of the profile above the mean line within the assessment length.

S, the spacing of adjacent peaks.

Sm, the mean spacing between profile peaks at the mean line.

Del.q. the rms slope of the profile.

Coefficients (Bi) for four surface topography variables (Del.q, Sm, H5, and T5) related to the eight textures used in Experiment 3 are presented in Appendix 3 (Table 11.18). The standard surface topography variables Del.q and Sm had a considerably smaller impact on μ than the unique variables T5 and H5 (which were newly identified in this experiment). They contribute to μ both in the main effect and in the interactions. H5 increases μ, and so does T5 under "normal" clean conditions. The extent to which this occurs is presented in Figure 1 in in Appendix 3 and is illustrated in Figure 11.10..

[2] Thorvald Eriksson, Sören Andersson KTH Stockholm

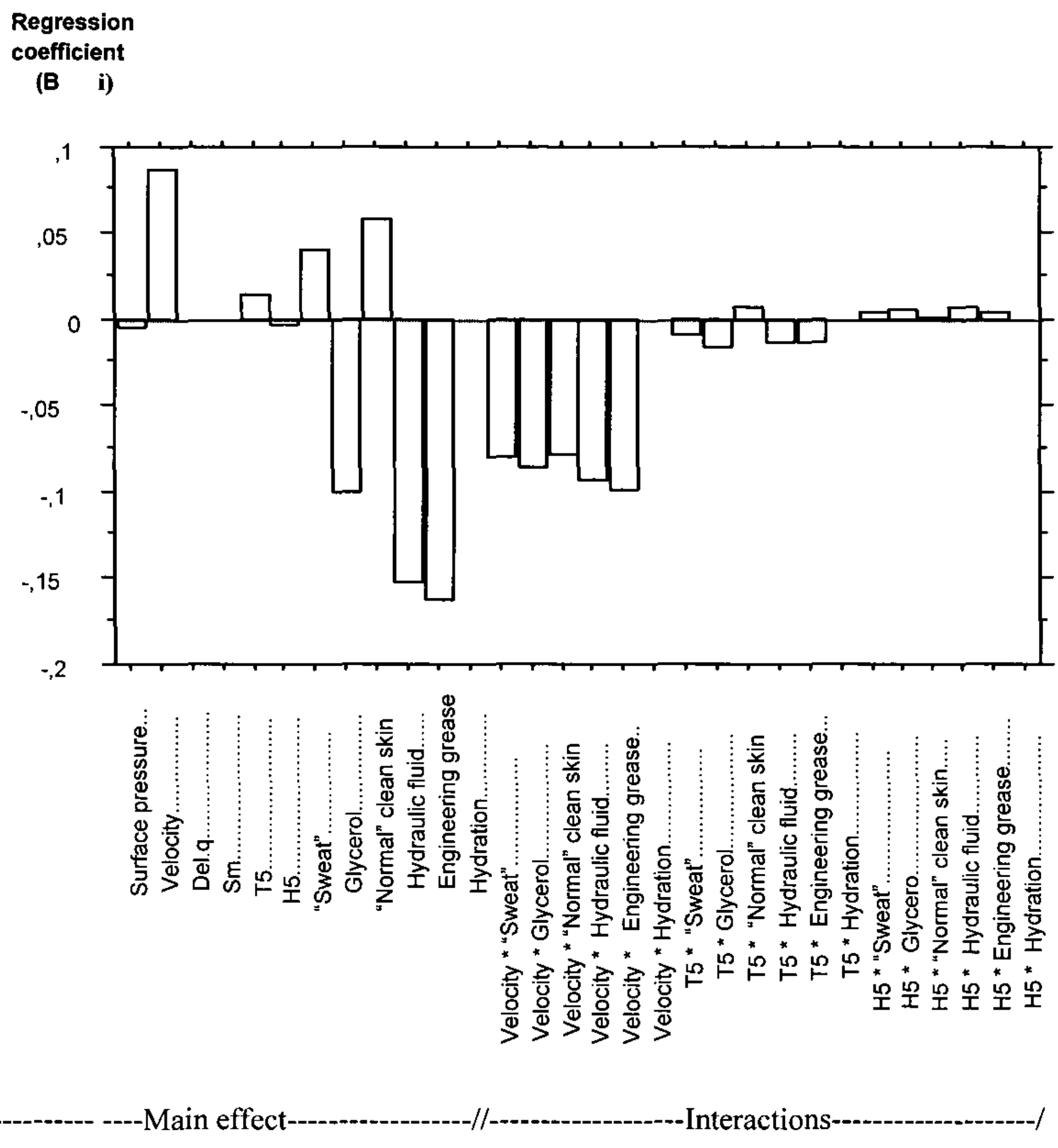


Figure 11.10 **Illustration of the coefficients in the regression model. Three skin conditions, three contaminants surface pressure, velocity and surface topographies (Del.q, Sm, T5, H5). Reference level (0) is the hydrated condition. Data from Tables 4 and 5 in Appendix 3.**

11.6 Discussion

Introduction

The findings in Experiment 3 present a series of new details on palm friction useful in the design and choice of safe and comfortable hand tools and hand held objects. From the studies involving hands in different skin conditions and exposed to contaminants it is evident that the dedicated choice of texture design is essential for safe and comfortable handling. A dilemma is, however, obvious and supported by the basic findings of Experiments 1 and 2. Namely, that when comparing the environmental impact on type of texture, coarse textures act in favour of higher friction under contaminated as well as under "sweat"" conditions, whilst fine textures act in favour of higher friction under "normal" clean skin conditions. The controversy is that for lower friction the situation is vice versa. These findings are illustrated in Table 11.15, earlier presented in Section 11.5.2.

	Contamination and "sweat""	"Normal" clean skin
Coarse	H	L
Fine	L	H

Where:

H = Combination act in favour of higher friction

L = Combination act in favour of lower friction

Table 11.15 The influence on friction from type of texture and environmental condition on friction

These results are supported by the regression model according to which three interactions need to be considered in estimating coefficient of friction, all involving contaminants and skin conditions with their respective regression coefficient. The interactions are

- contaminants / skin conditions * velocity
- contaminants / skin conditions * surface topography element T5
- contaminants / skin conditions * surface topography element H5

The complete model explains 67% of the variance.

There are "least common denominator" solutions to this controversy, such as textures which are fairly coarse but which provide a substantial skin contact, e.g. texture No. 9004 examined in Experiment 3.

The benefits of dedicating the texture design to the environmental conditions, the task (forces, velocities) user (size of hands) are several. Such choice would provide the operator with high friction without large forces for prehension, which is a means to reduce one of the risk factors for musculoskeletal injuries (Armstrong and Chaffin, 1979a). It could also result in lower shear forces which reduce the generation of calluses and skin oedema (Klingman et al 1985). Lower normal forces would reduce pressure points and smaller grooves would reduce the discomfort. Such choices can be made by using the empirical data available in Tables 9.5, 10.5, 11.7 in Chapters 9, 10 and 11 respectively, and Tables 1, 2 and 4 in Appendix 1 for estimated data, but also by applying the more detailed regression model available in Appendix 3.

In Experiment 3 two types of textures were investigated, mass-produced and purpose made machine cut textures. The mass-produced textures were made in an established way by which toolings are photo etched and products injection moulded. This technique is frequently used to generate textures and products of polymer material. The mass produced textures were selected by industrial designers to represent a span of textures likely to be applied in the design of handles and other hand held equipment. The machine cut had variations in groove depth. They were selected on grounds that they generated high friction under contaminated conditions in Experiments 1 and 2 but the focus was here on groove depth

The surface topography of the textures were specifically analysed by experts in tribology using standardised methods and instruments. Multiple regression analysis in which these data were used revealed surface details of significant importance to the generation of friction in partnership with palm skin. The model explains the coefficient of friction by 12 regression coefficients with a main effect and three interactions.

Three non-contaminated conditions ("normal" clean, "sweat", hydrated skin) and three contaminated environmental conditions (glycerol, hydraulic oil and engineering grease on were examined at velocities from 0 to 128 mm/s. These results add information to the findings in Experiment 1 and 2 that $\mu_S<\mu_K$ with details on how friction changes over the entire velocity span. Gradients of the changes in friction per velocity increments are presented.

The influence of skin moisture on coefficient of friction was addressed in two studies.

Coarse and fine textures

Type of texture

Coarse textures such as No. 202-204 are a safe choice if high friction is requested. The coefficient of friction is high and contaminated conditions only provide 21.1% less friction than the non-contaminated conditions. This is a unique feature that was not observed for any of the other examined textures, where it was found that contaminants reduce friction in the range 57.7-81.2 % of the respective non-contaminated condition. These coarse textures are however uncomfortable under both contaminated and non-contaminated conditions as shown in Experiment 1 and 2 in this thesis.

The coarse mass-produced texture No.9004 provides high friction under non-contaminated conditions but at contaminated conditions the topographies do not provide enough deformation to the skin to provide friction at the levels found in textures No. 202-204. Still this texture provided the highest coefficient of friction of the mass produced samples under contaminated conditions (Figure 11.11).

Another of the coarse mass-produced textures, No.9078, is designed with a mixture of randomly scattered patches of small dots and flat spots and will provide both very high and very low friction depending on the environmental conditions. This may be useful in some applications but the dramatic drop in friction from 0.652 to 0.122 i.e. a drop of 81.3% may be a risk factor in such applications where oil and grease may appear and surprise the user (Figure 11.11). In such environments a safer choice could be the finely striped mass-produced texture No.9006 for which friction under not contaminated conditions is lower, 0.584 but the reduction is less, 57.5%.

Texture No 9050 has very small evenly distributed dots that provide a large contact area with skin, but too small to contribute substantially to friction under contaminated conditions. Texture No.9057 has coarser dots than No. 9050, which result in higher friction under contaminated conditions (Figure 11.11).

Figure 11.11 illustrates mean coefficient of friction for all textures under contaminated and non contaminated conditions in Experiment 3. Means and standard deviations are specified in Table 11.7 on page 228, and summarized in Table 11.16 below. The low levels of friction for the contaminated conditions, ranging from 0.087 to 0.248, are naturally a consequence of the well-known lubricants glycerol, hydraulic oil and engineering grease on the friction interface. Still major differences are observed among the samples some of which can provide safety and ability to the user if well selected in design applications. The lowest friction observed was for texture No. 9050 (49.2% of the highest, texture No.9006).

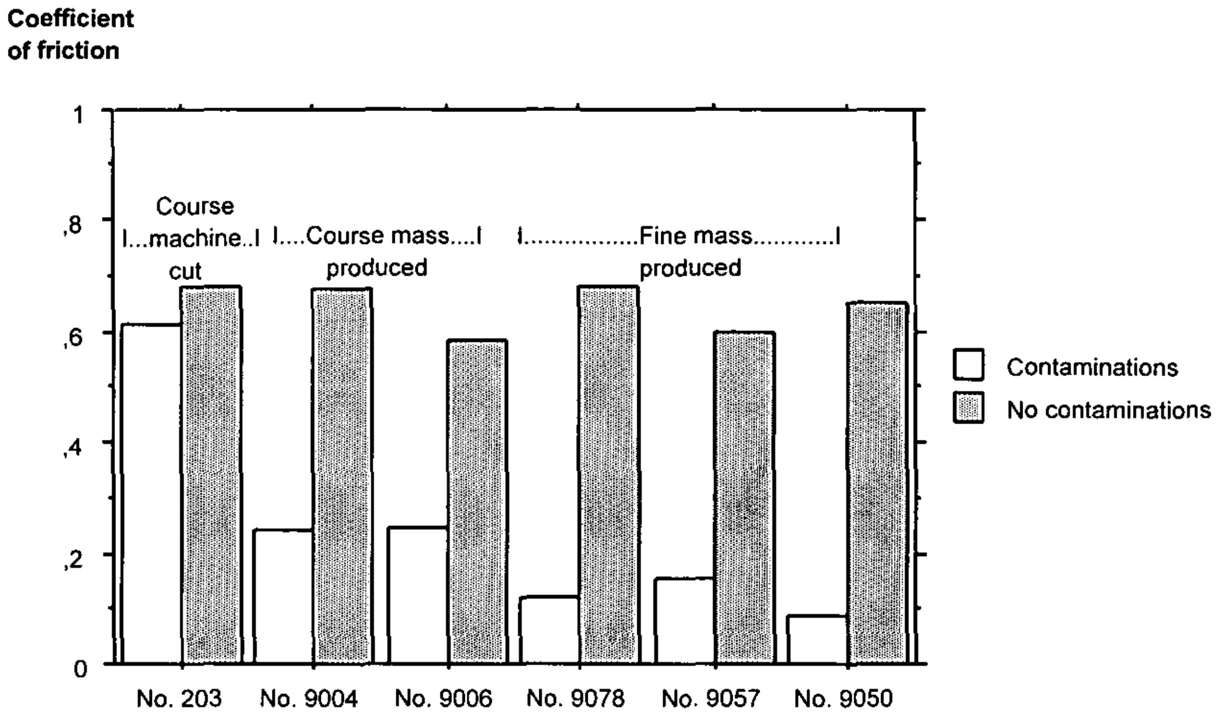


Figure 11.11 **Illustrates the coefficient of friction for μ under contaminated and non contaminated conditions for six examined textures under 20 N palm pressures over the velocity range 0-128 mm/s in Experiment 3. The textures are presented in rank order of contaminated conditions.**

	Coarse mass produced textures Mean and SD at 20N,				
Textures	**No. 9004**	**No. 9006**	**No. 9057**	**No. 9078**	**No. 9050**
Contaminated conditions	0.243 (0.109)	0.248 (0.130)	0.153 (0.075)	0.122 (0.070)	0.087 (0.043)
Non-contaminated conditions	0.674 (0.274)	0.584 (0.259)	0.599 (0.224)	0.652 (0.310)	0.683 (0.320)

Table 11.16 **Contaminated and non-contaminated conditions conditions. Means and standard deviations for μ for 20N finger force.**

Effect of skin condition and contaminants.

It appears that the non-contaminated human palm friction is fairly unaffected by the type of texture (whether machine cut or mass produced, see Figure 11.11). The mean coefficient of friction for these conditions was 0.658 with a coefficient of variation of 0.073. No differences were statistically significant. The coarsest of these textures are however known from Experiment 1 and 2 to be uncomfortable.

Contamination in the friction interface (glycerol, hydraulic oil and engineering grease) generated less friction (Figure 11.11). The differences in friction between machine cut and the mass produced texture was however considerable. At the normal force of 20 N the coarse machine cut texture No.203 generated the highest friction, $\mu = 0.612$, followed by the coarse mass produced textures, $\mu_{mean} = 0.223$, and fine mass produced textures, $\mu_{mean} = 0.121$.

Considerable environmental dependence may be a risk factor in such applications when the contaminated conditions may change suddenly. In such situations the user may be taken unaware and major changes in the required gripping forces is required to regain a safe control of a tool or other hand held object. For coarse machine cut textures friction under contaminated conditions was 21.1% less. For the coarse mass-produced textures friction was 57.7% less and for the fine mass-produced textures friction was 81.2% less than friction generated under not contaminated conditions. Mean coefficient of friction and standard deviations for each of the coarse and fine textures in Experiment 3 are presented in Table 11.7 in section 11.5.1

The importance of carefully selecting textures to fit the environmental conditions (i.e. non-contaminated, contaminated or a mixed condition) is clear when looking at the mean differences in groups of coarse and fine textures described in Table 11.17. Under contaminated conditions, fine mass produced textures generate only 18.8% of the friction under non- contaminated conditions. In real terms of μ this is 0.645 (SD=0.285) and 0.121 (SD=0.063) respectively. Major differences between individual textures are also seen when looking at the individual samples in Figures 11.10-11.12.

	Non-contaminated conditions µmean	Contaminated conditions µmean	Contaminated conditions as fraction of µ at non-contaminated conditions	
			%	p-value
All textures at 20 Newton	0.645 (0.253)	0.303 (0.127)	47%	$p < 0.01$
All machine cut textures No. 202, 203, 204. at 20 Newton	0.681 (0.211)	0.537 (0.197)	78.9%	$p < 0.05$
All coarse mass produced textures No. 9004, 9006. at 20 Newton	0.629 (0.267)	0.266 (0.118)	42.3%	$p < 0.01$
All fine mass produced textures No. 9057, 9078. at 20 Newton	0.645 (0.285)	0.121 (0.063)	18.8%	$p < 0.001$
All textures, contaminations and skin conditions at 1 Newton	0.666 (0.309)			
All textures, contaminations and skin conditions at 20 Newton	0.479 (0.190)			

Table 11.17 Means and standard deviations for the different type of coarse and fine textures in Experiment 3 under non-contaminated and contaminated skin conditions together with mean friction for all textures, contamination's and skin conditions at 20N finger force. p-values (n = 14)

The ratio between friction values for the coarse and fine textures (columns to rows) are shown in Table 11.18. The *italic* figures relate to contaminated conditions. The figures in the last column show the ratio between "normal" clean skin conditions and contaminated conditions (for textures presented in column 1 and 2). All figures refer to 20N, finger force.

It can be observed from these findings that, under contaminated conditions, the coarse mass produced textures generate 219.8 % more friction than the fine mass-produced textures.

The last column shows that under "normal" clean skin conditions all textures generate more friction than under the contaminated conditions. The difference is 533%, for the fine mass-produced textures, 236.5% for the <u>coarse</u> mass-produced textures and 126.8% for the coarse machine cut textures.

Thus eliminating or adding contamination on the friction interface will have the most dominant effect on friction, as changes in the range 1.3 to 5.3 can be expected depending on differences in texture characteristics such as those investigated in Experiment 3.

		Contaminated conditions			Ratio "normal" clean skin conditions to contaminated conditions
		Coarse	Coarse	Fine	
		All machine cut textures 20N	All coarse mass produced textures 20N	All fine mass produced textures 20N	
Coarse	All machine cut textures 20N	-	*0.495*	*0.225*	1.268
Coarse	All coarse mass produced textures 20N	*2.019*	-	*0.459*	2.365
Fine	All fine mass produced textures 20N	*4.438*	*2.198*	-	5.330

Table 11.18 The ratio of friction values for different type of textures. Under contaminated conditions (first five columns) and ratio between 'normal' clean skin and contaminated conditions for different textures, last column. Data refer to 20N finger force.

Coarse textures

Details from friction results are illustrated by the coarse purposely made machine cut texture No.204 and the mass produced coarse texture No.9004, in Figures 11.12 and 11.13. For texture No.204 the influence on friction from the investigated contaminants and skin conditions were small and not significant. Hydrated skin provided the highest and engineering grease the lowest friction. For texture No. 9004 the difference was due to contaminants and skin conditions was more pronounced

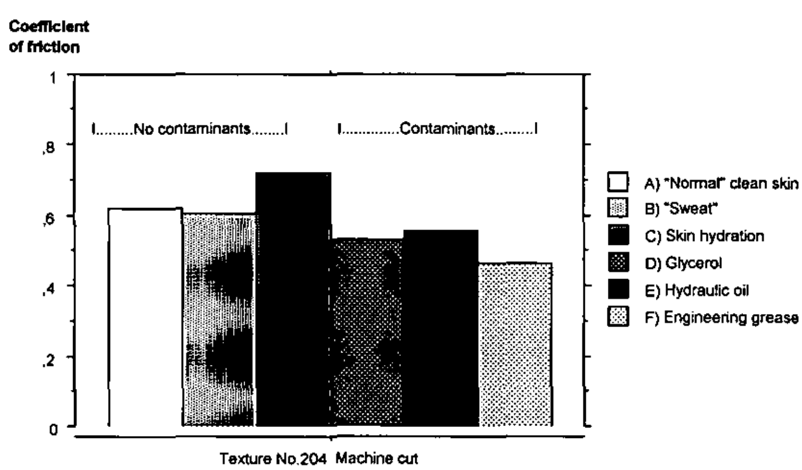


Figure 11.12 The coarse machine cut texture No.204 in friction partnership with three skin conditions and three contaminants referring to 20 N normal force (70kPa)

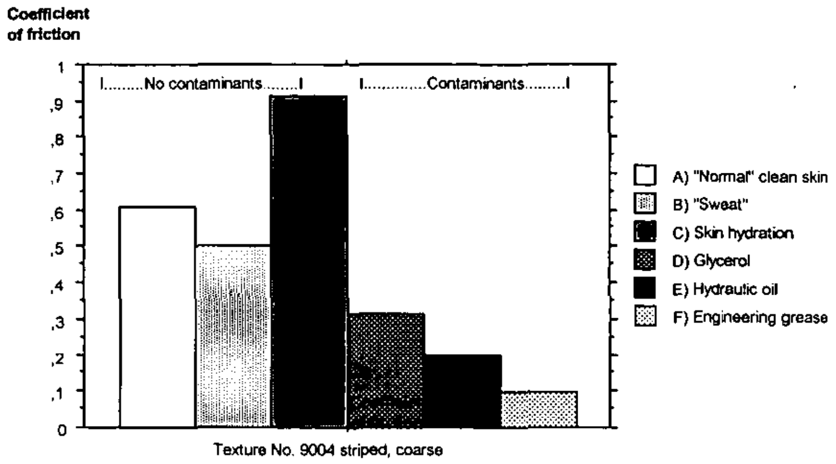


Figure 11.13 The coarse mass produced texture No.9004 in friction partnership with palm skin under contaminated and non-contaminated conditions

Fine mass produced textures

Friction results related to the fine mass produced texture No.9004, are presented in Figure 11.14. Hydrated skin provided the highest and engineering grease the lowest friction. The differences due to the examined textures are large and the difference due to contaminants and skin conditions was the largest of the three categories of coarse and fine textures.

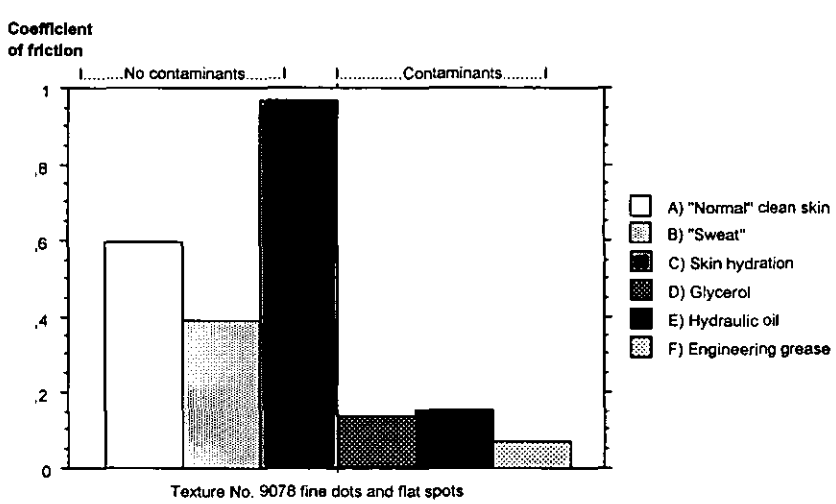


Figure 11.14 The finest of the mass produced textures in Experiment 3, No. 9078, in friction partnership with palm skin under contaminated and non-contaminated conditions at 20 N normal force (70kPa).

Influence of load

Experiment 3 confirms the findings in Experiments 1 and 2 that palm skin in friction is pressure dependent. The correlation was negative. Considering all textures, all contaminations and skin condotions, μ at 20N is 71.9 % of that at 1N. For contaminated conditions separately the difference is 70,1% while for the non-contaminated conditions the difference is 74.5%. Figure 11.15 show the coefficients of friction for coarse and fine mass produced textures and all contamination's and skin conditions under low and high load, 1N and 20N respectively.

For the coarse machine cut textures No.202-204 the effect of load was considerably smaller than for the mass-produced. There may be two reasons for this. Firstly a considerably higher level of surface pressure was generated from the few and narrow ridges on the coarse machine cut textures, the duty cycle of 25%, will increase from 22.4kPa (at 1N) and 288.5 kPa (at 20N) respectively. In this higher range the effect of load may be smaller as is the case for elastomers according to Suh (1986).

Secondly, the friction generating deformation component μ_d, which according Suh *ibid* has a dominant role in providing friction forces, may be given more room to operate in the larger space provided by the wider grooves on the coarse machine cut textures, i.e. an effect of the wider grooves. Further investigations would be required to determine the relative importance of these two factors.

Thus providing for low surface pressure between palm skin and objects will act in favour of a high coefficient of friction. Consequently in situations where_lower friction is requested a smaller contact area may be one design option. Such textures tend however be more uncomfortable than textures with larger duty cycle.

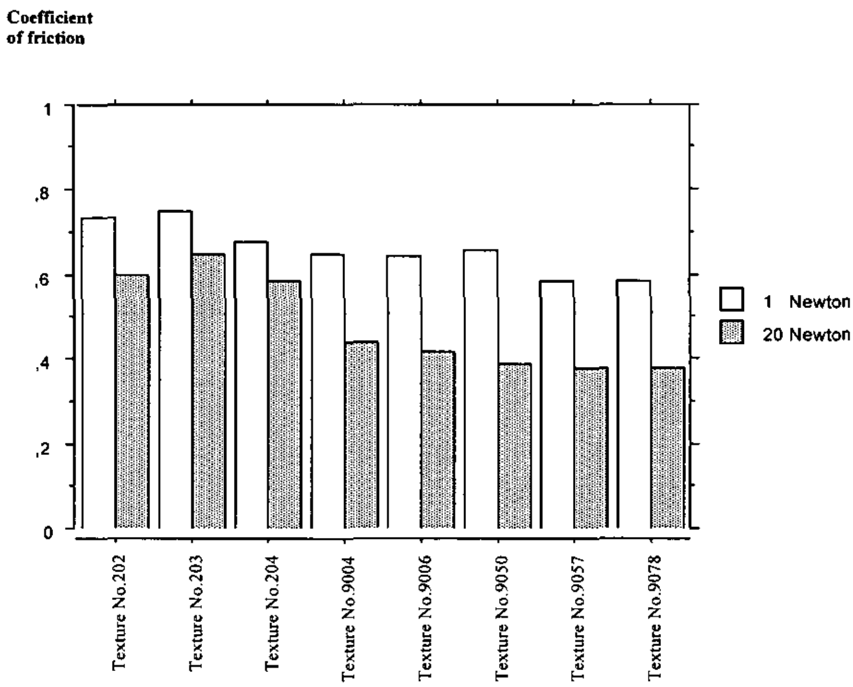


Figure 11.15 Mean coefficients of friction means for all textures, contamination's and skin conditions under low and high load (1 and 20N respectively).

Influence of velocity

Experiment 3 reveals previously not published details of the velocity dependence in skin friction under several skin and environmental conditions. It appears that all tested textures, under all contaminations, show a characteristic increase of the coefficient of friction with increased velocity in the skin-texture contact. Friction rises steadily from when there was static friction to when the velocity was approximately 12 mm/sec. Some characteristic differences in this pattern are however seen. For the "normal" and the "sweat" hand the friction is still increasing within the velocity range 12 to 48 mm/sec. When oil, grease and hydraulic fluid are present on the friction interface, the peak friction values is still at 12 mm/sec., but slight reduction in the velocity range 12 - 48 mm/sec is seen. This pattern is clearly seen in Figures 11.4-11.9 in section 11.5.8.

Friction-velocity gradient

According to the classic "law of friction" dynamic friction will be less than static friction. For many materials this still is true although the difference usually is small (Bowden and Tabor 1976). For viscoelastic materials, like glabrous skin, however this need not necessarily be the case (Suh 1986). This concept seems however not to have been recognised in most of the studies of palm friction according to the literature survey of this thesis references and details of which are available in Appendix 1. In most such studies a static skin exposure is changed to a dynamic, thus introducing a velocity in the friction interface that rarely is controlled for. Buchholz et al (1988) however observed that subjects reduced their pinch grip as a dynamic situation developed and calculated the coefficient of friction based on these lower Normal forces. Also Bullinger et al (1979), who investigated friction under "normal" clean palm conditions, published data showing a successive increase in friction during the change from static to dynamic conditions.

In Experiment 3 there was consequently a positive gradient between coefficient of friction and velocity in the friction interface in the range 0-12 mm/s. The gradients and the range they cover are presented in Table 11.13 in Section 11.5 9. A considerable difference in this gradient was observed between the not contaminated and the contaminated conditions, with gradient means from 0.0030 to 0.0257 units of μ per mm/s respectively.

Influence of skin moisture, hydration and friction

Two studies under Experiment 3 were dedicated to the influence of skin moisture on friction. The first investigation concerned the relationship between μ and TEWL for one subject over a period of 16 successive weekdays. In the other study seven subjects who in earlier experiments were observed to produce low and high palm moisture TEWL were engaged in dynamic friction contact with differently textured materials.

From the first study it was found that variations of skin moisture over the period were considerable, ranging 40-70 $g/m^2/h$. The variation of μ was also large, ranging 0.14-0.58. The coefficient of friction could be related to several velocity spectra, and it was possible to identify correlations at different velocity groups. The best correlation between skin moisture and coefficient of friction referred to static friction, $r = 0.66$, while the correlation with mean velocity (over 0-128 mm/s) was considerably lower, $r = 0.28$, both significant ($p<0.05$).

It is not clear why skin moisture TEWL better express static than dynamic friction. The present results were based on data collected over 16 successive weekdays, but on one subject only. His daily routines, prior to these recordings, which took place between 9 and 10 am, were intended to be the same, but mental stress varies and is the most dominant stimuli for palm sweat (Nilsson 1977). Washing the hands may not always generate the same cleanliness. Moreover the dynamics in the friction interface is more complex when velocities are present (Suh. 1986) and it may be that the activities of the sweat glands and the mechanism activating the transepidermal water loss, TEWL, may be differently affected under static and dynamic conditions. These results indicate that velocity, as an expression of static or dynamic conditions in the friction interface, should be specified when skin friction is considered.

In the only study identified where velocity and palm moisture were related (Cua, et al 1990b) the material was Teflon, the velocity was 120 mm/s and correlation μ * TEWL was 0.578.

The second study focused on subjects showing naturally low or high palm skin moisture (TEWL) to explain the low correlation μ * TEWL observed in the present series of research (and also by Cua, et al (*ibid*)). Acknowledging the low number of subjects n = 7, and the low correlation found −0.32 and 0.21, ($p<0.05$), the results suggest a non linear and U-shaped relation between skin moisture TEWL and coefficient of friction. The low level of palm moisture was 46.17 (SD=5.37) range 41.1-56.5 $g/m^2/h$, and the high level was 109.48 (SD=12.77) range 95.25-114.75 $g/m^2/h$.

Thus special attention should be paid to the choice of correlation models in palm friction studies were skin moisture is controlled, as linear models are unlikely to detect these moisture effects.

Contributors to friction according to a regression model

The developed linear multiple regression model explains 67% of the variance and includes a main model and three interactions. The main model included coefficients for the environmental conditions in the friction interface i.e. surface pressure and velocity, but also four topographic characteristics of the textured samples. Two of these are standard surface topography recordings, Del.q (which specifies the slope of the profiles) and S_m (which is an expression of the spacing between profile peaks). The other two characteristics have been identified as being of significant importance for friction against palm skin. They specify the upper part of the topographies only and ignore the details further down from the peaks to the bottom of the profile. They have not previously been published and are referred to in this thesis as T5 and H5. The specifications of these four characteristics are reported in Appendix 2.

Scientists[7] at the Royal University of Technology in Stockholm suggested these two new characteristics to the author. Their long experience in the field of tribology suggested generating a specific analysis based on topography and load bearing data, which are gained

[7] Thorvald Eriksson and Lennart Nilsson

when using a standard procedure for surface recordings, and include these data in a mathematical function in a new and previously unpublished way. In addition to these four characteristics i.e. Del.q, Sm, T5 and H5, other frequently used standard surface topography characteristics (Ra, Rp and S) were also included in the regression model but were found not to add any valuable information to the analysis.

The coefficients in the main effect consider:

- -surface pressure (7–70 kPa)
- -the velocity in the friction interface (0-12 mm/s)
- -three contaminants, (glycerol, hydraulic oil, engineering grease)
- -three skin conditions, ("normal" clean skin, "sweat", hydrated skin)
- - surface topography variables, (T5 and H5)

The three interactions consider each of these contaminants and skin conditions in combination with velocity of the contact and the surface topography as expressed in T5 and H5. The respective regression coefficients are shown in Table 11.16 and 11.17 in Appendix 3. The original variables and the range they cover are presented in Table 11.15 in the same section.

The model was only valid for the material polycarbonate since all samples were made of this polymer.

Thus it appears that the dependent variable, i.e. the coefficient of friction, is affected to a different degree by the independent variables. The situation is most clearly seen on the effect of velocity and surface pressure on friction, where increased velocity act in favour of high friction while increased surface pressure reduces friction. Such results clearly require interaction terms. The various contaminants as well as "sweat" require separate coefficients due to the different ways they affect the friction forces. The treatments clearly lubricate the interface while hydration of the palm affects the elasticity of the glabrous skin of the palm. Table 11.20, in Appendix 1, presents estimated coefficients of friction data according to this regression model for all textures in Experiment 3 at six environmental conditions, two levels of load and three velocities.

11.7 Summary and conclusions

The choice of fine or coarse textures will not per se determine high or low friction. Environmental and skin conditions but also surface pressure and the velocity between skin and the friction partner all affect friction. The results from Experiment 3 reveal several not earlier published details on palm friction with reference to fine and coarse textures, velocity in the friction interface, skin moisture and surface pressure. The relative contribution to coefficient of friction is expressed in a regression model which explains 67% of the variance.

Fine and coarse textures

Contaminations in the friction interface have a strong reducing effect on friction. Under such conditions the coarse machine cut textures such as textures No. 202- 204 may be preferred when stability in friction is of prime concern, as the difference is small between contaminated and non-contaminated conditions. The duty cycle of these textures was only 25%, the grooves being 1.5 mm wide and the ridges 0.5 mm wide. Such textures were found in Experiment 1 and 2 to be uncomfortable and the 5%-ile user will found it extremely uncomfortable. Reduction of the groove width will generate less discomfort but too small will affect the deformation effect, μ_d, of friction generation and reduce the coefficient of friction.

Coarse mass produced textures

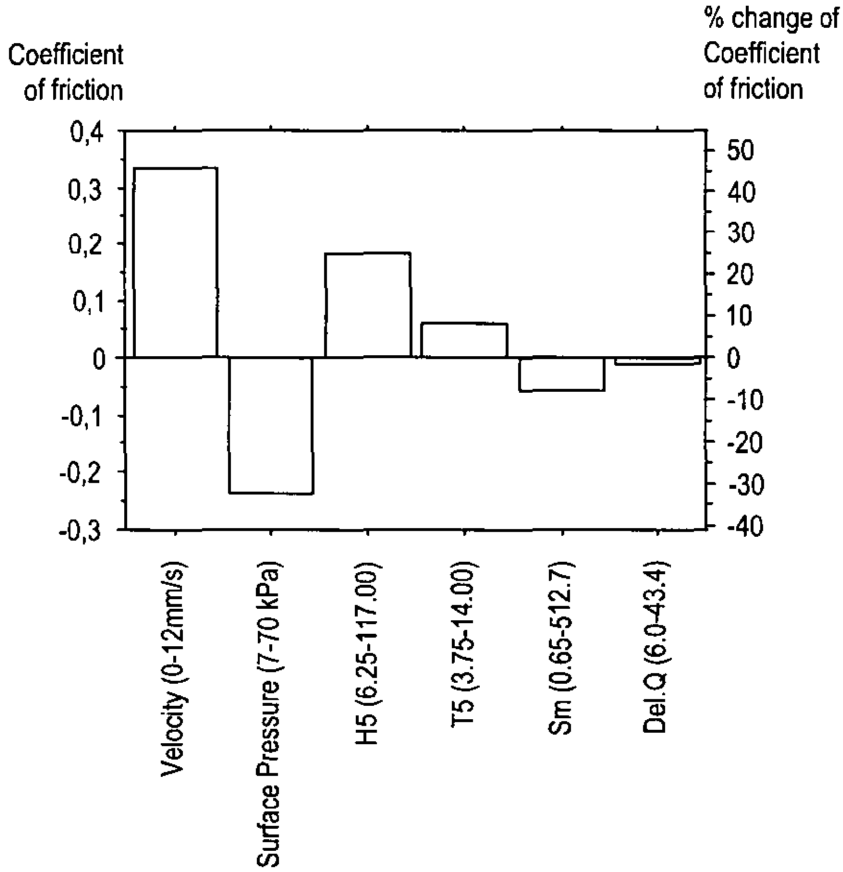
Texture No.9006 was similarly designed as texture No.204 with grooves and ridges but less coarse. The texture provides high friction under not contaminated conditions but the topographies do not provide enough deformation to the skin to provide high friction at contaminated conditions.

Fine mass produced textures

Textures No. 9078 and No.9050 provided the highest recorded coefficient of friction in Experiment 3 when subjects' hands were hydrated and had gained the characteristic wavy "swimming pool hand" state. μ was 1.43 and 1.12 respectively at a load of 1N (6kPa). These high figures are probably an effect of the ability of such a conditioned palm skin to adhere to the material and to deform over the surface topographies.

Regression analysis

The degree to which the independent variables affect the coefficient of friction is expressed in the regression model, which explains 67% of the variance. It is a fairly complex model, with interaction terms for each of the six examined environmental conditions, but also the velocity in the friction interface and four surface topography variables. The reason for the many interactions are however clear. The dependent variable, coefficient of friction, is shown to be affected to a different degree by the independent variables. The situation is most clearly seen on the effect of velocity and surface pressure on friction, where increasd velocity acts in favour of high friction while increased surface pressure reduces friction. From other palm friction studies individual factors are known to affect friction (Johansson and Westling 1984a). With the present findings these factors are placed in relation to the error term. 20% of the variance was due to individual factors and 47% of the variance was explained by the regression model, 33% of the variance was due to error. Figure 11.16 illustrates the consequences, in terms of coefficient of friction μ for different velocities, surface pressures and surface topographies. The basis for these calculations is the coarse machine cut texture No.202.



Figures 11.16 The effect on coefficient of friction, according to the regression model, of changing the original variables over the ranges shown along the variables along the abscissa. The illustration refers to texture No. 202 and "sweat" skin condition.

Increased friction can be expected when velocity and the surface specifications H5 and T5 increase their numeric value. Decreased friction can be expected when surface pressure and the surface specifications Sm and Del.q will increase their numeric value.

Depth of grooves
The differently deep cut grooves in the machine cut textures (No.202-204) did not show any significant effect on the coefficient of friction. Different mechanisms generate friction under normal clean and contaminated conditions respectly. In clean conditions adhesion forces in the friction interface provide friction. Under contaminated conditions, however, the deformation of the skin down the grooves and over the ridges generates the friction forces.

Surface pressure
Experiment 3 confirms the findings in Experiment 1 and 2 that palm skin in friction is pressure dependent. The correlation was negative and μ at 20N was 71.9 % of that at 1N. For the coarse machine cut textures the effect of load was considerably smaller than for the mass-produced. Surface pressure is included in the main model of the regression equation but not in the interactions.

Velocity
Skin-sample velocities ranging 0 - 128 mm/s were recorded. According to Experiment 3 all examined textures, under all six environmental conditions, present a characteristic increase of the coefficient of friction with increased velocity in the skin-texture contact. There was consequently a positive gradient in the friction interface in the range 0-12 mm/s where most combinations of textures and environmental conditions presented peaak friction. For some materials this positive gradient was evident over a larger velocity range, 0-48 mm/s until peaaks were reached. At these points only slight deviations from steady state were noticed.

Skin moisture, hydration and friction
Daily recordings of skin moisture and coefficient of friction in one subject over a period of 16 days showed that the best correlation referred to static friction where $r = 0.658$ ($p<0.05$). Seven subjects who in earlier experiments were observed having naturally low palm skin moisture, mean 46.17 (SD=5.37) or high, mean 109.48 (SD=12.77) palm skin moisture expressed as TEWL $g/m^2/h$, were engaged in friction analysis. Subjects with low palm moisture showed negative correlation with friction, (–0.32) while subjects with high palm moisture showed positive correlation, (0.21). These results suggest a non-linear and U-shaped relationship between skin moisture and coefficient of palm friction.

Special attention should be paid to the choice of correlation models when skin moisture is controlled for in palm friction studies.

Chapter 12 Discussion and application of findings

12.1 Introduction

Friction of palm skin is difficult to specify as it varies widely. Regression models show its dependence on the surface topographies of the friction partner, but also on pressure, velocity, contaminants and skin conditions.

The need to research the field of palm friction arose when producers of hand tools asked for design recommendation for handle textures for a series of traditional hand tools such as screwdrivers, wrenches, spanners, pliers, knives, hammers, etc. The designers of screw caps on, for example, medical containers also expressed the same need but their focus was on people who only had low prehension force capacity.

Most users of bottles of shampoo or hand lotion also have experienced that the lid or cap is very slippery and maybe they wished for a better choice as far as shape or texture to ease or allow access to the contents. In industry, tools such as knives, wrenches and power tools need to be designed for safe use under different contaminated conditions. In search for design guides in the ergonomics literature (see Chapter 4) it became clear that qualitative information on textures for hand tool handles was available in scientific reports and in text books. As to quantitative details, the information was however scarce.

Only two publications were found in the scientific community, namely Bullinger et al (1979) and Buchholz et al (1988), addressing the same issue as this thesis Neither of these considered contamination on the friction interface or the comfort - discomfort - pain situation in the palm - textured friction context. Bullinger *ibid* investigated a large number of materials with a variety of shapes and pattern but very few general systematic design recommendations were presented. Bucholz *ibid* discovered that significant changes in palm friction took place when the skin was wet. Two types of material were examined, porous and non-porous materials. The former increased friction while the letter type decreased it. No general texture recommendations were made to guide industrial and engineering designers. Such details are required as textures can be produced in many varieties. Information on the expected friction and discomfort from palm contact would increase the quality of industrial designers' deliverables.

Several of the findings presented in this thesis provide new details for the design and use of textures on tools and objects touched and handled with the palm of our hands. The results also provide details for experimental design and data collection when glabrous skin is a friction partner. This chapter discusses the major results and their implications for users, designers and practitioners.

12.2 Methodological considerations

The pad of the distal phalanx of the index finger of a subject's dominant hand was the area used for friction exposure in the experiments presented in this thesis. The basis for selecting the locations at the distal phalanx is the frequent exposure of this site to friction forces when hand tools are used. These regions frequently are the sites where forces are transmitted and calluses develop as a supporting structure. In addition, this pad is predominantly homogenous as there is an accumulation of lipid cells under the layers of skin and these cells distribute applied forces fairly evenly over the researched area. This structure is basically the same over the entire load bearing glabrous skin of the palm. The distal phalanx is the easiest to access and the subjects can control the experiment forces they apply very accurately. The most relevant of the earlier identified palm friction research (Buchholz et al 1988 and Bullinger et al 1979) were performed using this location.

The direction of palm displacement towards the subject (i.e. as when an object is pulled out from a pinch grip) was adopted based on studies of tools in use (Forskning & Praktik Research and Practice 1993). These reports showed that hand tools which had either been identified as hazardous or problem tools, were typically operated in this direction when used in a power grip. Examples of such tools were screwdrivers and other rotating tools, ratchets and wrenches.

The role of the dermal ridges of palm skin (dermatoglyphs) in the generation of friction is not clear. No references have been found to give details of their contribution to friction. The shape, size and dynamics of the dermal ridges have however been suggested (MacKenzie and Iberall 1994) as contributing towards friction in glabrous (hairless) skin on palm of hands and sole of feet in relation to the hairy skin. These characteristic skin features do not exist on the rest of human dermal (hairy) skin. The basic shape of the dermal ridges on the distal pads follows generally the same oval pattern of which 70% are oriented in the direction along the fingers. It seems therefore reasonable to anticipate a difference in coefficient of friction in the lateral and distal-proximal direction. This was also the case according to Bullinger et al (1979) who found that lateral friction (transverse fingers) exceeds the distal friction (as when an object is pulled away from a pinched grip) by on average a factor 1.39 when the pressure was 40 kPa. In addition, Jones and Hunter (1992) showed that forces acting proximally on finger pads (as when an object is pushed into a pinch grip) generated higher friction, by on average a factor of 1.45, compared to forces that are acting distally (objects pulled away) on finger pads.

Most identified studies of palm friction, summarized in Table 5 in Appendix 1; were performed in lateral (transverse) or distal (objects pulled away) directions. Thus, in order to calculate friction in the proximal direction, based on such statistics, factors of in the region of 1.39 and 1.45 should be taken into account. It is unclear why these differences exist. As the human hand has been basically the same since the beginning of mankind, these physiological factors may be attributed to basic existential factors such as providing food and safety to the species. High as well as low friction may have been essential to protect the hand and to provide an appropriate grip.

System reliability

The reliability of the experimentation is determined by a number of instrumental, data collection and analysis factors. The sum of errors in the present series of experiments due to data recordings and instrumental reliability was calculated to be less than 4%. In these experiments where skin moisture was sampled an additional ± 15% error could be incurred.

Instrumental errors referring to Normal force and Friction force gauges and amplifiers were < 0.01%. Overall mechanical and electrical errors identified by gravimetric calibration using precision weights were in the range < -0.5% to 2.0%.

Multiple regression analysis was used in order to identify models for explaining the complex relations between the independent variables and their relative importance as contributors to friction. Support in this work was provided by from Dr. Sven-Erik Johansson at the Statistics Institution at Stockholm University.

Two regression models were developed. The first model, developed in Experiment 2 (Chapter 11), explained 54% of the variance for coefficient of static friction and 45 % of the variance for coefficient of dynamic friction. For perceived discomfort, CR-10_S and CR-10_K, the model is less sensitive and only 45 and 33 % were explained respectively. The model included regression coefficients for the three levels of surface pressure, three levels of texture pitch, as well as four levels of texture duty cycle.

The second regression model, developed in Experiment 3 (Chapter 12), explained 67% of the variance. The model specifically describes the contribution to coefficient of friction from the velocity in the friction interface, standard and uniquely identified surface topography variables.

Data collection and analysis
Three levels of normal forces were investigated in the experiments in this thesis, 1N, 10N and 20N. The limit for logging the related friction data was ±10% of these nominal levels. The standard error for skin to sample interface area ranged 18% to 6% for these forces respectively. Data was logged at finger velocities ranging 0 to 128 mm/s but these are reported as mean velocities at intervals of 0 - 4 m/s, 4 - 8 m/s, 8 - 16 m/s, 16 - 32 m/s, 32 - 64 m/s and 64 – 128 m/s. Data sampling errors occurred in < 0.1% of the samples. These were identified by visual checking and removed. The standard error from interpretation of the ink prints from digit pulp was 3%. Sampling frequency was 10 Hz.

12.3 Discussion

The thesis presents empirical results (from data sampling) as well as estimated results from the established regression analysis. Coefficients of static and dynamic friction as well as perceived discomfort data are available from entries based on surface texture, environmental data such as duty cycle and pitch, skin condition, type of contamination, velocity and surface pressure. Consequently to two identified regression models, friction data may be calculated for other textures than those 12 samples which were used in the experiments.

Three skin conditions and five contaminants, three levels of load and six velocity groups with means of 3, 6, 12, 24, 48 and 96 mm/s were employed. The results are however only applicable for the one material used in the presented experiments, the polymer polycarbonate. Other materials are likely to differ due to differences in surface energy, Young's modulus of elasticity as well as inherent surface topography in materials such as cork and leather. Transfer of the present data to other materials is therefore not recommended before analysis of the validity of such transfer has been conducted.

Human palm skin, which is likely to have been basically the same at least since man started to walk upright 3-4 million years ago, appears to have qualities well suited for use under many different conditions. The present series of experiments show that different types of texture have little influence on friction for hands which are not contaminated (i.e. "normal" clean skin, "sweat" and hydrated). The texture with the lowest mean coefficient of friction was only 14.5% less than the texture presenting the highest mean for these not contaminated conditions. Such difference is small in relation to that generated through velocity and surface pressure, contaminants and skin conditions. Increase of velocity in the friction interface from 0 to 12 mm/s will increase the mean coefficient of friction by 236% under not contaminated conditions and 121% under contaminated conditions. The increase in surface pressure from 7 to 70 kPa will however decrease the mean coefficient of friction by 28.2%. Contaminated conditions generate 22.5% less mean friction than not contaminated conditions.

Consequently, reports of coefficient of friction where palm skin is one of the friction partners, requires the additional specification of the velocity, surface pressure and environmental conditions in order that reliable conclusions can be drawn.
Moreover, according to Bullinger et al (1979) Jones and Hunter (1992), bidirectional palm friction differences are of considerable magnitude. Coefficient of friction acting transversly and proximally on finger pads, (as when pushing an object into a pinch grip) generated mean 145% higher friction than when pulling an object out from such a grip, as was the direction in the studies presented in this thesis.
Previous published studies have not recorded all this information.

12.3.1 Coefficient of friction

The coefficient of friction is a factor contributing to the transformation of the forces acting in the direction towards a surface (the Normal forces F_n) to forces acting in the direction along the surface (the Friction forces F_f). The relationship was suggested by Amonton (1699) to be expressed as $F_f=\mu*F_n$ and introduced the factor, μ, the "coefficient of friction", to express the relationship (expressed alternatively, $\mu= F_f/F_n$). As these findings were published in the early history of mechanics they have been regarded as the "laws" of friction. In contradiction to the experiments presented in this thesis, those laws were based on studies where both friction partners were commonly found materials and not, as presently, one partner being living human palm skin. Comaish and Bottoms (1971) found that skin friction deviated in many respects from Amonton's law and, according to Suh (1986), those simple and general laws of friction should be treated with great care, in particular when "new" materials, such as polymers, are involved. The present series of experiments refer to textures of one material only, the polymer polycarbonate.

- The present thesis shows that that several of these classic laws donot apply when palm skin (digit pulp) is one of the friction partners. Rather:

- μ shows <u>negative</u> correlation with surface pressure.

- The friction forces F_f show positive correlations with the velocity between the friction partners.

- The friction forces F_f are <u>smaller</u> in static friction than in dynamic (kinaesthetic) friction under the same normal force.

Well-designed hand tools, including the consideration of friction aspects of their surface, will improve user performance, quality of work and operator comfort (Armstrong et al 1986). Many hand tool injuries are cumulative in nature and working with improperly designed tools may result in chronic ailments (Armstrong et al 1986, Putz-Anderson 1988, Mital 1992a, Mital 1992b).

Much of the evidence for the association between hand force and cumulative trauma disorders is qualitative and is not supported by quantitative definitions of excessive force for specific tasks. In many instances, changing the friction may directly affect the forces required from the musculoskeletal hand / arm system to perform a given task e.g. to generate a specific torque using a screwdriver or a slicing action with a knife. Using gloves does not appear to generally improve this situation as the reduced tactile feedback results in an increase in the muscle forces adopted for prehension when gripping objects. Consequently, glove use often means more stress and strain on the hand-arm system and increased risk for musculoskeletal injuries. Thus, it is important to investigate the coefficient of friction as a factor, among several others in calculating and avoiding such risks.

The palm is the obvious location for studies of friction in the use of hand tools and other hand held objects. Due to additional features such as dense innervations and flexibility, the palm appears to be a suitable location for many laboratory experiments. Thus, several researchers have involved the palm in experiments where skin friction was used to trigger sensor motor impulses in studies of nervous reactions, as reported in Chapter 5. Materials frequently used in these experiments were silk, suede, and sandpaper. General conclusions as to friction from these materials are difficult to make as the mechanical qualities as well as the topographies of each of these materials are very different.

12.3.2 Discomfort

Comfort was defined by Hertzberg (1958) as the absence, and the opposite, of discomfort. Following this perceptual theory, focus in the experiments was set on discomfort (rather than comfort) and subjects were asked to rate the degree of discomfort. Consequently the comfort panorama was omitted in the present studies and focus was placed on discomfort only. It seems difficult to connect comfort sensations to exposing the densely innervated digit pulp of the fingers to textured surfaces used in industrial tasks.

Following private communication with Professor Gunnar Borg and Dr. Sven-Erik Johansson, both at Stockholm University, the Borg CR-10 scale (Borg 1982) was considered paramount. Other scales were considered but decided against as alternative methods required reference surfaces and longer periods of subject training. The Borg CR-10 scale is intended to measure human sensations when one can expect a subjectively defined maximum. On reflection it seems, however, that the sensation of discomfort from finger pad contact had no stringent maximum that is easily defined for most people. The results showed that each individual seems to have chosen their own "subscale" i.e. they tended to generally score low, or high or utilising the entire scale. This has led to large standard deviations and only few significant differences of discomfort sensations between textures.

Subjects may perceive several sensations when exposing the palm to static and dynamic friction. Under considerable load, pain will be experienced. Fransson-Hall and Kilbom (1993) found this level to have a mean of 825 kPa (84.5 N/cm2) for men, and reported that subjects then experienced a sudden and distinct pain sensation which was clearly different from discomfort.

Other sensations include those of roughness. Lederman and Taylor (1972) investigated grooved tiles that were similar to the machine cut samples used in the present series of experiment. They found that the perception of roughness was primarily associated with the width of the grooves and, to a much lesser extent, to the narrowness of the ridges. They developed a model to express the relationship between grooves, ridges and perceived roughness.

Yet another sensation is that of friction. This was not investigated in the three experiments presented in the present thesis but in Experiment 8 "Perception of palm friction in textured and not textured surfaces" of the series of palm friction studies performed by the author that does not form part of this thesis. These results showed that subjects had great difficulties in separating the sensation of discomfort from that of friction when different textured samples were rated. Nearly an equal number of subjects judged, falsely, coarse and uncomfortable textures to provide the highest friction under normal clean conditions, as those who, correctly, judged the not textured and comfortable sample to provide the highest friction.

Experiment 3 (reported in this thesis) revealed that there is a low correlation between instrumentally recorded coefficient of friction μ_k and perceived discomfort ($r = \leq 0.3$). Macro-effects of texture upon palm skin appear to dominate the perception of discomfort but not the actual (instrumentally recorded) coefficient of friction. Lederman and Taylor (1972) also made such observations. Perception of sensations from textures is an intricate matter and indeed a specialist area in itself beyond the scope of this thesis. The publication of these findings which contradict the perceptive sensations seems vital as touching and striking textures is the obvious means for examination, but this is surprisingly unpredictable and it is essential that designers are informed of these facts.

12.3.3 Subjects and conditions

The selection of subjects was limited to Caucasian male white-collar workers in the age range 19-57, median 42 years. Females were not included due to the confounding effect that skin care products could have on friction and perceived discomfort. Sivamani et al (2003a) report that no gender differences in palm friction have been published.

In all, twenty different subjects participated. Thirteen to fourteen subjects took part per experiment. The same fourteen subjects participated in both Experiment 1 and Experiment 2. Thirteen subjects participated in Experiment 3. Six subjects were new to that experiment and seven had participated in the earlier two experiments. Instructions of these subjects in the experimental routines and how to use the subjective scales were given high priority and particularly the training of how to apply the requested normal forces accurately and to keep them within the requested limits

Considering the time and costs available, priority was put to these qualities rather than expanding the number of subjects. The statistics methods adopted, Bonferroni t-test, account for the fact that the same subject performed repeated trials (Holm,1979).

12.3.4 Within and between subject differences

Data on coefficient of friction for common engineering materials in friction partnership with materials of the same kind show fairly homogenous readings with only small deviations from means. This situation is in strong contradiction to the large inter- and intra-individual variations of μ reported by several researchers. For example, Westling and Johansson (1984) and Kinoshita et al (1997) found that coefficient of friction could vary "up to about ±20% of the experiment average value" between different trials even when carried out with the same texture and by the same subject. Bullinger et al (1979) report mean variation of 81% between subjects, while Buchholz et al (1988) reported 5% inter-individual differences. Variances in palm qualities are however rarely reported, e.g. the presence of sweat, skin moisture or the area of skin contact under the different forces used. Differences in these variables may have been one reason for the large variance.

In attempts to reduce large variances and to identify texture and environmental factors significantly contributing to friction and discomfort in this thesis, care was taken to control for skin conditions (moisture) and also task aspects (velocity, normal forces, area of friction contact) and contamination conditions (Paraffin oil, Glycerol, Lard, Hydraulic oil, and Engineering grease) and skin conditions (Normal clean skin, "Sweat", and Hydrated) were also controlled. Moreover, the sample side of the friction partnership was controlled by adopting standard methods and instruments from tribology[8]. The recording of surface topography variables Ra, Rp, Del.q. S and Sm and two additional variables (referred to as were recommended to the author by scientists[9] at the Royal University of Technology in Stockholm T5 and H5), have not previously been published. They specify the upper part of the topographies only and ignore the details below 5 % of the distance from peaks to valley (i.e. below 5% bearing ratio (Appendix 3). Details of all variables in the thesis are reported in Chapter 8 "Dependent / Independent and Controlled variables".

In this thesis the focus was initially put on the sample (texture) side of the friction partnership which was extensively examined by tribology experts in order to meet the aim of providing texture recommendations to designers. The palm side of the friction partnership was controlled for as to the moisture content, and wetting of the skin was introduced as a variable. Several reports, Buchholz et al (1987), Roberts and Brackly (1990), Smith and Scott (1996), demonstrate that the moisture condition of skin affects friction. In the present series of

[8] The science of friction, lubrication and wear.

experiments an evaporimeter was used to record the transepidermal water loss, i.e. the evaporation from skin that cannot be noticed as sweat. This method and the related instrument has been used by other researchers of skin friction, Cua, et al (1990a), but other methods may be better suited to detect skin moisture, or the effects of skin moisture on the mechanical properties of palm skin. Sivamani et al (2003a) conclude with reference to skin friction:

> "To date, no significant differences have been found with regard to gender or race but with skin hydration. Differences are present between anatomical sites. Conflicting results are found regarding age". "The probe geometry and material, influence the value of the friction coefficient, because friction is a probe-skin interaction phenomena, geometry and material + normal force + probe movement". "Much effort has been made in understanding how skin friction changes with different biological conditions and upon the application of various products to the skin surface". "Water has an effect of softening the skin and this in turn allows for greater contact area between the probe and the skin."

The work by Sivamani *ibid* does not refer to any work investigating the influence of velocity or pressure in the friction interface.

Prall (1973) was unable to make a direct correlation of skin smoothness with friction coefficient until he added skin topography and hardness to the analysis. In accordance with findings presented in this thesis a higher coefficient of friction was observed with skin in partnership with non-textured than with roughened probes of stainless steel material.

The importance of controlling other skin factors than the moisture of the skin was evident to the author in the course of the present series of experiments. Casts of subjects' digit pulp were taken in attempts to analyse the topographies in the same way as the samples. Unfortunately the instrument available at the time (Taylor-Hobson 1997) did not accept as large curvature as on these casts. In future studies, an additional focus on the human side of the partnership e.g. shape, size and orientation of the dermal ridges is recommended.

Palm skin responds to physical exposure by developing areas of thicker skin and eventually calluses the viscoelastic properties of which, along with viscoelastic properties of the dermal ridges, also could be subject to investigation in order to better explain the variance in subjects. Reports to support such investigations are presented in Sivamani et al (2003a).

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[9] Torvald Eriksson, Lennart Nilsson and Sören Andersson

12.3.5 Skin trauma and injuries

From the dedicated literature search focusing on injury from tools slipping out of the hands, presented in Chapter 3, it was found that tools with sharp edges (e.g. knives and axes) are frequently cited in these reports but also wrenches, spanners, and hammers. Such slip accidents cause an average of 13.7 days of work absence per case according to Swedish statistics. 3.9 of hand amputations in USA relate to hand tools.

Other studies (Samitz 1985) show mechanical trauma of palm skin in hand intensive trades e.g. blister/friction injuries, hyperkeratosis/calluses, tattooing from occupational exposures to metals. The job categories examined included meat cutters, painters, barbers, and jewellers, flooring installers, farmers, musicians and others. Not unexpectedly, hands and fingers were common sites of injury. Compensation costs to work-related repeated mechanical traumas in USA were, according to Samitz *ibid* estimated to have a national economic impact of at least $14-17 million.

From the findings in this thesis it is likely that the use of hand tools with too low friction may increase the risk of the worker developing repetitive strain injury. Low friction surfaces on objects may require more force for control and operation, and as a result impose additional strain on tendons, tendon sheaths and nerves with the possible development of carpal syndrome as a consequence. Thus too high as well as too low friction may be risk factors for accidents and repetitive strain injuries. Design recommendations on how to generate appropriate friction conditions considering task, user and environmental factors are therefore essential.

12.3.6 Textures

The selected textures for experimentation were all likely candidates for use on handles and similar textured objects. Care was taken not to expose the subjects to palm pressures that may cause pain. The coarseness of textures and the normal forces F_n were selected to limit the pressure on the digit pulp to below 35% of the pain threshold as reported by Hall (1995). Photographs and topographic details of the samples examined are presented in Appendix 3. Seven coarse textures were purpose made for use in Experiment 1 and 2. They were machine cut to produce grooves and land of specific width and spacing for the purpose of establishing the influences of width and depth of grooves, pitch and duty cycle on friction and discomfort. In addition, five commercially available mass produced textures were researched. Two types were chosen. One having grooves and land similar to the machine cut textures, the other having random scattered patterns. Identical textures to the machine cut would have given a better understanding of the transfer effect from machine cut to mass produced. Under the current circumstances such comparisons are more difficult due to the interactions between production method and texture details. No such calculations were made in the thesis and each type of texture is treated separately.

As a reference one non-textured sample was included in the textured samples. All samples used in the present series of research were made from the same polymer material Polycarbonate. Friction on the grooved textures was recorded across the patterns in order to research the deformation component μ_d of friction and compare that to μ_p - the ploughing component of the friction, and μ_a - the adhesion components of the friction. The total coefficient of friction μ is frequently described as the sum of μ_d, μ_p and μ_a (Suh 1986).

Five standard and, in tribilogy, commonly used topographic representation were suggested by scientists at the Royal University of Technology as suitable to include in investigations of friction generated when textured samples are in friction partnership with palm skin. These were Ra, Rp, S, Sm, Del.q. Of these only Sm and Del.q. were shown to contribute significantly to coefficient of friction. The reason may be found in the relatively low surface pressures which human palm skin may be exposed to without pain, 700-800 kPa, while in the mechanical engineering context pressures 10 to 100- fold are not unusual. In calculating Ra, Rp and **S,** numeric information from such texture details deep below the part of the surface which are in contact with the skin are accounted for just as much as information from the parts in active skin contact. The unique in vivo property of the human skin in this thesis caused the scientists engaged by the author to consider alternatives for surface specifications. These are based on Bearing data (%) and consider HSC and Depth respectively, presented in Appendix 3. When included in the regression analysis in Experiment 3, the uppermost 5% of the textures provided significant information for transfer of friction forces from palm skin. Surface topography may be seen upon as a landscape with mountains, e.g. the Alps. The uppermost 5% of this landscape is what at times may protrude above the clouds. On such a day, the height of these protrusions may be 5% of the (mean) peak height. The clouds may some times cover 95% of the region (area), while mountain peaks protrude the remaining 5%. These 5% peaks height and area of textures are the unique surface specifications presented as H5 and T5 in Experiment 3. Their contribution to friction is higher than that from any of the investigated standard topographic representations.

The contribution from surface topographies on friction was reflected on in Sivamani et al (2003a), but investigated in only one of the references in this thesis, Bullinger et al (1979), who differentiated between smooth, finely and coarsley textured surfaces and analysed the smooth surface roughness parameter Rz (which is similar to Ra) in 22 different materals. The Rz value varied from <1 to 70 μ_m and appeared to be related to decreasing coefficient of friction. The wide span of different investigated material (from cork to glass) makes it, however, difficult to separate the effect of Rz from the effect of intrinsic material properties. Textured surfaces were classified with reference to width of grooves and ridges, as in the present thesis. In agreement with the findings presented in this thesis, finely and coarsly textured surfaces were found to generate less friction than the non-contoured. Only "normal" clean hands were, however, investigated. Coarse contoured surfaces having grooves wider than 3 mm were considered by Bullinger *ibid* to constitute risk of injury, the type of which was not specified.

12.4 Application of the findings reported in this thesis

Unlike most materials, palm skin showed sticky characteristics and μ_k frequently exceeded 1.0 when the surface loads were low. A plain, glossy non-textured surface of polycarbonate under normal skin conditions yielded μ_k of 2.22 when the surface pressure was low (6.3 kPa). Only a few studies have shown palm friction in this magnitude. Bullinger et al (1979) report $\mu_k = 2.92$ when the pressure was 5 kPa, however in partnership with a non textured sample of Perspex® but with surface topographies close to that of Polycarbonate examined in this thesis. The effect of type of texture on friction is largely dependent on skin conditions and contaminants on the friction interface. In a clean environment, high friction is associated with a large skin contact area, i.e. no or fine textures. Under the same clean environmental conditions, a lower μ_k was gained when the surface was designed with textures that reduce the contact area with the skin, i.e. coarse textures. In a contaminated environment, a coarse pattern was required (i.e. small duty cycle) to gain high friction. In a <u>contaminated</u> environment the non-textured surface gave the <u>lowest</u> coefficient of friction.

All three experiments in this thesis show the same palm-texture friction behaviour. Namely, that when comparing the environmental impact, coarse textures act in favour of higher friction under contaminated and "sweat'" conditions, whilst fine textures act in favour of higher friction under "normal" clean skin conditions. These relations are illustrated in Table 12.1 below, repeated for ease of reading from Chapter 12.

	"Normal" clean skin	"Contamination and "sweat"
High friction	Fine	Coarse
Low friction	Coarse	Fine

- H = Combination act in favour of higher friction
- L = Combination act in favour of lower friction

Table 12.1 The influence on friction from type of texture and environmental condition on friction

There is a low correlation between coefficient of friction μ_k and perceived discomfort ($r \leq 0.3$). Most people like to believe that a coarse and uncomfortable texture should generate the highest coefficient of friction against palm skin. This appears not to be the case under normal clean skin conditions. Under contaminated conditions however a small duty cycle such as on the coarse texture No. 4, acts in favour of high friction. This is at the cost of increased discomfort. Macro effects of texture upon palm skin dominate the perception of discomfort but not the actual friction. Figure 12.1, earlier presented in Chapter 12 illustrates the effect of contaminants and skin conditions on coefficient of friction for fine and coarse textures investigated in Experiment 3.

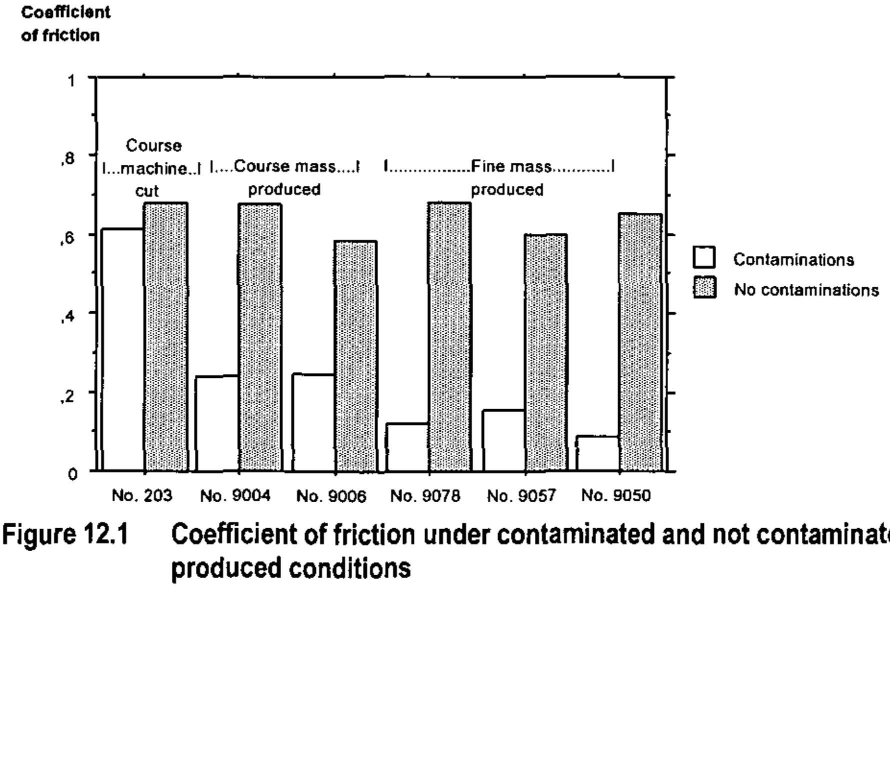

Figure 12.1 Coefficient of friction under contaminated and not contaminated coarse and mass-produced conditions

12.4.1 Contamination and skin conditions

The contaminants were selected to represent the variety of contaminants that may be found on the friction interface between operator's hands and objects they handle in industry, offices and homes. The contaminants were glycerol and paraffin oil (both are common ingredients in skin care products), lard (the animal fat that affects tool handling in the food industry), engineering grease (also known as wheel bearing grease) and hydraulic fluid (commonly found in the automotive industry in transmission systems).

Three skin conditions were chosen as they represent different states of skin moisture with the aim of investigating the effect of moisture on friction. In agreement with Comaish and Bottoms (1971) the hydrated hand, with the typically wrinkled fingertips, provided the highest coefficient of friction. In the present study, additional information shows that type of texture may increase friction under such conditions from 0.70 (SD=0.21) to 1.06 (SD=0.50) finer textures provide higher friction than coarse textures.

Experimental sessions always started with the three non-contaminated conditions.

1. Normal clean skin, 2. "Sweat", 3. Hydrated, which was followed by one or (depending on the experiment) several of the following five exposures, in the following order of greasiness.

2. Glycerol, 2. Paraffin oil, 3. Hydraulic oil, 4. Lard, 5. Engineering grease. A separate set of test samples was dedicated to each type of contaminant.

The reason for not randomizing the order of these treatments lies with the influence these independent variables have on the dependent variable. This is specifically the case for the lubricating contaminants in relation to the (non-contaminated) skin conditions. Some reasons are;

Careful cleaning of the hands after exposure to the lubricants is unlikely to return the skin conditions to the normal state.

- Too little cleaning may leave traces of lubricants on the skin.

- The use of too strong detergents may affect the normal state of the skin.

Exposing skin to grease was shown by Nacht et al (1981) to reduce friction approximately for 1 hour, but this effect was changed to increased friction, to 25-40% over the baseline, 2-6 hours after exposure, introducing a confounding timing aspect to the experiment and analysis. In each of the experiments presented in this thesis, each subject was exposed to the contaminants for 20-30 seconds per sample-contamination combination, in all 10-15 minutes (Figure 8.6, Section 8.15 for details). The set order within the non-contaminated conditions was determined by the long lasting hydrating effect of moisturizing the hydrophilic palm skin by exposure to water. The set order within the contaminated conditions was determined by the different lubricating effect of the investigated contaminants and the risk of more greasy substances being carried over to less greasy samples.

Under contaminated conditions the fine mass produced textures generate very low friction. At these low levels some textures show, in relative terms, considerable more friction than other (fairly similar) textures. Glycerol, which is a common ingredient in body care products (including hand lotion), generates μ_{mean} of 0.14 on texture No. 9078 (a texture characterised by having small dots and flat spots), but for another fine texture No. 9057 (characterised by larger dots) μ is 0.20. Thus, a 43% increase of the coefficient of friction. This difference means that a given task (e.g. applying a certain torque in a screwdriver) may be performed with 43% less applied force, or expressed alternatively, only 70% of the gripping force will be needed to perform certain tasks.

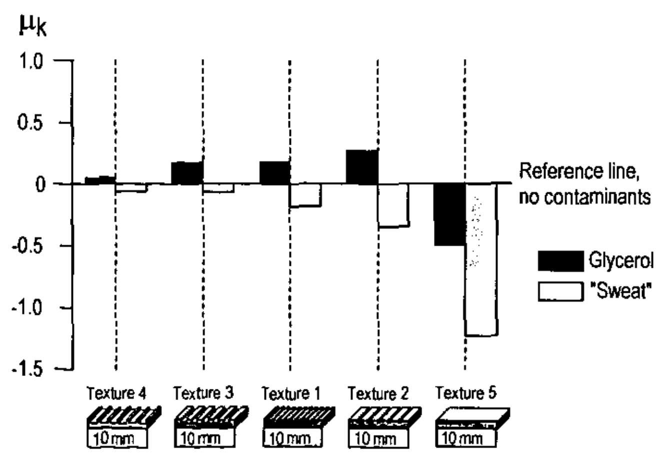

Figure 12.2 The coefficient of dynamic friction and how it is affected by sample surface characteristics, skin conditions ("sweat") and contaminants (glycerol). By choosing different textures on surfaces, high or low friction readings can be gained depending largely on the skin and environmental conditions.

By choosing different textures on surfaces, high or low friction readings can be gained depending largely on the skin and environmental conditions. Figure 12.2 shows how the coefficient of dynamic friction is affected by sample surface characteristics, skin conditions ("sweat") and contaminants (glycerol).

12.4.2 Skin moisture, hydration and friction

Cua, et al (1990b) analysed correlations between the coefficient of palm friction and skin moisture. They found a significant linear correlation between dynamic palm friction and TEWL ($r = 0.578$). In Experiment 3, one subject performed daily recordings of skin moisture and static as well as dynamic coefficient of friction over a period of 16 days. Skin moisture recordings varied between days, and so did the coefficient of friction, but the co-variation was low. The best correlation (moisture over days) referred to static friction, ($r = 0.66$), $p<0.05$.

Moreover, seven subjects who in earlier experiments were observed having naturally low or high palm skin moisture, were engaged in friction analysis. Those subjects with low palm moisture showed negative correlation with friction ($r = -0.32$) while subjects with high palm moisture showed positive correlation ($r = 0.21$), both significant, $p<0.05$. These results suggest a non-linear and U-shaped relationship between skin moisture and coefficient of friction with a level of skin moisture range of 41.1 to 114.75 $g/m^2/h$. The reason for this friction-moisture relation is not clear but may be an effect of a shift in the relative contribution of the components that generate friction forces. As described in Section 5.3 these are described by Suh (1986) and Yamaguchi (1990) as:

- asperity deformation (μ_d)
- molecular adhesion between surfaces (μ_a)
- ploughing in the surface by protruding particles (μ_p)

For viscoelastic materials like skin, the three components μ_d, μ_p and μ_a, contribute to friction to different degrees sequentially, as well as concurrently (Suh 1986).

It is likely that high moist skin conditions, e.g. water evaporation rates (TEWL) of 90-120 $g/m^2/h$, will increase skin elasticity, and the consequently larger molecular contact between the friction partner may increase the relative contribution of the molecular adhesion between surfaces (μ_a) and provide higher friction forces.

At low moist, dry, skin conditions, e.g. at water evaporation rates (TEWL) of 40 - 70 g/m2/h, the superficial epidermal, flat cells, (not unlike slate), may take a more dominant part in generating friction forces by allowing ploughing in the surface by protruding topographies and loose cell particles and increase the relative contribution of the component μp in the generation of friction forces.

The relative contribution of the friction generating components in palm skin is one of the areas suggested for further research in this thesis (Section 12.5). Until more detailed information is available special attention should be paid to the choice of linear or non-linear correlation models when skin moisture is controlled for in palm friction studies.

12.4.3 Static- and dynamic friction

Static- and dynamic friction were investigated in the velocity spectrum 0 to 128 mm/s. In static friction research the subjects pulled the hand towards the body just a short distance, 10-15 mm, until the speed reached 4 mm/s. Data were sampled while the speed of the finger was in the range 2 to 4 mm/s. These conditions defined the coefficient of static friction μ_S in this thesis. The reason for selecting a velocity > 0 to represent static friction, which in traditional friction theory (Amonton 1699) and in the engineering context is seen as dynamic friction, are found in reports by Johansson and Westling (1984a), Bullinger et al (1979) and in pilot studies for this thesis presented in Section 9.5. According to these reports it was found that when velocities of the hand in relation to the friction partner was lower than 2 mm/s only the underlying palm tissue moves while the epidermis sticks to the sample. Within the speed range 2 to 4 mm/s, similarly recorded, a gradual slip starts to take place starting at minor locations in the skin-sample contact area. At velocities exceeding 4 mm/s a general slip is manifest and dynamic friction is developed. Dynamic skin friction was recorded continuously while the speed of the finger was in the range 4-128 mm/s, but grouped in six velocity categories for analysis. In Experiment 1, friction was recorded only while the speed of the finger was in the range 32 - 64 mm/s.

In fourteen identified reports from the literature survey concerning palm friction, presented in Section 5.6.2 and Appendix 1, few descriptions are presented of the sampling conditions for the collection of static or dynamic friction data. Bullinger et al (1979), however, discussed the issue of elasticity in palm skin and the problem of defining μ_S and μ_K. Bullinger considered that data recorded when the underlying tissue had been stretched, at skin displacement of approximately 8 mm, should be treated as static friction μ_S, and data recorded after some 10 to 15 mm of displacement should be treated as coefficient dynamic friction μ_K. Bullinger *ibid* based their definition on their findings that maximum friction was identified. The equipment for digit pulp finger friction was however limited to generate maximal velocities of 15.5 mm/s. Thus the present data is not entirely compatible to that in Bullinger *ibid* (Table 12.2).

	μ_S		μ_K	
	Velocity mm/s	Skin displacement mm	Velocity mm/s	Skin displacement mm
Bobjer thesis	2 to < 4	10-15	4-128	> 15
Bullinger et al (1979)	Approx. 2	8	15.5	10-15

Table 12.2 Static and dynamic friction as recorded in the present thesis and Bullinger et al (1979)

The difference in μ_S due to the state of skin stretching appear to be smaller than that of dynamic friction where the examined velocity range in the present thesis is wider. According to the results in the present thesis the velocity dependence in palm friction is considerable with peak friction for "normal" clean, "sweat" and contaminated skin being found at velocities > 96 mm/s, while for hydrated skin peaks are found at 24 mm/s.

No definition of how to record static and dynamic friction in skin or similar in vivo tissue has been identified. This area is a suggested topic for further research.

This thesis presents details of the velocity dependence in skin friction under several skin, pressure, texture and environmental conditions. It appears that the tested textures, under most contaminations, show a characteristic increase of the coefficient of friction with increased velocity in the skin-texture contact. Friction rises steadily from when there was static friction to where the mean velocity was approximately 24 mm/sec, illustrated in Figure 12.5 in Section 12.5.8 and below in Figure 12.3 for ease of access. The changes in coefficient of friction were grouped in six velocity categories. Some characteristic differences in this pattern are however seen. For the "normal" and the "sweat" hand, the friction still increases in the velocity range 24 to 96 mm/sec. When oil, grease and hydraulic fluid are present on the friction interface, however, the peak friction values are at 24 mm/sec., followed by slight reduction in the velocity range 24 - 96 mm/sec.

The findings are valid for the non-textured as well as the textured samples investigated. For all sample-texture combinations there was positive gradient between coefficient of friction and velocity in the friction interface. The mean gradient for the "sweat" skin condition were 0.025 units of μ per mm/s in the velocity range 2 to 20 mm/s. The consequence of this is that coefficient of friction will increase by 0.25 units when palm velocity on the friction partner increases from 2 to 20 mm/s. This is considerable bearing in mind that the mean coefficient of friction for all examined textures under "sweat" conditions was 0.38. Thus the increase in friction due to such velocity (0.25 units) is 66% of the mean μ (being 0.38). Details referring to all textures and conditions investigated in the thesis are found in Figures 12.4 – 12.9 (Section 12.5.8).

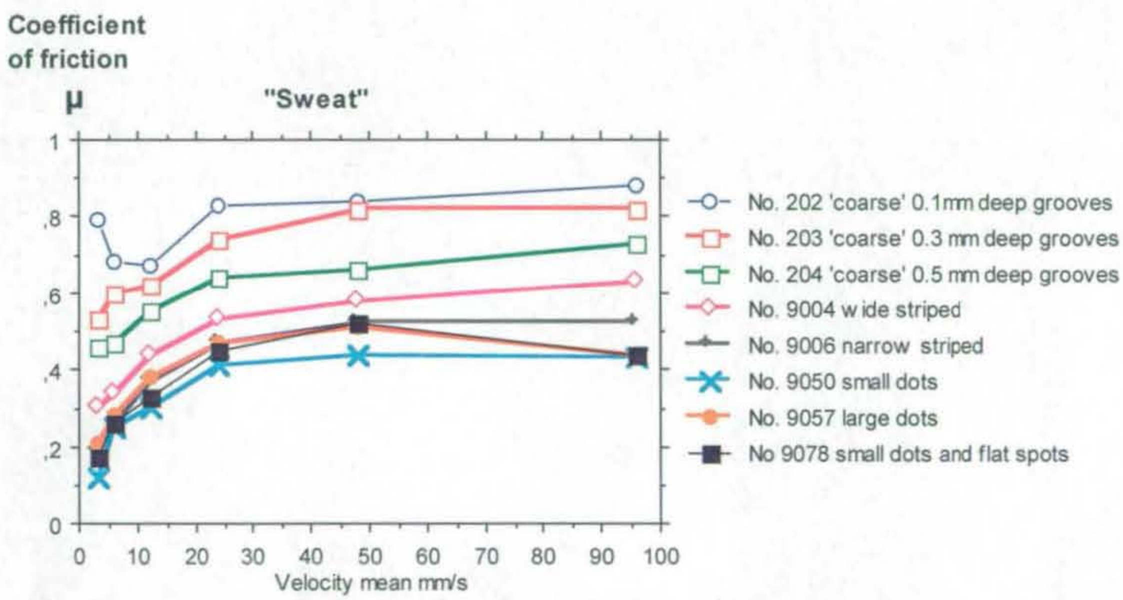

Figure 12.3 The influence of velocity in the span 9-96 mm/s on coefficient of friction given fine and coarse textured samples from Experiment 3 and "sweat" conditions", 20 N normal force.

Consequences for the practitioner

To the practitioner (and user of tools and hand held equipment) the implications of the identified velocity dependence are that more torque will be generated on e.g. a screwdriver, a lid or a cap, when dynamics are introduced in the friction interface. This effect, is more dominant than that of texture selection or surface pressure, and is only dominated by the (reducing) effect of lubricants on the friction interface. Due to this effect people with less muscle resources can increase their capacity by introducing dynamics in the friction interface. Thus, in order to achieve a certain torque the application of high normal forces, Fn, on a surface <u>is not the only</u> solution for gaining more friction force or torque; increasing the velocity in the friction interface is another potential solution. A negative consequence is, however, that the shear forces on skin and underlying structures will increase under dynamic conditions with the associated increase in the risk of blisters and calluses developing.

When the information on the velocity dependence of skin friction becomes general knowledge, then users may change their way of handling objects with increasing or decreasing frictional forces following. Resources for transmitting such information are producers of textured moulds e.g for injection moulded products, engineering and industrial design societies, colleges and universities.

12.4.4 Surface pressure and normal force

With increased normal force and surface pressure, coefficient of friction is reduced in all texture and environmental conditions presented in this thesis. Such deviations from Amonton's "Law of friction" are known to exist in modern polymers according to Suh (1986) and this thesis demonstrates that this also is the case for palm skin in vivo. The mean correation was r = - 0.36 and r= - 0.21 ($p<0.05$) for normal force and surface pressure respectively (Table 10.10, Section 10.5.7 for details). Figure 12.4 shows the mean coefficient of friction during exposure to low, 1N, and high, 20 N, load when digit pulp of palm is in dynamic friction contact with fine and coarse textures. Generally μ at 20N is 71.9 % of that at 1N.

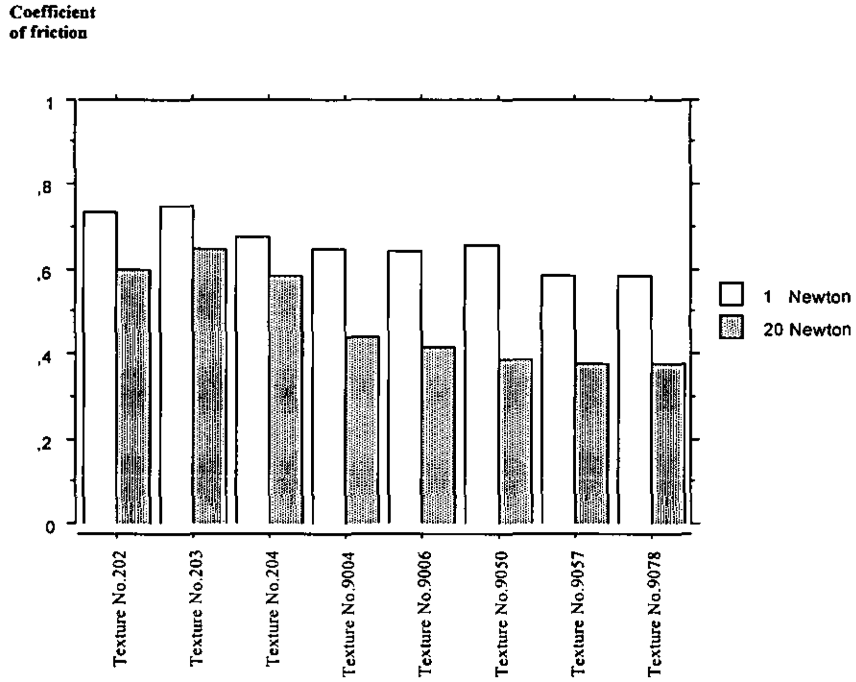

Figure 12.4 Mean coefficients of friction for all textures, contamination's and skin conditions under low and high load (1 and 20N respectively) [from Experiment 3]

When the normal force increased 20-fold from 1 to 20 Newtons, the surface pressure only increased 13-fold (from 6.3 to 81.4 kPa), due to the skin and supporting tissue enlarging following the higher normal forces. Due to this negative pressure dependence, μ_k dropped from 2.22 to 0.85 (when in friction partnership with a non-textured sample) resulting in only a 7.7-fold increase in frictional force. This is in contrast to the 20-fold increase that was to be expected if the classic "Law" of friction claiming pressure independence, was valid for palm skin. Similar decreases were noticed for all tested surfaces and during all tested environmental conditions. Figure 12.5 illustrates how load on the digit pulp affects palm skin. The left scale, relating to the thicker lines, shows the major reduction of coefficient of dynamic friction with increased load in the range 1 to 20 Newton. The right scale shows the increasing discomfort that follows such increased load. The Borg CR-10 scale has ratio properties. The verbal expression for the rating 4 is "fairly strong". These effects are evident regardless of skin conditions or contaminants on the friction interface. For means and standard deviations see Table 9.5 in Section 9.5.1.

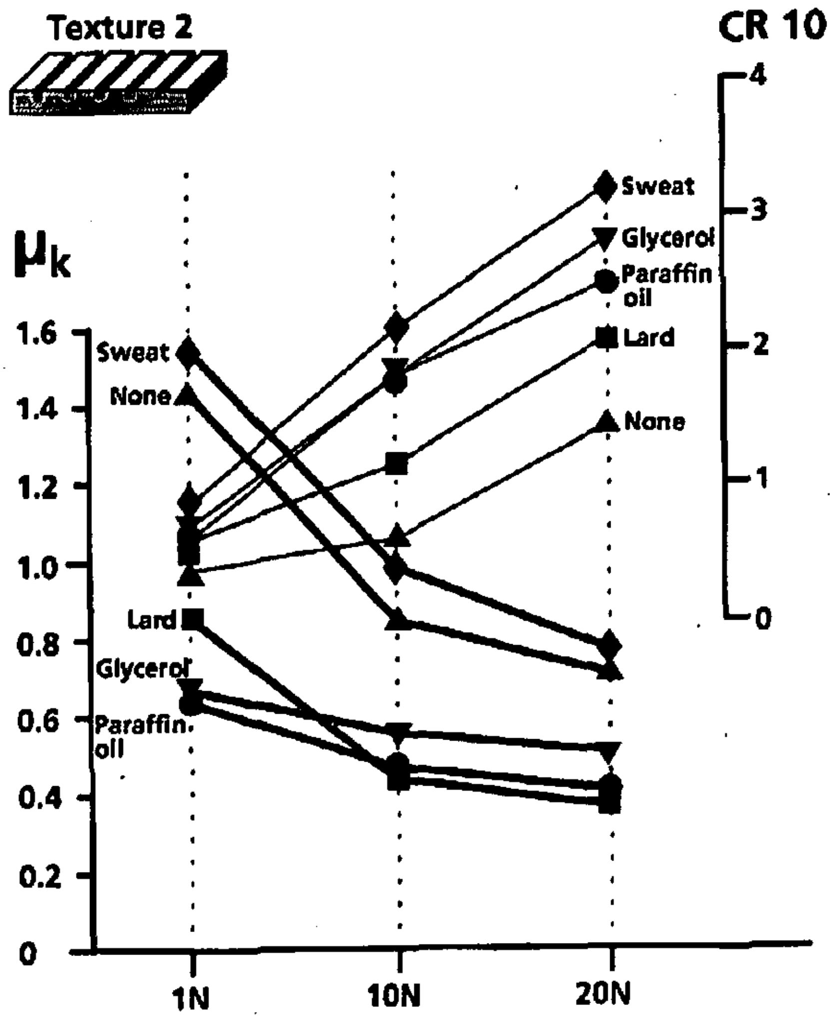

Figure 12.5 The influence of contaminants on μ_K and perceived discomfort CR10 at three force levels. Texture No 2 with 0.5 mm wide grooves and 1.5 mm wide ridges (n=14)

Consequences for the practitioner

A large skin/object contact area, in contrast to smaller such contact area will provide higher friction given the same normal force. For the user of hand held objects, the negative pressure dependence may not be obvious, as the forces generated in the direction of a surface (i.e. the friction force F_f) still increases with increased load, but not as much as would have been in the case had the classic "laws of friction" i.e. no pressure dependence, applied. It is also clear that the extreme friction of the palm under low load, $\mu > 2.2$, turns to less extreme figures under high load. Palm skin is therefore more efficient in transferring shear forces under low pressure than high.

As palm friction varies with the level of load, the designer has the option of selecting a specific texture. The designer needs to consider: Is high or low friction requested? Will the environment, and the hands of the users, be clean or contaminated?

Most of the results in this thesis are presented with reference to the surface pressure and expressed in kPa rather than normal force F_n. This way the users of this information (eg. industrial or other designers) need not relate back to the original documents and identify over what size area of skin a particular force was investigated.

Higher pressure reduces friction but higher velocity increases friction. The effect on friction from surface pressure is, however, not as dominant as that from velocity in the friction interface. The results repored in this thesis relate to textures only. It seems, however, reasonable to anticipate that these basic findings stand also for palm skin in friction contact with material other than polycarbonate, on which the present results are based. The relative dependence of the friction generating mechanisms; asperity deformation (μ_d), molecular adhesion between surfaces (μ_a), and ploughing in the surface by protruding particles (μ_p) is likely to act similarly for many materials suited for use in hand tools and hand held objects.

12.4.5 Discomfort from exposure to palm friction

The results presented in this thesis show that dynamics in the friction interface (at velocities 45 - 55-mm/sec) will introduce a mean of 100 - 300 % more discomfort than in static finger contact with the same friction partners (textures 1 to 5) examined in Experiments 1 and 2. Under "normal" and "sweat' conditions, no significant differences in perceived discomfort were demonstrated between any of the textured samples. Texture No.4, which has a large pitch with a small duty cycle, is however significantly ($p< 0.05$) more uncomfortable than the non-textured reference surface No. 5, but only under some contaminated conditions (glycerol, paraffin oil) and when the normal force was medium and high.

The mean variance for the discomfort index CR-10 for all sample-pressure- contamination-skin conditions was large (SE = 64%) and may be an effect of the subjective scale used (Borg 1982). This scale is intended to measure human sensations when one can expect a subjectively defined maximum, e.g. worst imaginable. On reflection it seems, however, that the sensation of discomfort from finger pad contact had no stringent maximum that is easily defined for most people. Each individual seems to have chosen their own "subscale" i.e. they tended to generally score low, or high or utilising the entire scale. This led to large inter-subject standard deviations. The results also indicate that sweat, oil/glycerol and lard on textured samples generated more <u>discomfort</u> than when they were not present on the textures. The mechanics behind such increased discomfort under the precense of lubricants and sweat may be similar to what British coach-work inspectors and German craftsmen experienced when inspecting irregularities on paint work as reported by Lederman (1978). They increased their ability to detect topographies when they applied a thin cotton cloth between the palm and the paintwork. This reduced the bias from lateral tension (i.e. friction forces), of the skin and allowed the mechano-receptors in the skin to respond and transmit more (and clearer) information on topographic details. The presence of lubricants and sweat on the surface in the dynamic situation may act similarly by emphasising the texture qualities which the subjects reported as more discomfort. Under static conditions, much less lateral bias would be present in the friction interface. On non-textured samples the effect of lubricants had no significant effect on discomfort.

In the present thesis, the expression "discomfort" rather than "friction" is used to express the tactile sensation in finger pad contact with samples under friction. The reason being that the meaning of the word friction may vary between subjects. Perception of friction is not addressed in this thesis in favour of the discomfort-comfort panorama as these expressions are more useful for application in industrial design and the use of hand tools.

One of the initial questions raised in this series of experiments was "Is it possible to combine high friction with comfort in the hand/handle interaction"? Discomfort was shown to be a poor estimate of coefficient of friction. It was found that discomfort was primarily associated with the width of the grooves and, to a much lesser extent, to the narrowness of the ridges. It was found that a 100 % increase in groove width from 0.5 to 1.0 mm gave rise to a 155 %

increased discomfort sensation. Lederman and Taylor (1972) who assessed the perceived roughness as subjects touched textured tiles, suggested the following relation between perceived roughness:

- Perceived roughness = $F*G^4$
- Normal force as F
- Groove width as G

Applying the same type of power function to the results in this experiment would require the exponent of 1.25 as below.

- Perceived discomfort = $F*G^{1.25}$

This is in poor agreement with the power of 4 as suggested by Lederman and Taylor *ibid.*

One explanation to this major discrepancy may be that in the present study the concern was with discomfort and not roughness. It may also be the case that roughness is easier to perceive and express than discomfort. There were also slight size differences. The samples used by Lederman and Taylor *(ibid)* had narrower grooves, narrower ridges and generally smaller pitch than those used in this experiment. Perception psychology is however a specialist area in its own and related literature were identified through ergonomics data basis and personal communication with Prof. Gunnar Borg at Stockholm University. This area lends itself to further analysis[10].

The correlation between instrumentally recorded coefficient of dynamic friction μ_K and discomfort was found to be very low ($r = \leq 0.3$). Figure 12.6 shows the relationship between μ_K and perceived discomfort for all textures and contamination in this investigation. It is obvious that the nicely ranked μ_K data lack good correlation to discomfort. Most people like to believe that a coarse and uncomfortable texture should generate the highest coefficient of friction against palm skin. However, according to the results presented in this thesis, such coarse textures are not associated with high friction under normal clean skin conditions.

[10] The correlation between instrumentally recorded coefficient of friction and subjects perceived friction was investigated by the author in other experiments, which do not form a part of this thesis. See Bobjer (1998).

Intuitively this would appear to be true under contaminated conditions. For "normal" clean palm skin, the coefficient of friction is reasonably correlated (r = 0.44) to the size of the friction interface area (duty cycle). Thus care must be taken not to confuse discomfort and roughness with friction, and the intuitive method to judge the friction by touching it with the hand will only yield valid results for contaminated conditions.

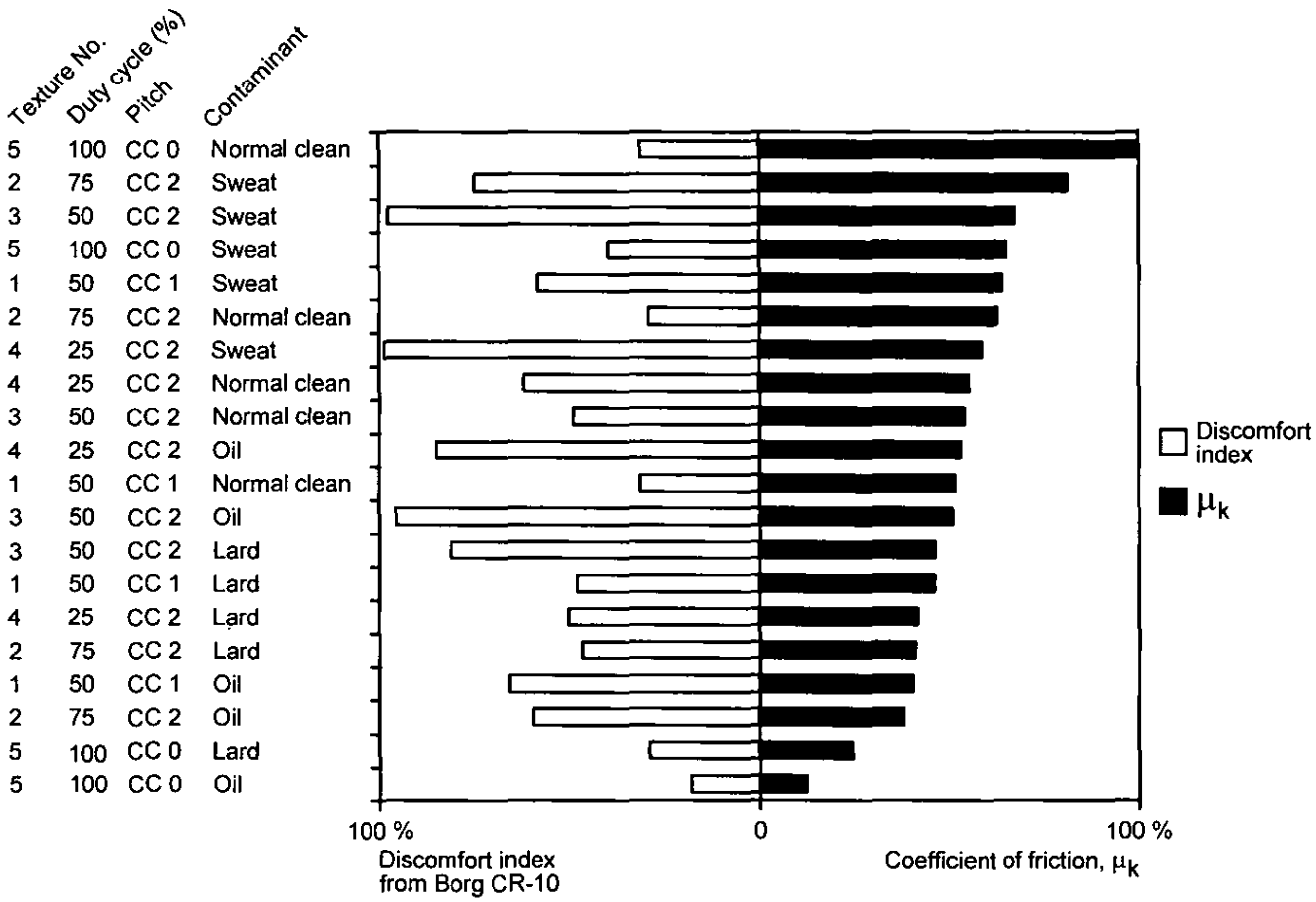

Figure 12.6 **The relationship between coefficient of dynamic friction μ_k and the related discomfort rating derived from Borg CR-10 scale. Coefficient of friction µk and the discomfort index are fractions of related maximum readings. 100 % coefficient of friction = 1.36. 100 % discomfort index = 2.8 units (moderate discomfort) according to Borg CR-10. Data in this graph are average from 1, 10 and 20 Newton normal force (n=14)**

Consequences for the practitioner

Coarse textured surfaces generate more discomfort than non- and fine textured surfaces. Discomfort is closely related to the surface pressure but also to the width of recess (grooves) between lands (ridges) on samples. Coarse textures will be painful if the pressure caused by the ridges is too high. Fransson-Hall and Kilbom (1993) show that the mean perceived pain threshold (PPT) for the distal pad of the index finger is 845 kPa for men and 566 kPa for females. The most sensitive area of the palm is, however, the thumb and thenar region where the mean perceived pain threshold (PPT) is approximately 700 kPa for men and 33% lower for females.

Hall (1995) investigated the levels of palm pressure that may be expected in hand tool use. The results are shown in Table 12.3.

Tool in use	Recorded pressure on distal phalanx kPa *	Safety margin until pain commences kPa		Design option for texture selection until pain commences kPa
		Men	Women	Women
Pen	30	815	536	> 5.6 % land < 94.4 % grooves
Drill	40	805	526	> 7.6 % land < 92.4 % grooves
Saw	75	770	491	> 15.3 % land < 84.7 % grooves
Screwdriver	20	825	546	> 3.7 % land < 96.3 % grooves
Metal shear	100	745	466	> 21.4 % land < 77.6 % grooves

* Mean contact pressure in kPa on the palm during laboratory use by non-professional subjects (Hall 1995).

Table 12.3 Design options for textures on different handtools without exceeding the pain threshold as reported by Hall (1995)

Several design options for textured surfaces are available. Handles on some tools e.g. metal shears may be provided with textures the duty cycle of which can be 21.4 % until pain will be expected for the 50 % of the population.

For tools which in use causes pressure in excess of the pain threshold the design recommendation is to enlarge the size of the skin to handle contact e.g. by increasing the duty cycle of the texture or by generally increasing the handle size, so that PPT is not reached.

The present thesis shows that the duty cycle has an obvious effect on discomfort, with the coarsest texture investigated in the present series of experiments (No. 4) being the most uncomfortable. Figure 13.7 below shows that the perceived discomfort rating CR-10_S at 20 N normal forces.

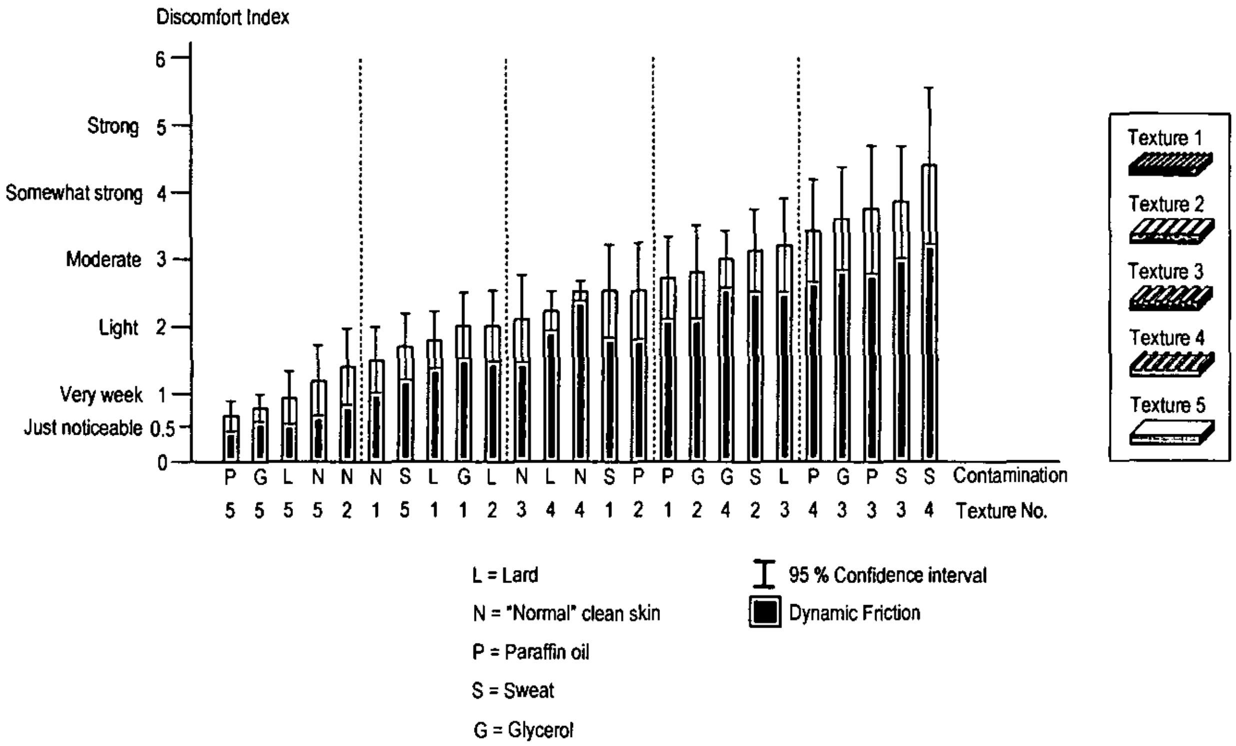

Figure 12.7 Recorded mean discomfort index from Borg CR-10 scale and 95 % confidence interval for dynamic friction conditions at 20 N normal force, ranked in order of mean discomfort. The individual surface numbers are indicated adjacent to each bar. The mean palm- sample pressures range 81.4 to 325.6 kPa depending on texture duty cycle.

12.4.6 Regression

Empirical data from the Experiments 1 2 and 3 in this thesis are available in Tables 9.5, 10.5 and 11.7 in the respective chapter. These may act as guides in the selection of coefficient of friction and discomfort data. The results are, however, only valid for the specific conditions investigated. In order to provide industrial and engineering designers with a larger variety of data, two regression models have been developed in this thesis, and both are presented in in Appendix 3.

The first model

The first model estimates regression coefficients of static and dynamic friction (μ_S, μ_k), but also perceived discomfort (CR-10_S, CR-10_k). This model explains 54 and 45 % of the variance for μ_s and μ_k, and 45 and 33 % respectively for perceived discomfort. In application of the regression model, friction and discomfort data can be established for not only the five examined samples but also for "virtual" textures having other, and combinations other texture measures, within the limitations of the original variables. Predicted friction and discomfort data for two virtual textures are presented, with such predictions of five examined samples in Table 3 in Appendix 3. These samples are characterised by 1 mm pitch, 25 and 75% duty cycles, 15, 60, and 120 kPa surface pressures. These predictions are found within frames of double lines.

The second model

The second regression model, estimates regression coefficients for $\boldsymbol{\mu}$. It is a fairly complex model, with a main model and interactions. The main model covers regression coefficients for velocity, surface pressure, four surface topographies, six contaminants and skin conditions. The interactions include the examined contaminants and skin conditions, velocity in the friction interface and the surface topography variables, T5 and H5.

The model, which explains 67% of the variance, predicts the coefficient of friction:

when the velocity is within the range 0 to 12 mm/sec

when the surface pressure is within the range 7 - 70 kPa

when the hand is "normal", "sweat" or hydrated and contaminated with glycerol, hydraulic fluid and engineering grease.

The reasons for the many interactions are clear as coefficient of friction is affected to a different degree by the independent variables. The situation is most clearly seen in the effect of velocity and surface pressure on friction, where increased velocity acts in favour of high friction while increased surface pressure reduces friction.

In the second model the main model includes coefficients for four different topographic characteristics of the textured samples. Two of these are standard surface topography recordings, Del.q (which specifies the slope of the profiles) and S_m (which is an expression of the spacing between profile peaks). The other two, which are referred to in this thesis as T5 and H5 respectively, have been identified as being characteristic for friction against palm skin. They specify the upper part of the sample topographies only and ignore the details below 5% of the distance from the highest peaks to the deepest groove, i.e. in tribology terms the 5% bearing ratio. They have not previously been published but appear to be close to the standard tribology variable Rpk available in the Rk analysis of surface bearing data. H5 can be compared to the triangular area 1/2*Rpk *MR1. Both Rpk and MR1are however arithmetic simplifications of the more accurate topographic details, which constitutes the basis for H5 and T5 presented in Appendix 2.

The four topographic presentations identified in Experiment 3 affect friction by 1.4 –27.7% considering their minimum and maximum of the original values in the examined texture.

The major contributors to friction according to the second model are:

H5, which may increase μ by 27.7 % as the value increases from 6.25 to 117 among the investigated samples.

T5, which may increase μ by 9.2% as the value increases from 3.75 to 14.00

S_m, which decreases μ by 8.5% as the value decreases from 0.65 to 512.7

Del.q, which decreases μ by 1.4% as the value increases from 6.0 to 43.4

With these regression models the aim of this thesis of presenting objective data for textured surfaces under such velocities, contamination, and skin conditions relevant for e.g. hand tool use is met. Using the model as an algorithm the practitioner may predict friction data for all textures within the qualities and quantities of the researched conditions.

12.5 Selecting dedicated textures for appropriate friction - An industrial design case.

Ergonomically designed handles have been developed for use for advanced mountain cycle racing. An ergonomic grip needs to be designed with consideration of the TASK, the USER and the ENVIRONMENT (Appendix 4). Forces in prehension, the frequent changes of the hand position, varied hand sizes for the relevant population, with wet and sweaty skin conditions all need to be considered. The handles have been designed as multifunctional handles. Four handles were created to consider A) The requirements for male and female users respective palm pressure pain thresholds and B) Competitive and Performance mountain biking.

Their size, shape, texture and material are created particularly for either the male or female hand. The mirrored three-dimensional form fits both the right and left hand, thus allowing a defined, precise steering. The design for women is particularly innovative; differences in shape, size and proportions have been considered. Optimised distribution of pressure, a sustained pain prevention of the hands as well as task oriented position and considerate vibration damping has formed the ergonomic base for industrial design. The handle design allows a straight mountain handle bar to be used more like a more biomechanically optimized "old style" handle bar. The new design adds some volume to the middle of the handle which together with a "wing" shape gives the user the possibility to hold with different grips many of which cause less press pressure on the palm and with the wrist as straight as possible.

Figure 12.8 show the effect of palm pressure from a traditional handle, left, and the new design, right.

Figure 12.8 The effect of palm pressure from a traditional handle, left, and the new design, right.

The palm will get red for anyone who has used bicycle handles for some time. This is a physiological response to external factors acting on the skin and sub-cutaneous tissues. This "redness" is basically a result of increased blood flow in the underlying palm tissues. The opposite of this is white tissue that comes from reduced, or absence of, blood flow in the tissues, which may affect the nutrition of the tissue with skin damage as a consequence

In the bicycle handle case people are getting red palms from a number of different factors. Of these there are 4 significant in this case.

- Pressure (as a result of force from the rider acting upon the handle bar)

- Friction (as a result of the skin rubbing against the handle)

- Heat (between hand and handle)

- Sweat (as a result of the pressure, not the heat)

Different people have different sensitivity to the all of these factors.

Pressure

The new handles have a larger contact surface (male about 40 %) compared to regular handles. The increase results in a lower surface pressure. This is favourable as of all the factors acting on the skin pressure are the one that can cause the most damage and pain. However even low pressure will produce redness of the skin when that pressure is removed.

Friction

Since the fact that the new design handles have a larger area that produces friction the overall friction will be higher. This is advantageous since we want to have a good grip without having to grip the handle forcefully. This larger surface area will, however, for some, cause redness because of friction forces.

Heat

If you grip the handles, as discussed above, a larger surface will be covered by the hand. The handle is insulating and does not transport away any excess skin heat. Adding to this is heat produced by friction forces. This heat will induce an increased blood flow in the finest blood vessels close to the surface of the skin. Hence redness will occur.

Sweat

The palmar skin produces sweat in order to make us grip better. A moist skin has better friction properties than dry. The sweat glands are triggered by <u>pressure</u> acting on the palmar surface and by mental stress but not as most people think by heat. We will however always have sweat present between the skin and the handle. Since sweat is sour (low pH) and contains salts (NaCl) this may induce redness for some people with sensitive skin.

Experimental models
A series of prototypes were made for evaluation among selected groups of users, see Figure 12.9.

Figure 12.9 Prototypes for evaluation among users

User test
Experienced users were engaged to test and evaluate a series of experimental models in performance and race conditions. Focus was put on:

-riding surface/surroundings,

-weather conditions (rain, wet, dry etc.)

-hand sizes, body weight and stature,

Symptoms and their location during or after the ride:

-fingers swelling

-pain in the wrist area

-pain in the palmar area

-numbness of fingertips

-difficulty picking up small objects such as pins and needles directly after riding

The complete questionnaire is available in Bobjer et al (2004)

Design models

Final design models, see Figure 12.10, were provided with a top area to reduce palm pressure that was equipped with a shallow, fine knurled texture. The grooves provide drainage to sweat (and water). Ridges are wide, to provide a large skin contact area which will increase friction under normal and dry operating conditions. The material is a soft elastomer. The lower, finger side, of the handle are coarser in correspondence to the higher pain threshold on the palm side of the fingers. The material is harder for stability and control while riding. Figure 12.10 show the enlargement of the fine knurled texture.

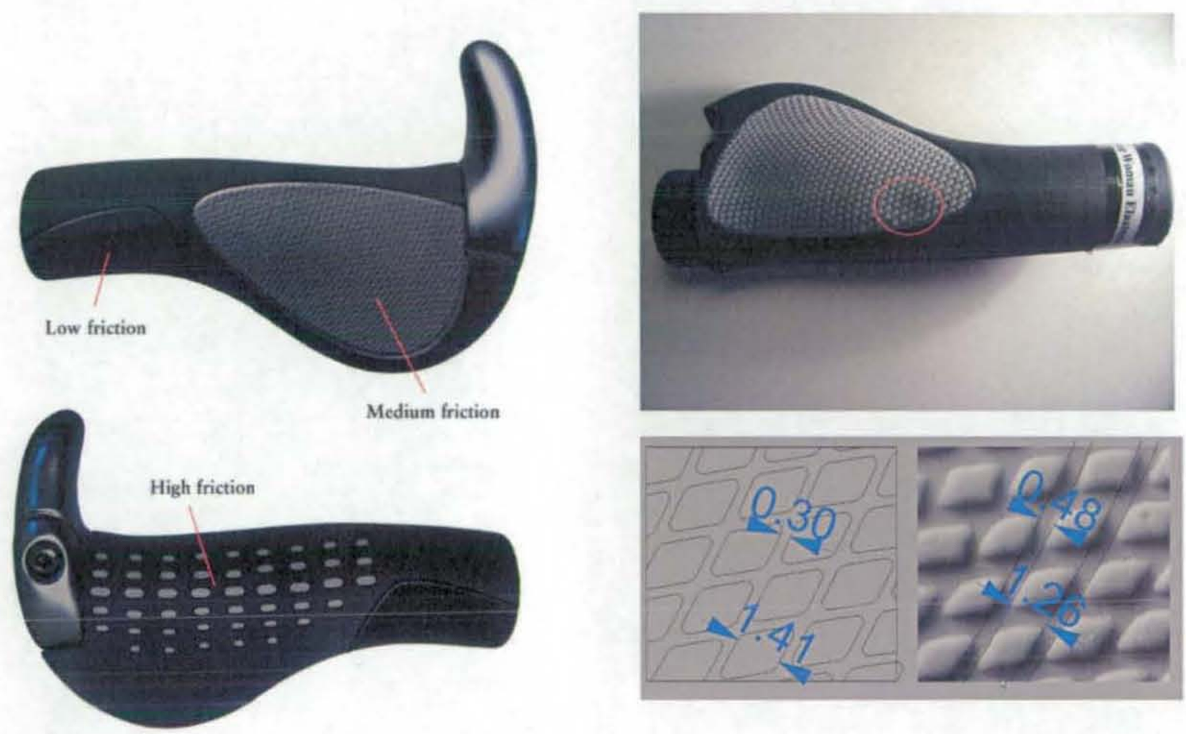

Figure 12.10 Final design models

12.5 Suggestions for further research

The present thesis reports three experiments in a series of eight studies on the topic palm friction. Those not presented in this thesis are briefly described in Appendix 5. They focus on:

- Palm friction for 89 different materials
- Coefficient of dynamic palm friction in white and blue collar workers
- Palm friction in different palm locations.
- Palm friction in dry, normal and moist hands
- Perception of palm friction in textured and not textured surfaces.

Additional research could be directed towards a wider range of people including children, youngsters and senior citicens. The female population should be addressed with studies on comfort, perceived roughness and perceived friction in materials and textures.
Generally, other elements of textures and materials, as well as specific elements of the palm contributing to friction forces, and their interaction in friction partnership, should be addressed. Such elements are:

Handle-side the friction partnership.

- Friction and discomfort in soft and hard materials.
- Interactions between textures and materials.
- The role of textures along and across the line of displacement
- Material surface energy parameters

Palm side the friction partnership.

- Palm surface energy parameters.
- The role of the dermal ridges in transformation of friction forces. Particularly size, shape, orientation and viscoelasticity.
- The area of friction contact being molecular, cellular or nominal.
- Pressure distribution in the friction interface
- The contribution to friction from epidermis, dermis and subcutaneous lipids
- The significance of different skin moisture parameters and their interaction.

Access and use of palm friction data

Tabulated data and results from regression models are well suited for access through computer media. Attempts should be made to design software carrying palm friction data, for use by industrial and other designers

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Appendix 1 Tables

Skin conditions / Contaminants	Velocity mean mm/s	Machine cut textures			Mass produced textures				
		No. 202	No. 203	No. 204	No. 9004	No. 9006	No. 9050	No. 9057	No. 9078
		Coarse textures					Fine textures		
"Normal" clean skin	3	053	0.63	0.56	0.52	0.42	0.56	0.57	0.54
"Normal" clean skin	6	0.53	0.57	0.61	0.47	0.51	0.48	0.54	0.48
"Normal" clean skin	12	0.6	0.65	0.51	0.65	0.4	0.53	0.55	0.57
"Normal" clean skin	24	0.76	0.63	0.59	0.66	0.62	0.63	0.55	0.63
"Normal" clean skin	48	0.64	0.57	0.6	0.67	0.71	0.7	0.59	0.64
"Normal" clean skin	96	0.66	0.68	0.67	0.7	0.58	0.73	0.66	0.67
"Sweat"	3	0.79	0.53	0.46	0.3	0.19	0.12	0.21	0.17
"Sweat"	6	0.68	0.6	0.47	0.34	0.26	0.25	0.28	0.26
"Sweat"	12	0.67	0.62	0.55	0.44	0.37	0.3	0.38	0.33
"Sweat"	24	0.83	0.74	0.64	0.53	0.47	0.41	0.47	0.45
"Sweat"	48	0.84	0.82	0.66	0.58	0.52	0.44	0.51	0.52
"Sweat"	96	0.88	0.82	0.73	0.63	0.52	0.43	0.44	0.44
Hydrated	3	0.45	0.43	0.53	0.58	0.67	0.65	0.54	0.52
Hydrated	6	0.54	0.52	0.56	0.68	0.51	0.71	0.51	0.56
Hydrated	12	0.62	0.6	0.65	0.82	0.67	1	0.55	0.93
Hydrated	24	0.78	0.7	0.86	1.1	0.88	1.33	0.86	1.36
Hydrated	48	0.81	0.76	0.8	1.05	0.97	1.2	0.96	1.22
Hydrated	96	0.79	0.8	0.74	1	0.84	1.14	0.88	0.93
Glycerol	3	0.39	0.48	0.41	0	0.41	0.07	0.16	0.12
Glycerol	6	0.4	0.53	0.5	0	0.33	0.11	0.2	0.13
Glycerol	12	0.48	0.56	0.56	0	0.32	0.09	0.27	0.14
Glycerol	24	0.62	0.68	0.6	0	0.34	0.14	0.22	0.13
Glycerol	48	0.61	0.61	0.55	0	0.3	0.14	0.22	0.15
Glycerol	96	0.55	0.65	0.58	0	0.27	0.1	0.21	0.14
Hydraulic oil	3	0.43	0.45	0.38	0.11	0.24	0.09	0.13	0.1
Hydraulic oil	6	0.54	0.62	0.51	0.17	0.24	0.09	0.15	0.11
Hydraulic oil	12	0.5	0.7	0.55	0.2	0.3	0.09	0.18	0.17
Hydraulic oil	24	0.77	0.8	0.59	0.26	0.39	0.11	0.21	0.16
Hydraulic oil	48	0.74	0.85	0.65	0.29	0.4	0.09	0.2	0.21
Hydraulic oil	96	0.61	0.78	0.63	0.22	0.31	0.09	0.21	0.16
Engineering grease	3	0.34	0.44	0.39	0.05	0.2	0.02	0.03	0.04
Engineering grease	6	0.36	0.47	0.43	0.06	0.1	0.03	0.04	0.04
Engineering grease	12	0.34	0.51	0.45	0.07	0.07	0.04	0.03	0.05
Engineering grease	24	0.35	0.6	0.52	0.1	0.1	0.05	0.06	0.06
Engineering grease	48	0.39	0.6	0.49	0.12	0.13	0.07	0.07	0.08
Engineering grease	96	0.43	0.6	0.51	0.13	0.15	0.08	0.09	0.09

Table 1. **Recorded coefficient of friction for course and fine textures at three contaminated and three skin conditions at mean velocities 3, 6, 12, 24, 48 and 96 mm/s. Mean nominal surface pressure 70 kPa.**

Contaminations and skin conditions	Surface pressure kPa	Velocity mm/s	Texture							
			No. 202	No. 203	No. 204	No. 90046	No. 9006	No. 9050	No. 9057	No. 9078
"Normal" clean skin	7	0	0.84	0.53	0.67	0.67	0.77	0.76	**1.10**	0.59
		3	0.86	0.55	0.69	0.69	0.80	0.78	**1.13**	0.62
		12	0.94	0.63	0.77	0.77	0.87	0.86	**1.21**	0.69
	70	0	0.59	0.28	0.42	0.42	0.52	0.51	**0.85**	0.34
		3	0.61	0.3	0.44	0.45	0.55	0.54	**0.88**	0.37
		12	0.69	0.38	0.52	0.52	0.62	0.61	**0.96**	0.45
"Sweat"	7	0	0.71	0.77	0.71	0.61	0.57	0.60	0.73	0.54
		3	0.74	0.79	0.73	0.63	0.59	0.62	0.75	0.56
		12	0.80	0.85	0.79	0.69	0.65	0.68	0.81	0.62
	70	0	0.47	0.52	0.46	0.36	0.32	0.35	0.48	0.29
		3	0.49	0.54	0.48	0.38	0.34	0.37	0.50	0.31
		12	0.55	0.61	0.54	0.44	0.41	0.43	0.56	0.37
Hydration	7	0	0.62	0.32	0.41	0.57	0.61	0.62	**0.81**	0.50
		3	0.89	0.58	0.67	0.83	0.87	0.88	**1.07**	0.75
		12	1.67	1.35	1.45	1.61	1.65	1.66	**1.85**	1.53
	70	0	0.37	0.07	0.16	0.32	0.36	0.37	**0.56**	0.25
		3	0.69	0.33	0.42	0.58	0.62	0.63	**0.82**	0.51
		12	1.42	1.11	1.20	1.36	1.40	1.41	**1.60**	1.29
Glycerol	7	0	0.53	**0.76**	0.60	0.44	0.34	0.39	0.41	0.38
		3	0.53	**0.76**	0.60	0.45	0.35	0.40	0.41	0.38
		12	0.54	**0.78**	0.61	0.46	0.36	0.41	0.43	0.39
	70	0	0.28	**0.51**	0.35	0.20	0.10	0.14	0.16	0.13
		3	0.28	**0.52**	0.35	0.20	0.10	0.15	0.17	0.13
		12	0.29	**0.53**	0.36	0.21	0.11	0.16	0.18	0.15
Hydraulic fluid	7	0	0.58	**0.88**	0.72	0.42	0.34	0.38	0.49	0.35
		3	0.56	**0.86**	0.70	0.40	0.32	0.36	0.47	0.33
		12	0.50	**0.81**	0.64	0.34	0.27	0.31	0.41	0.28
	70	0	0.33	**0.63**	0.47	0.17	0.09	0.14	0.24	0.10
		3	0.31	**0.61**	0.45	0.15	0.07	0.12	0.22	0.08
		12	0.26	**0.56**	0.39	0.10	0.02	0.06	0.16	0.03
Engineering grease	7	0	0.50	**0.70**	0.56	0.40	0.32	0.36	0.42	0.34
		3	0.46	**0.66**	0.52	0.36	0.28	0.33	0.38	0.30
		12	0.35	**0.55**	0.41	0.25	0.17	0.21	0.27	0.18
	70	0	0.25	**0.45**	0.31	0.15	0.07	0.12	0.17	0.09
		3	0.22	**0.41**	0.27	0.12	0.03	0.08	0.14	0.05
		12	0.10	**0.30**	0.16	0	0	0	0.02	0

Table 2 **Predicted μ for textures * contamination's * surface pressure * velocity and their interactions according to the regression model. Bold figures illustrates which texture provides the highest μ for each skin condition and contaminant.**

	Gradients Units of μ per mm/s		Range	
	Mean	sd	Minimum	Maximum
Skin condition				
"Normal" clean skin	0.0047	0.00390	0.00047	0.01095
"Sweat"	0.0257	0.00890	0.01204	0.03600
Hydrated	0.0210	0.01057	0.01000	0.04000
Contaminants				
Glycerol	0.0049	0.00433	0.0047	0.01095
Hydraulic oil	0.0235	0.00819	0.00190	0.02809
Engineering grease	0.0030	0.00266	0.00095	0.00762

Table 3, **Increase in coefficient of dynamic friction (friction-velocity gradient) per of 1 mm/s over the velocity range 3 to 24 mm/s for non-contaminated and contaminated conditions. Means of all textured samples in Experiment 3.**

Author	Location	Direction of applied force	Type of friction	Friction partner					Normal force F_n. Newton Friction force F_f Newton	Velocity Mm/s	Contaminant
				Material		Shape	Size	Surface properties			
Comaish and Bottoms 1971	Palm	Distal	μ_s	Polyetene sheet		Flat		Smooth	F_n = 0.03 - 10 N		None
μ_s normal skin/ polythene = 0.5-2.2											
Taylor, MM., Lederman, SJ. (1975)	**Fingertips**	**Distal and proximal**	μ_k	**Aluminium**		**Flat**		**Grooves and land**	F_n **= 1.12**		**None and liquid detergent**
μ_k normal fingertip skin / grooved aluminium = 0.6, μ_k normal fingertip skin / soaped grooved aluminium = < 0.15											
Bullinger et al (1979)	Palm, digit pulp of thumb and index finger	Distally on palm. Along and across digit pulp	μ_s and μ_k	In palm test Aluminium Ash Brass Cellidor Cork Copper Enamel Glass Leather PU-foam Pressed material Skiver Steel	In finger test Aluminium Beech Brass Cast iron Copper PVC Plexiglass Rubber Steel Varnished wood	Flat for palm,cyl-inder for digit pulp	Flat 200 x 250 Cylinder diam. 35 Length = 30	Rough, fine, diagonally/ knurled, knobby	Palm Nf = 40 Fingers Nf = 15	3 - 140	None
3 to 5 subjects. µk normal hand, finger contact/ non textured surfaces, transverse finger: Aluminium = 1.01, Brass = 1.03, Copper = 1.08, Hard rubber, untreated =1.8, PVC non-rigid = 1.53, PVC rigid = 1.26, Plymethacrylat = 1.17, Red beech = 1.04, Wood warnished = 1.06, Steel V2A polished = 0.9. µk normal hand, finger contact/ textured surfaces, transverse fingers: Aluminium, finely and coarsely contoured, grooved = 0.95 to 1.07, PVC rigid, finely, coarsely contoured and knurled = 0.92 to 1.11, Rubber, finely contoured = 1.58, Rubber, rough grooved = 1.34. µk transverse fingers exceeds the distal values with a factor 1.3 at 40 kPa. Standardised variance range 5-70%.											

Author	Location	Direction of applied force	Type of friction	Friction partner				Normal force F_n. Newton Friction force F_f Newton	Velocity Mm/s	Contaminant
Westling and Johansson (1984)	Digit pulp of thumb and index finger	Across digit pulp	μ_S	Sandpaper Suede Silk	Flat	Circular diam. 30	# 320 Sandpaper	Ff = 1 – 10 and 2, 4, 8.		None
16 subjects. µs normal hand condition transverse fingers in partnership with: Sandpaper # 320 = 1.21, Silk, finely textured = 0.35, Suede = 0.68. Load has only small effect on mu. Safety margin against slip ranging 25 to 60% of static grip force. Standardised variance within subjects could vary+-20% of average under same conditions. Average within subjects differences in mu between sandpaper and suede/silk differ with factors ranging 1.6-2.6/1.9-4.6 respectively.										
Bushholz, B et.al (1988)	Digit pulp of thumb and index finger	Across digit pulp	μ_S	Adhesive tape Aluminium Paper Sandpaper Suede Vinyl	Flat		# 320 Sandpaper	Fn = 19.6 and 39.2		None and moist skin
7 subjects. µk Dry/ Moist hand condition transverse fingers: Adhesive tape = 0.42/0.66, Aluminium = 0.33/0,42, Paper = 0.27/0.42, Sandpaper = 0.66/0.57, Smooth vinyl = 0.56/0.49, Suede = 0.39/ 0.66, Textured vinyl = 0.50/0.45.										

Table 4. Published research on friction between palm skin of the hand and probes under different experimental conditions. (Tables continues on three pages.)

Author	Location	Direction of applied force	Type of friction	Friction Partner				Normal force F_n. Newton Friction force F_f Newton	Velocity Mm/s	Contaminant
				Material	Shape	Size	Surface properties			
Cua, et.al (1990b)	Palm	Rotating	μ_k	Teflon	Diam. 15 mm	Radius 5	Smooth	Fn = 2.0	150 rmp	None
29 subjects. μk normal hand/ teflon = 0.21										
Roberts,A.D.,Brackly, C.A (1990)	**Digit pulp of index finger**	**Distal and proximal**	**Average of μ_s & μ_k**	**Latex glove**	**Flat**	**40 x 30**	**Untreated and treated rubber, starched chlorinated halogen-action Ra = 1.1-2.0 μ_m contact angle = 34 -68°**	**Fn = 0.32 N**	**10**	**None, 50 µl water, hydrogel**
μk normal/wet palm along the finger in partnership with rubber of different roughness, Ra. Rougher surfaces decrease friction. Ra 1.10 = 0.75/1.15, Ra 1.20 = 0.40/0.60, Ra 1.35 = 0.25/0.55, Ra 1.45 = 0.50/0.80, Ra 1.60 = 0.30/0.80, Ra 1.7-2.0 = 0.25/0.50. Interpretation from graph.										
Cole and Johansson (1993)	**Digit pulp of thumb and index finger**	**Distal and proximal**	**μ_s**	Polyester Rayon Sandpaper Suede	**Flat**		**# 320 Sandpaper**			**None**
13 subjects. Rayon-polyester = 0.46 (sd 0.25), Sandpaper # 320 = 1.10 (sd 0.11), Suede leather = 0.72 (sd 0.17)										
Jones.L.A., Hunter.I.W (1992)	**Digit pulp of thumb and index finger**	**Distal and proximal**	**μ_s and μ_k**	Sandpaper Suede **Plastic**	**Flat**	**Diam. 9**	**# 120 Sandpaper**	**Ff = 0-15 Fn = 17.96 19.75 22.39**	**< 15**	**None**
10 subjects. μ_s normal hand condition along fingers in partnership with: Plastic = 0.71, Sandpaper # 120 =1.21, Suede = 1.0										
Mossel, W. P., Roosen, C. P. G. (1994)	**Digit pulp of index finger**	**Distal**	**μ_k**	**Stainless steel**	**Bell form Spherical Conical Parabolic**	**Diam. 7**	**Polished**	**Fn = 0.04 - 1.0 N**	**1.0**	**None**
4 subjects. μ_k normal hand/stainless steel gange 0.35-1.19										
Frederic and Armstrong (1995)	**Digit pulp of thumb, index and middle fingers**	**Towards ulna**	**μ_s**	**Sandpaper Aluminium**	**Flat**		**# 320 Sandpaper Smooth aluminium**	**Ff = 7.5 24.5 41.5**		**None**
10 subjects. μs normal palm transverse finger in partnership with: Sandpaper #320 = 0.66, Smooth aluminium = 0.33. 5-fold increase in friction force, Ff, produces 3-fold increase in normal force, Fn. (Causing a reduction in μs with a factor 0.6). Cleaning methods, soap and water, generate 10% less friction than cleaning with a towellette										
Smith, A.M., Scott S. H, (1996)	Tip of index finger	Towards ulna	μ_k	Aluminium Glass PVC Polyamide Teflon	Flat	80 x 30	Sticky coating	Ff = 0.1-< 5 Fn = 0.1–1.3	80-260	None and sticky rosin varnish
7 subjects. μk normal skin in friction partnership with: glass = 1.4 (sd 0.5), polyamide (nylonprint) = 0.43 (sd 0.15), PVC = 0.48 (sd 0.25), rosin coated glass = 2.79 (sd 1.2), satin finish aluminium = 0.5 (sd 0.25), teflon = 0.45 (sd 0.2). Data are interpretations from graphs. Relative differences in friction can be detected. r, subjective estimates/objective recordings = 0.85										

Table 4. (Contd.)

Author	Location	Direction of applied force	Type of friction	Friction Partner				Normal force F_n. Newton Friction force F_f Newton	Velocity Mm/s	Contami-nant
				Material	Shape	Size	Surface properties			
Smith, A. M., et. al., (1997)	Digit pulp of thumb and index finger	Towards ulna	μ_k	Polyamid	Flat		Smooth Etched braille heads	Ff = 2.5		Normal and reduced sweating by administration of scopolamine
8 subjects. μ_S normal skin/pharmacological sweat blockade against smooth polyamide = 1.5 (sd 0.25)/1.0 (sd 0.15), μ_S normal skin/pharmacological sweat blockade against densely dotted polyamide = 1.5 (sd 0.1)/1.2 (sd 0.1), μ_S normal skin/pharmacological sweat blockade against sparsely dotted polyamide = 1.9 (sd 0.1)/1.85 (sd 0.15). Data are interpretations from graphs. Electrical resistance in skin varied widely between subjects, sweat blockade increased resistance somewhat										
Seals, P., et. al., (1999)	Digit pulp of thumb and index finger	Across digit pulp	μ_S	Brass	Flat	Circular	Smooth	Ff = 4.18 and 10.7 Fn = 21 -		None and talcum powder
7 subjects. μs normal washed and dried hand /Dry brass = 0.52-1.18, μs normal washed and dried hand /Brass coated with dry talcum powder = 0.24-0.34. μs calculated as average of before and after test recordings										

Table 4. Published research on friction between palm skin of the hand and probes under different experimental conditions.

Author	Location	Direction of applied force	Type of fric-tion	Friction partner			Normal force Fn, Newton	Velocity	Contaminant
				Material	Shape	Size			
Naylor P.F.D (1955)	Anterior surface of tibia	Distally reciprocating	μ_k	Silver, polythene	Sphere	Diameter 8 mm	2.0 - 7.0	-	Talc. archaises oil, water
μ normal skin /polythene = 0.6 μ sweaty skin /polythene = 0.9-1.1 μ dry skin /polythene = 0.75 Interpretation from graph.									
Sulzberger MB (1966)	Back, buttock, skin, fore arm, upper arm, thigh	Reciprocating twists	μ_k	Leather, cloth, plastics			2.15 - 11.54		Water, liquid emollients
No data on coefficient of friction was reported									
Comaish and Bottoms 1971	Abdomen, mid thibia, palm, dorsum of hand	Distally	μ_s / μ_k	Teflon, nylon, polythene, knitted wool, knitted nylon, knitted terylene	Flat, metal, cap		0.03 - 10		Propylene glycol, silicon fluid, liquid paraffin, talcum powder, sebum
μ_s / μ_k dorsum of normal hand in friction partnership with : PTEF = 0.23/0.20 Nylon = 0.55/0.48 Polythene = 0.42/0.30 Wool, knitted = 0.44/0.40 Nylon, knitted = 0.41/0.38 Terylene, knitted = 0.44/0.40 Interpretation from graph μ_s dorsum was lower than μ_s palm 5-fold increase in μ_s dorsum after 30 min. exposure to water at 37°C $F_f = \mu F_n$ to the power of m were m<1									
Highly K.R et.al.1977	Volar fore arm		μ_k	Nylon	Mantel side of wheel		0.28		Water, mineral oil
μ_k nornal skin /teflon = 0.19-0.28 Wetting the skin rise μ_k Oil lubricate and reduce friction but will with time cause occlusive hydration which rise friction									
Cua. et al 1990b	Forehead upper arm, volar fore arm, post-auricular, abdomen, upper back, thigh, ankle	Rotating	μ_k	Teflon	"Donut ring"	Diam. 15 mm	2.0	150 rpm	None
Nacht S et.al (1981)	Volar fore arm	Rotating	μ_k	Teflon	"Donut ring"		2.0	150 rpm	Grease (petrolatum), heavy mineral oil, glycerine, water
5-fold increase in μ_k after 7 min. of exposure to water. 5-25% decrease in μ_k after application of oiland grease which turn to 30-50% increase in μ_k 2-6 hours after exposure.									

Table 5. Published research on friction between hairy skin and probes under different experimental conditions.

Body location covered with hairy skin	Reference
Palm	Comaish and Bottoms (1971), Cua,et al (1990b)
Palm, digit pulp of thumb and index finger	Bullinger et al (1979)
Fingertip	**Lederman (1972), Taylor (1975), Smith (1996)**
Digit pulp of thumb and index finger	Smith (1997), Saels et al (1999), Westling and Johansson (1984), Bucholz (1988), Jones (1992)
Digit pulp of index finger	**Roberts (1990), Mossel (1994)**
Digit pulp of thumb, index and middle fingers	**Frederic and Armstrong (1995)**

Table 6. Published research on friction in, glaborous skin.

Appendix 2 Surface topography

The characteristics of surface topographies in tribology are spesified in the international standard ISO 4288: 1996 "Geometric Product Specification (GPS) - Surface texture: profile method - rules and procedures for the assessment of surface texture". The standard basically present how a well described stylus is traced a defined distance (the assessment length), frequently 5.6 mm, over different locations on the surface, normally 20 times. The recorded profile data is used in various specified algorithms (presented in figures A1-A5 below) to generate a range of topographic representations for different tribology purposes e.g. friction, lubrication and wear. The textures used in the present series of research were recorded with the instrument Talysurf Mk 1, and analysed according to Taylor and Hobson (1997). These standards basically present how a well described stylus is traced a defined distance (the assessment length), frequently 5.6 mm, over different locations on the surface, normally 20 times. The recorded profile data is used in various specified algorithms to generate a range of topographic representations for different tribology purposes e.g friction, lubrication and wear.

Five standard topographic representations were suggested by scientists [11] as suitable to include in investigations of friction generated when textured samples are in friction partnership with palmar skin. The surface profiles are presented in Figure 1-5. These standard profiles are :

Ra, the universally recognised, and most used, international parameter of surface roughness. It is the arithmetic mean of the departures of the roughness profile from the mean line.

Rp, the maximum height of the profile above the mean line.

S, the mean spacing of adjacent local peaks.

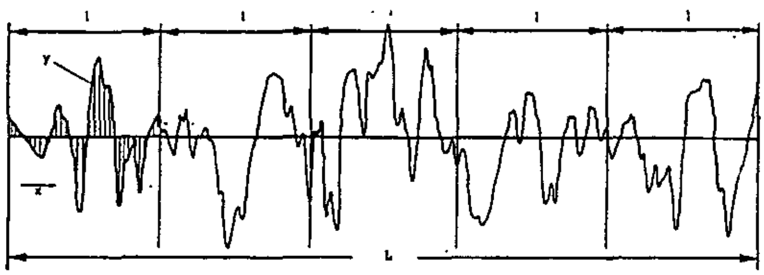
Sm, the mean spacing between profile peaks at the mean line.

Del.q. the rms slope of the profile.

[11] Thorvald Eriksson, Sören Andersson KTH Stockholm

The topographic profiles for the samples in the present series of experiments are presented in Figures 6-15.

R_a



$l_1 \ldots l_5$ are consecutive and equal sampling lengths (l the sampling length corresponds to filter cut-off length).

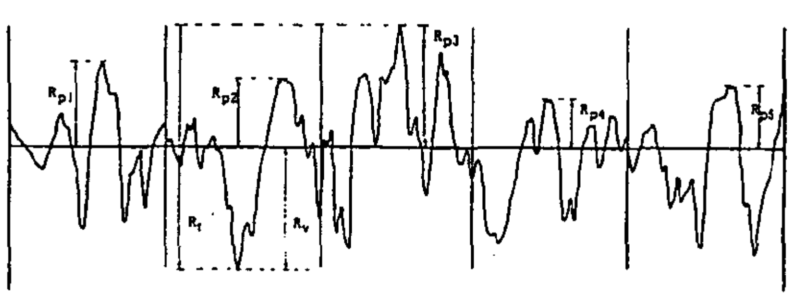
The assessment length L* is defined as the length of profile used for the measurement of surface roughness parameters (usually containing several sampling lengths; five consecutive sampling lengths are taken as standard).

R_a R_a is the universally recognised, and most used, international parameter of roughness. It is the arithmetic mean of the departures of the roughness profile from the mean line.

$$R_a = \frac{1}{L}\int_0^L |y(x)|\,dx$$

Figure 1. **Ra, is the the universally most recognised and most used, international parameter of surface roughness. It is the arithmetic mean of the departures of the roughness profile from the mean line.**

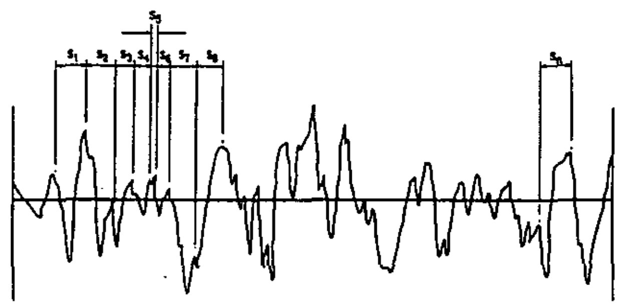
R_p



R_p R_p is the maximum height of the profile above the mean line within the assessment length.

Figure 2. Rp, represent the maximum height of the profile above the mean line within the assessment length.

S



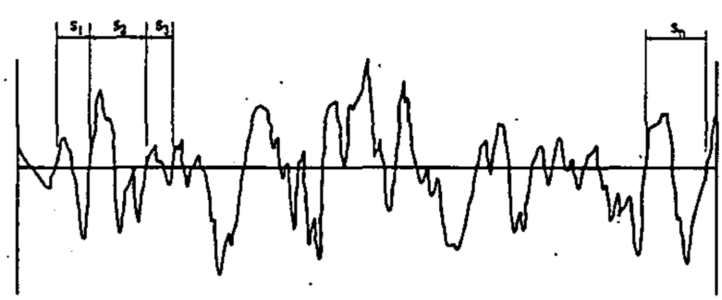
S S is the mean spacing of adjacent local peaks, measured over the assessment length. (A local peak is the highest part of the profile measured between two adjacent minima, and is only included if the distance between the peak and its preceding minima is at least 1% of the P+V of the profile.)

Where n = number of peak spacings then

$$S = \frac{1}{n}\sum_{i=1}^{i=n} S_i = \frac{S1+S2+S3\ldots+S_n}{n}$$

Figure 3. S, represent the spacing of adjacent peaks.

S_m

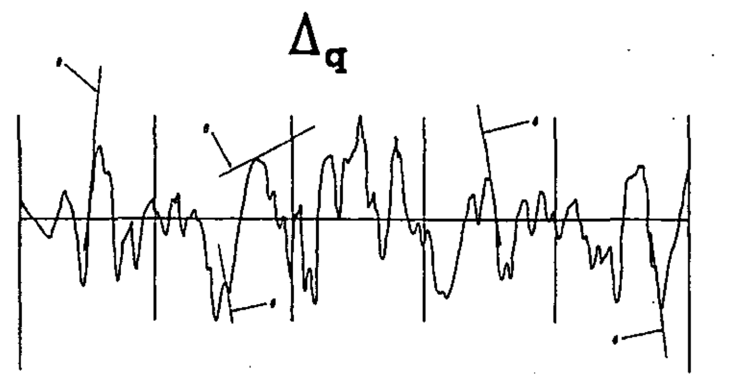


S_m S_m is the mean spacing between profile peaks at the mean line, measured over the assessment length. (A profile peak is the highest point of the profile between an upwards and downwards crossing of the mean line.)

Where n = number of peak spacings then

$$S_m = \frac{1}{n}\sum_{i=1}^{i=n} S_i = \frac{S1+S2+S3\ldots+S_n}{n}$$

Figure 4 Sm, represent the mean spacing between profile peaks at the mean line.



Δ_q is the rms slope of the profile throughout the assessment length.

$$\Delta_q = \sqrt{\frac{1}{L}\int_0^L (\theta(x) - \bar{\theta})^2 \, dx}$$

$$\bar{\theta} = \frac{1}{L}\int_0^L \theta(x)\, dx$$

Where θ is the slope of the profile at any given point

$$\theta(x) = y'(x)$$

Figure 5. Del.q. represent the rms slope of the profile.

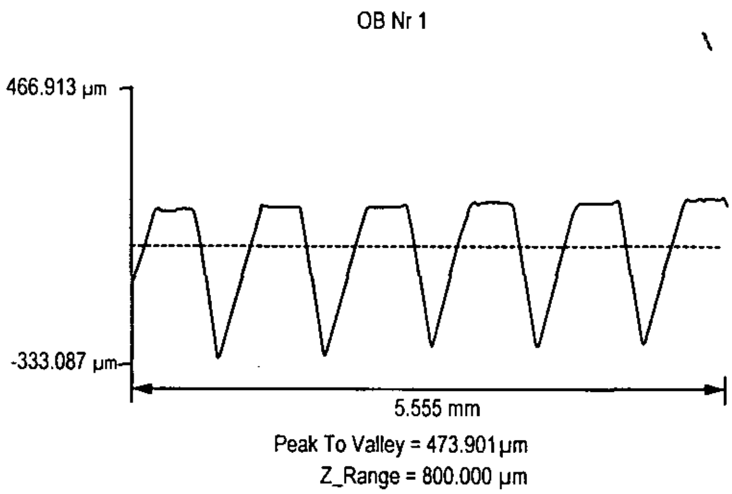


Figure 6. Illustration of the topography profile of the machine cut texture No. 1 "fine striped" texture. Unfiltered signal.

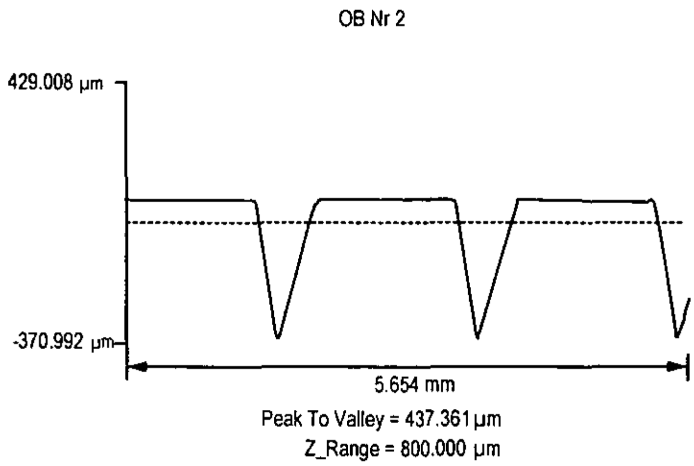


Figure 7. Illustration of the topography profile of the machine cut texture No. 2 "wide striped" texture. Unfiltered signal.

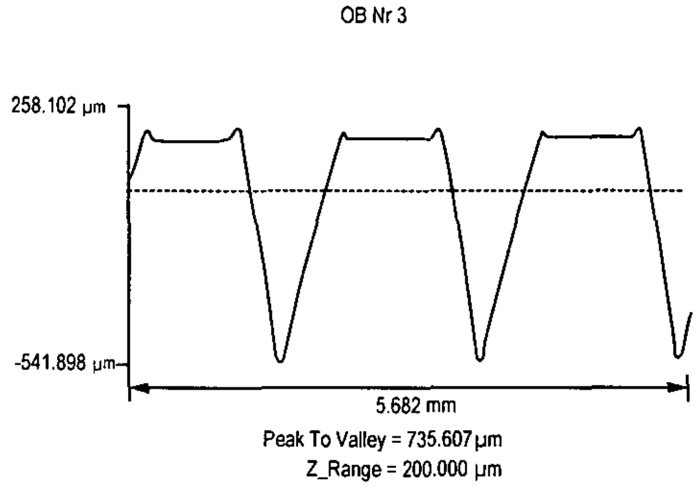


Figure 8. Illustration of the topography profile of the machine cut texture No. 3 "striped" texture. Unfiltered signal.

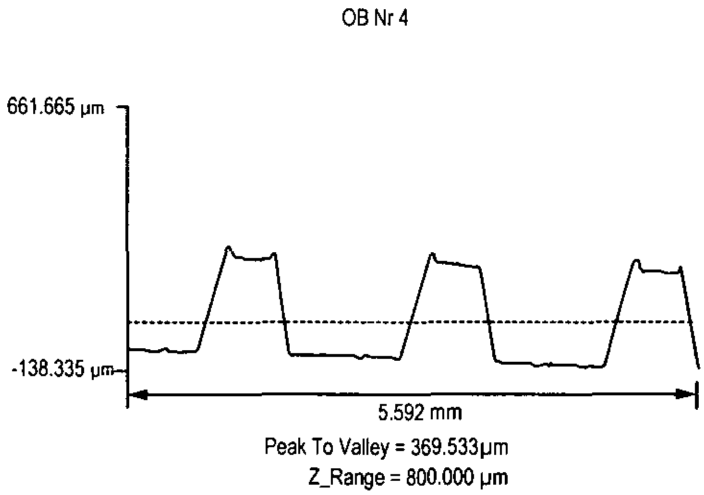


Figure 9. Illustration of the topography profile of the machine cut texture No. 4 "coarse striped" texture. Unfiltered signal.

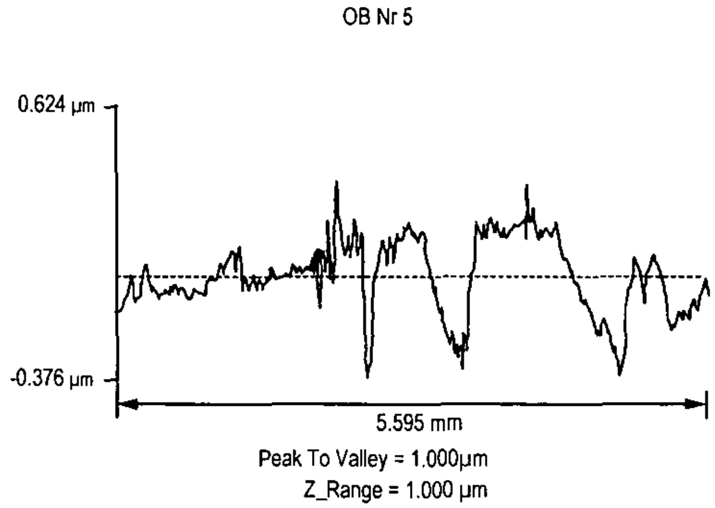


Figure 10. **Illustration of the topography profile of the not textured sample No. 5 "glossy". Unfiltered signal.**

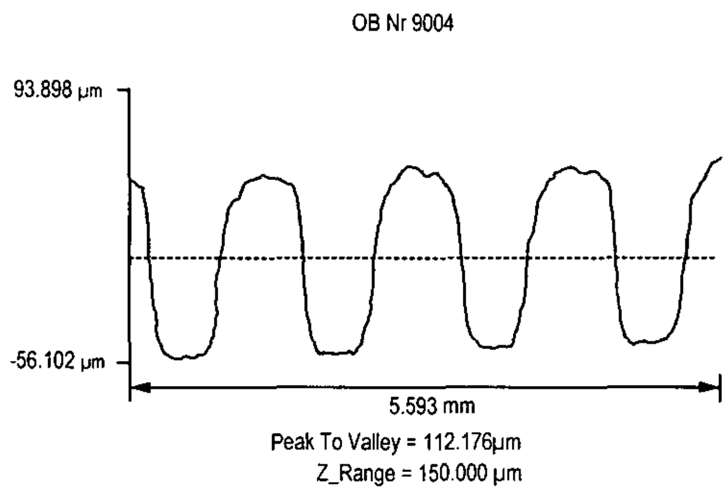


Figure 11. **Illustration of the topography profile of the coarse mass produced texture No. 9004 "wide striped", Unfiltered signal.**

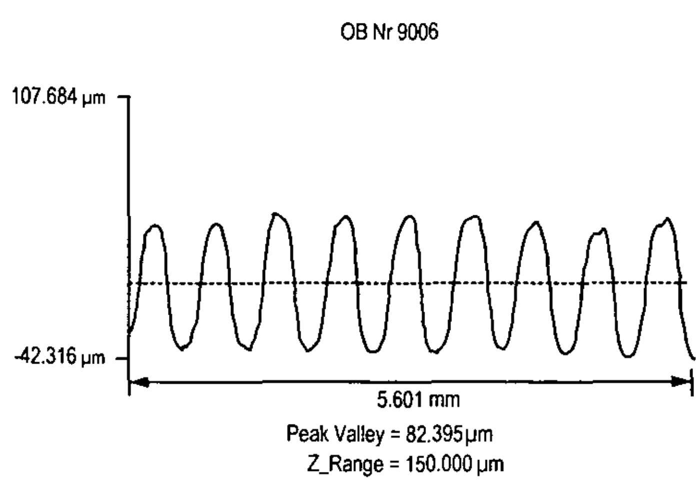


Figure 12. **Illustration of the topography profile of the coarse mass produced texture No. 9006 "fine striped". Unfiltered signal.**

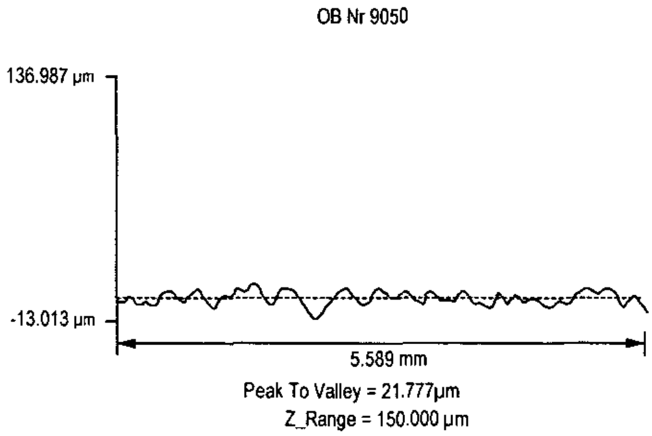


Figure 13. Illustration of the topography profile of the fine mass produced texture No. 9050 "small dots" Unfiltered signal.

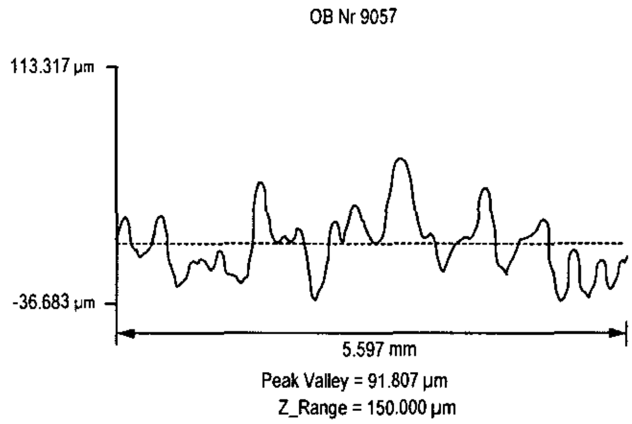


Figure 14. Illustration of the topography profile of the fine mass produced texture No. 9057 "large dots". Unfiltered signal.

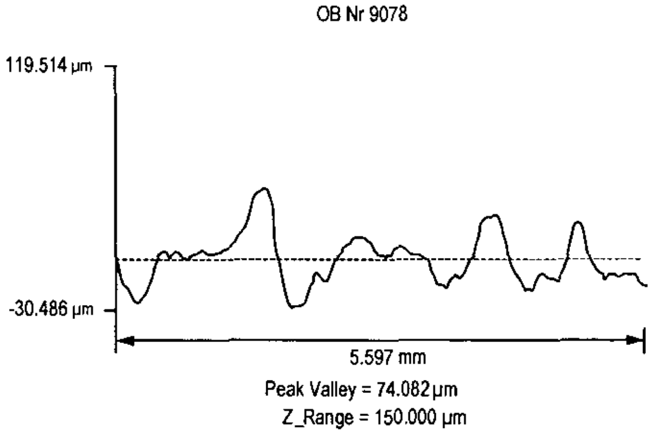


Figure 15. Illustration of the topography profile of the fine mass produced texture Texture No. 9078 "small dots and flat spots". Unfiltered signal.

These recorded data (Ra, Rp, S, Sm and Del.q) for the investigated twelve samples, are presented in the first seven columns of Table 1. The last two columns, labeled T5 and H5 reate to textures investigated in Experiment 3. These are the result of unique and specifically for the purpose of palmar skin friction analysis developed aritmetic calculations based on data gained using standard methods (ISO 4288: 1996).Details of T5 and H5 are presented in the section below below. They are closely related to the Rpk-analysis of bearing data but are in the present thesis based on unfiltered data from the last of the 20 traces, expressed in the readings as "LAST X".

Figure 6 to 15 contain illustrations of the topography profiles of the fine and course mass produced textures examined in this thesis. The unfiltered signal is presented to give as true picture of the topography as possible given the Talisurf Mk1 instrument.

The stylus in this instrument is less suitable for steep grooved textures such as Textures 1 to 4 and 202 to 204, and is unable to trace the vertical sides of the grooves, and not the bottom of the most narrow grooves. The magnification in this figure is different in the X and Y coordinates but the measure is indicated in each illustration. The instrument was calibrated with the results in Table 2.

Analysis of a novel skin friction topographic representation

Most analysis of ISO standard surface topography recordings includes details from the entire depth of the texture. When palm skin is the friction partner all these details are not requiered to satisfactory relate the surface characteristics to the coefficient of friction. One reason being that due to perceived discomfort and pain, surface pressure is limited to much lower figures than in mechanic environments. Palm pain threshold for men is 840 kPa (Fransson-Hall and Kilbom 1993). Thus it is likely that the skin only will be in friction contact with the outmost parts of the profile and not compressed much down in the texture.

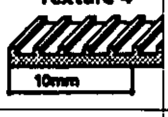
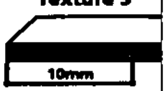
No.	Sample No.	R_p (μm)	R_a (μm)	Del.q (degr.)	S (μm)	S_m (mm)	T5	H5
1	Texture 1 	116.46	85.01	42.43	475.91	0.959	N/A	N/A
2	Texture 2 	93.46	45.65	32.23	888.58	2.02	N/A	N/A
3	Texture 3 	167.78	75.75	36.07	1024,00	2.04	N/A	N/A
4 and 204	Texture 4 	178.80	79.64	43.40	398.16	1.68	13.00	95.00
5	Texture 5 	0.56	0.015	0.61	59.72	0.12		
202	Texture 4 	76.27	18.96	24.18	170.27	1.53	14.00	43.00
203	Texture 4 	143.94	54.15	35.04	539.64	1.75	4.00	117.00
9004	Standex 9004	28.75	21.18	11.09	244.01	1.40	4.50	9.50
9006	Standex 9006	33.29	22.71	15.56	276.11	0.65	12.50	6.25
9050	Standex 9050	7.23	2.75	4.64	121.0	0.29	10.0	6.75
9057	Standex 9057	31.43	11.23	12.32	264.52	0.41	6.50	27.5
9078	Standex 9078	16.77	6.55	6.00	157.44	0.512	3.75	8.5
	Range among textures	7.23 - 178.80	2.75 –79.64	6.00 - 43.40	121.0-539.64	0.62-1.53	3.75-14.00	6.25-117.00

Table 1. Surface topography of the test samples in Experiments 1, 2 and 3.

Ball Radius	= 21.999 mm
Stylus radious	= 0.002 mm
Stylus type	= 60 mm
A	= 0.9774
B	= 0.0021
C	= 0.2023
D	= 0.0088
E	= 0.002

Table 2 Calibration of Talisurf Mk1

One hypothesis tested in Experiment 3 was to investigate what parts of the surface profile best describe friction between skin and the textures. Some surface topography parameters are dedicated to analyse the outmost part of textures, mainly for the mechanical engineering context. Some of these parameters, Rpk and MR1 were specifically designed for the control of the potential wear in cylinder bores in the automotive industry, see Figure 16. They attempt to describe in numeric terms the wear characteristics of the bore by use of a material ratio curve. The filter used, and its associated parameters, are described in ISO 13 565 Part 1.

Rpk - means Reduced Peak Height and is a measurement of surface topography peaks. These peaks will be the areas of most rapid wear. Mr1 - is the Material Ratio corresponding to the upper limit position of the roughness and is calculated as the area of a right angled triangle calculated as having the base length from Tp=0% to the recorded Tp-value at Mr1 while the height is the calculated Rpk-value, see graph in Figure 16 and data in Figure 18.

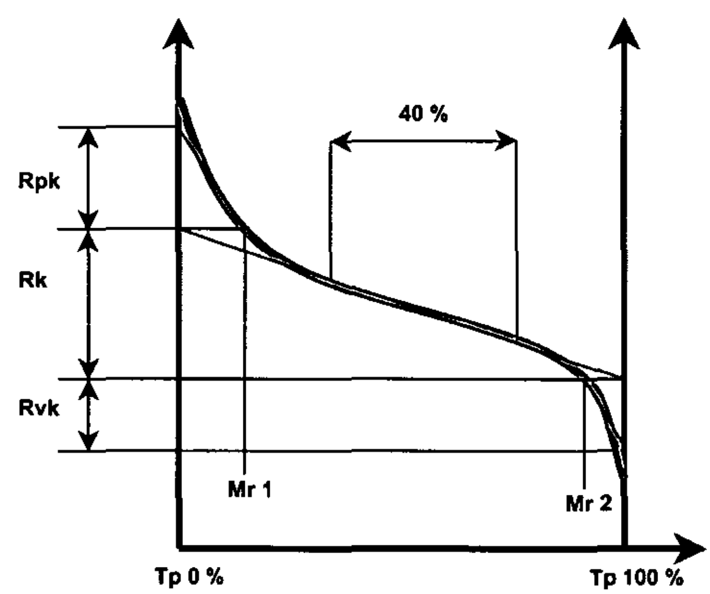


Figure 16. Description of Rk parameters. Curtsey to Taylor and Hobson (2004)

Both Rpk and MR1are, however, arithmetic simplifications of the true topographic details. Therefore a novel and more accurate method were suggested by scientists[12]to represent this part of the profile. According to this method, two parameters are identified from the analysis of a texture.

The first being High Spot Count "HSC", (see specification in Figure 18) per Bearing Ratio% "Tp%" (see specification in Figure 17). This parameter present how many topography peaks exist along the assessment length of the examined surface, at a selected level. The second parameter being the Depth (distance) from the highest profile peak to where a specific bearing ratio (tp%) is found. For each examined sample in Experiment 3 two curves were generated with "HSC" and "Depth" respectively as dependent variables, and Bearing Ratio "Tp%" as independent variable. An example related to Texture No. 9078 is shown in Figure 19. For this particular texture, the area under the "Depth" curve at 5% "Bearing Ratio" is indicated as a striped area and labelled T5. Moreover, the area under the "HSC" curve at 5% "Bearing Ratio" is indicated as a grey checked area and labelled H5.

The respective areas, A_H and A_T, under these graphs were calculated in six intervals in "Tp" steps of 0-5, 0-10, 0-20, 0-50, 0-75 and 0-100%, and analysed as:

$$H_X = \int_{0\%}^{X\%} HSC(Tp)\, dTp$$

and

$$T_X = \int_{0\%}^{X\%} Depth(Tp)\, dTp$$

[x = 5, 10, 20, 50, 75, 100 % respective]

Each of these areas was examined for their contribution to the coefficient of friction in partnership with palm skin in Experiment 3. The representations which according to regression analysis significantly contribute to coefficient of friction were the 5% Bearing Ratio of HSC, but also the 5% Bearing Ratio of Depth. These are presented in the present thesis as T5 and H5 respectively. They are closely related to the Rpk-analysis of bearing data but are in the present thesis based on unfiltered data from the last of the 20 traces, expressed in the Talisurf Mk1 readings (Taylor and Hobson 1997) as "LAST X", in relation to the by statistics means estimated best fit in the Rpk-analysis.

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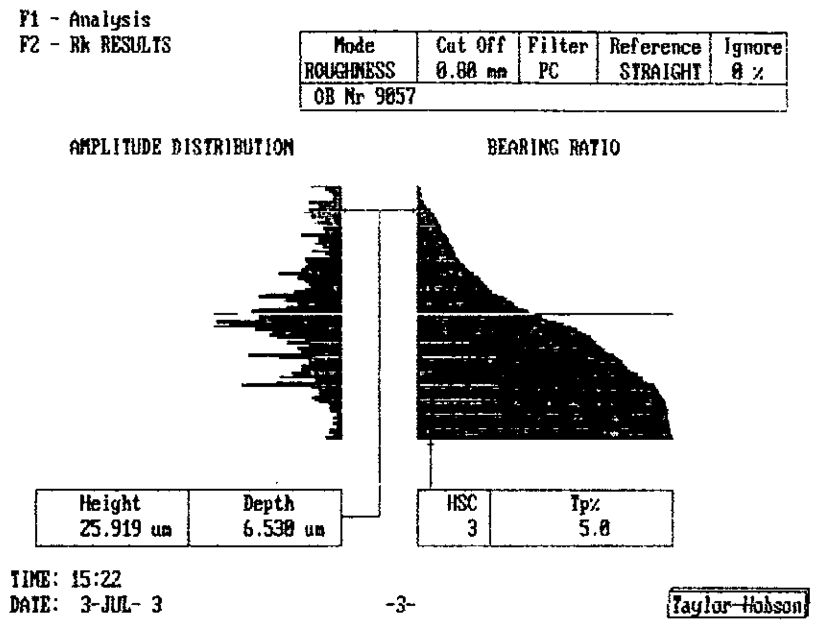
[12] Thorvald Eriksson, Sören Andersson KTH Stockholm



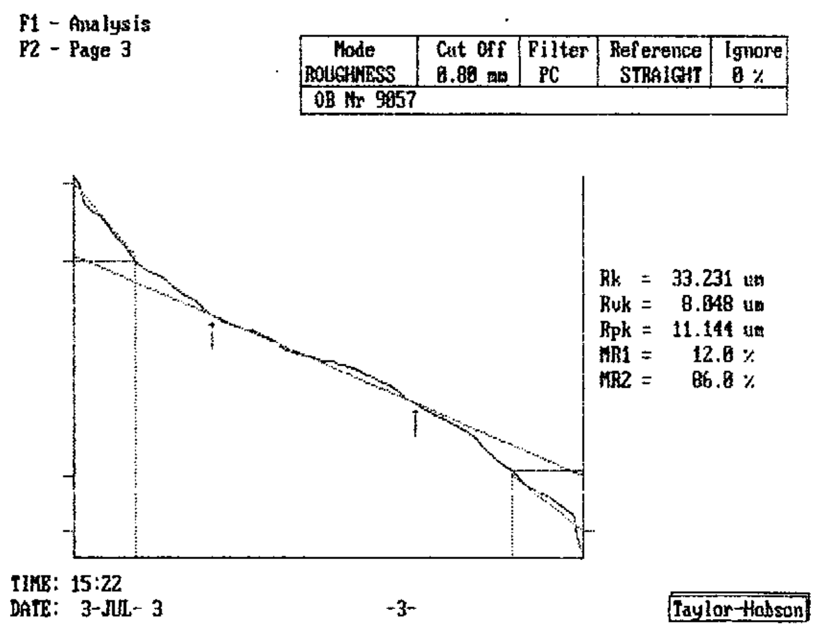
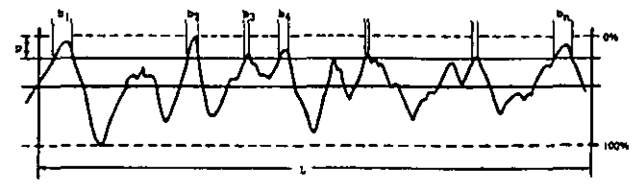


Figure 17. Copy of prints from Talisurf Mk1 referring to for Texture No. 9057 analysed in Experiment 3. Bearing Ratio (upper graph) and Rk analysis (lower graph) are showing Depth-, HSC- and tp%-data forming the basis for the graph in Figure 19. The lower graph shows Rpk at 5% Bearing Ratio which is illustrated in the upper graph.

Bearing Ratio t_p



Bearing ratio t_p is the length of bearing surface (expressed as a percentage of the assessment length L), at a depth p below the highest peak.

t_p (%) is the ratio at the depth p.

$$t_p = \frac{b_1 + b_2 + b_3 + b_4 \ldots b_n}{L} \times 100 = \frac{100}{L} \sum_{i=1}^{i=n} bi$$

The printout shows t_p% for each of the levels as for HSC.

The bearing ratio (or Abbott-Firestone) curve below, shows how the ratio varies with level.

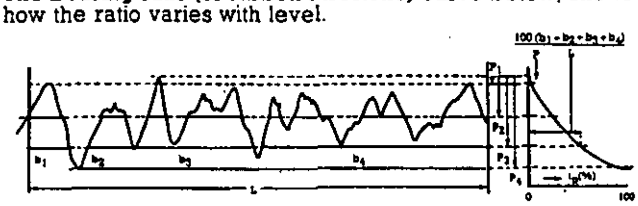
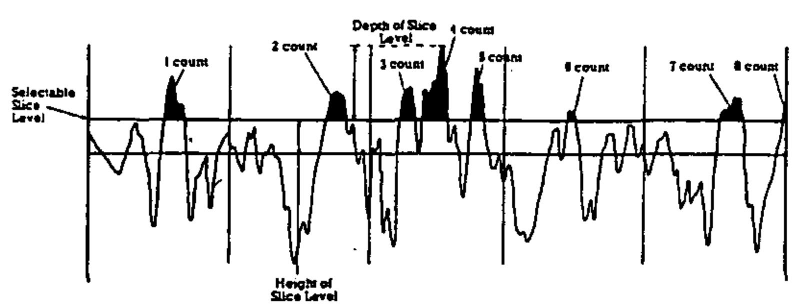


Figure 18. Specification of Bearing Ratio

HSC



HSC The high spot count is the number of complete profile peaks (within assessment length) projecting above the mean line, or a line parallel with the mean line. This line can be set at a selected depth below the highest peak or a selected distance above or below the mean line.

Figure 19. Specification of High Spot Count (HSC)

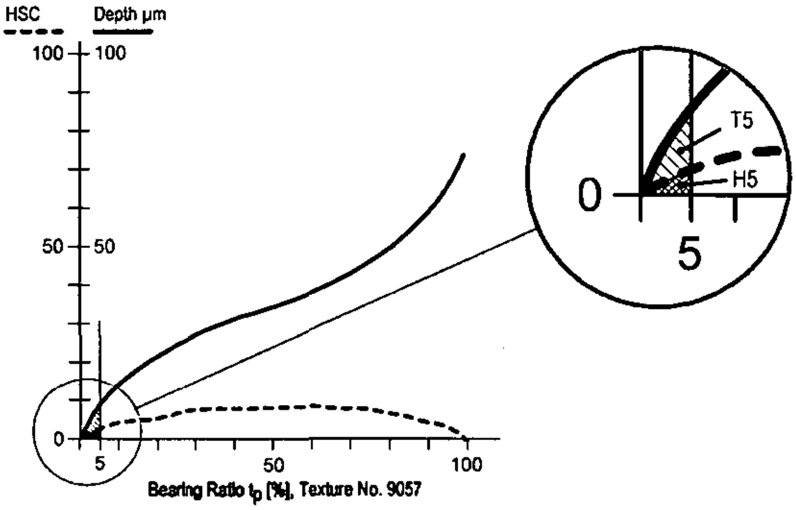


Figure 20. Graphic presentation of the calculations for texture No. 9057. The areas T5 and H5 under the Depth and HSC curves respectively, at 5% Bearing ratio are indicated as striped areas. Textures for which these areas are 5%of the total area under the respective curve can be expected to generate a high coefficient of friction in partnership with palm skin.

Appendix 3 Regression models

3.1 Regression model 1

Presentation of the regression model developed based on data collected in Experiment 2. The linear regression model selected for this analysis friction data, estimate coefficient of friction in real terms of μ when original variables (Xi see Table 1) are used along with regression coefficients, (Bi see Table 2), describing the textures (e.g. surface pressure) according to the equations in the regression model below. The data were analysed by linear regression according to the equation:

- $Y_i = B_0 + B_1 X_1 + B_2 X_2 + B_3 X_3 + E$

Where:

- Y_i = dependent variables μ_S, μ_k
- B_0 = intercept (Table 10:9)
- B_1 to B_3 = regression coefficients (Table 10.9)
- X_1 to X_3 = dummy coded variables (Table 10.8)
- E = error term

The dependent variables (Y_i) were μ_S, μ_k, CR-10_S and CR-10_K. Each texture was characteristic by three variables, surface pressure, pitch and duty cycle (Table 10.11).

Original variable	Level	Dummy variable	Level
Surface pressure (kPa)	15	X_1	-1
	60		0
	120		1
Pitch (mm)	0	X_2	-1
	1		0
	2		1
Duty cycle %	25	X_3	-1.5
	50		-0.5
	75		0.5
	100		1.5

Table 1 Original variables (surface pressure, pitch, duty cycle) and dummy variables (X1, X2, X3).

Estimated regression coefficients and explained variances are shown in Table 10.11. All coefficients for μk and μs were significant ($p< 0.05$), but not for CR-10s and CR-10k . Predicted values for texture No's. 1 to 5 and for two estimated textures estimated according to the equation above are presented in Table 10.13.

Contamination	Variable	Regression coefficient for			
		μs	**μk**	**CR-10s**	**CR-10k**
Sweat	Intercept	0.37	0.88	0.75	1.80
	X_1	- 0.045	- 0.27	0.58	0.96
	X_2	0.036	0.13	ns	0.62
	X_3	- 0.053	0.05	ns	ns
Explained variance	R^2 %	42	57	43	38
Paraffin oil	Intercept	0.44	0.47	0.84	1.62
	X_1	- 0.048	- 0.09	0.57	0.80
	X_2	0.067	0.12	ns	0.49
	X_3	- 0.10 *	- 0.15 *	- 0.24 *	ns
Explained variance	R^2 %	47	75	48	41
Lard	Intercept	0.34	0.52	0.83	1.32
	X_1	- 0.039	- 0.19	0.60	0.66
	X_2	0.069	0.058	ns	0.35
	X_3	- 0.10	- 0.11	-ns	ns
Explained variance	R^2 %	54	45	45	33

Table 2 **Regression coefficients for μs, μs CR-10s and CR-10k and contaminations. Explained variances (R^2 %) p-values if significant, otherwise ns.**

Example:

μ_s for texture No. 1, at 15 kPa surface pressure and "sweat" as hand condition, calculated as follows

- Surface load 15 kPa ($X_1 = -1$)
- Pitch = 1 mm ($X_2 = 0$)
- Duty cycle = 50 % ($X_3 = -0.5$)

$Y_i = B_0 + B_1 X_1 + B_2 X_2 + B_3 X_3 + E$

- $Y_i = \mu_s$
- $B_0 = 0.37$
- $B_1 = (-0.045)$
- $X_1 = (-1)$

- $B_2 = 0.036$
- $X_2 = 0$
- $B_3 = (-0.053)$
- $X_3 = (-0.5)$

$\mu_S = 0.37 + (-0.045) * (-1) + 0.036 * 0 + (-0.053) * (-0.5) = 0.44$ (also found in Table 10.13.)

Predicted values for coefficient of friction, (μ_S, μ_k) and discomfort (CR-10_S, CR-10_k) according to the regression model in the equation presented above are presented in Table 10.13. Friction and discomfort relates to surface pressures of 15, 60, and 120 kPa, pitches of 0, 1 and 2 mm, duty cycles 25, 50, 75, and 100 %.The skin conditions and contaminants which fitted the regression model were "sweat", paraffin oil and lard respectively. In application of the regression model, friction and discomfort data can be established for not only the five examined samples but also for "virtual" textures having other, and combinations other texture measures, within the limitations of the original variables. Predicted friction and discomfort data for two virtual textures are presented in table 10.13 along with such predictions of five examined samples. These samples are characterised by 1 mm pitch, 25 and 75% duty cycles, 15, 60, and 120 kPa surface pressures. These predictions are found within frames of double lines.

Duty cycle %		25%						50%						75%						100 %					
		Contamination								Contaminat ion						Contaminat ion				Contamination					
		"Sweat"		Paraffin oil		Lard		"Sweat"		Paraffin oil		Lard		"Sweat"		Paraffin oil		Lard		"Sweat"		Paraffin oil		Lard	
		μs	Cs	μs	Cs	μs	Cs	μs	Cs	μs	Cs	μs	Cs	μs	Cs	μs	Cs	μs	Cs	μs	Cs	μs	Cs	μs	Cs
		μk	Ck	μk	Ck	μk	Ck	μk	Ck	μk	Ck	μk	Ck	μk	Ck	μk	Ck	μk	Ck	μk	Ck	μk	Ck	μk	Ck
Pitch m.m	Pressure kPa																								
0	15																			0.30	0.0	0.27	0.00	0.15	0.00
																				1.09	0.33	0.22	0.00	0.48	0.29
	60																			0.25	0.45	0.22	0.48	0.11	0.50
																				0.83	1.30	0.13	0.76	0.29	0.95
	120																			0.21	1.03	0.17	1.05	0.08	1.10
																				0.56	2.26	0.04	1.56	0.11	1.61
1	15	0.49	0.36	0.65	0.62	0.53	0.47	0.44	0.23	0.54	0.39	0.43	0.31	0.39	0.10	0.44	0.15	0.33	0.16						
		1.06	0.72	0.78	1.19	0.88	0.67	1.12	0.79	0.64	0.94	0.77	0.66	1.17	0.87	0.49	0.70	0.65	0.65						
	60	0.45	0.94	0.60	1.19	0.50	1.06	0.40	0.81	0.49	0.96	0.34	0.91	0.34	0.68	0.39	0.72	0.29	0.76						
		0.80	1.68	0.69	1.99	0.70	1.33	0.85	1.76	0.55	1.74	0.58	1.32	0.90	1.84	0.40	1.49	0.47	1.31						
	120	0.40	1.52	0.55	1.76	0.46	1.66	0.35	1.39	0.45	1.53	0.35	1.51	0.30	1.26	0.34	1.29	0.25	1.36						
		0.53	2.64	0.60	2.79	0.51	1.99	0.58	2.72	0.46	2.54	0.40	1.98	0.63	2.80	0.31	2.29	0.28	1.98						
2	15	0.53	0.46	0.71	0.63	0.60	0.57	0.48	0.33	0.61	0.39	0.50	0.42	0.42	0.21	0.51	0.15	0.39	0.26						
		1.19	1.33	0.90	1.68	0.94	1.02	1.24	1.41	0.75	1.43	0.83	1.01	1.30	1.49	0.61	1.18	1.71	1.01						
	60	0.48	1.04	0.67	1.20	0.56	1.17	0.43	0.91	0.56	0.96	0.46	1.01	0.38	0.78	0.46	0.72	0.36	0.86						
		0.92	2.30	0.81	2.47	0.75	1.68	0.98	2.38	0.66	02.2	0.64	1.68	1.03	2.45	0.52	1.98	0.53	1.67						
	120	0.44	1.62	0.62	1.77	0.53	1.77	0.39	1.49	0.51	1.53	0.42	1.61	0.33	1.36	0.41	1.29	0.32	1.46						
		0.66	3.26	0.72	3.27	0.57	2.34	0.71	3.34	0.58	3.02	0.45	2.34	0.76	3.42	0.43	2.78	0.34	2.33						

Table 3 Predicted values for coefficient of friction, (μs,, μk) and discomfort (CR-10s, CR-10k) according to the regression model in Equation (4). Friction and discomfort relates to surface pressure, pitch, duty cycle and skin-sample condition.

3.2 Regression model 2

Presentation of the regression model developed based on data collected in Experiment 3. The linear regression model selected for this analysis friction data, estimate coefficient of friction in real terms of μ when regression coefficients, (Bi see Tables 4 and 5), are used along with original variables (Xi see Table 6) describing the textures (e.g. surface pressure) according to the equations in the regression model below. In addition to calculations in the main model, three interactions are required to complete the calculations according to the presented regression model. These are:

- Contamination * velocity
- Contamination * T5
- Contamination * H5

Regression coefficients and original variables

The regression coefficients (Bi) for the main effect and for interactions are presented in Table 4 and Table 5 respectively.

The original variables (Xi) for the main effect and for interactions and the range they cover are presented in Table 6

Regression coefficients (B_i) and original variables for the surface topography measures (Del.q, Sm, T5, H5) are presented in Table 7 and Table 8 respectively.--------------

Table 9 show an example of how original variables and regression coefficient are used in the main and interaction models to estimate the static coefficient of friction (velocity is 0 mm/s) for Texture No. 202 under "sweat " conditions and 7 kPa surface pressure.

Table 10 illustrates the contribution from the identified interactions with velocity and the surface topographies to the examined skin conditions and contaminants. A graphic illustration of the regression coefficients is presented in Figure 1.

The predicted coefficient of friction according to the regression model is presented in Table 11.

The linear regression model

The linear regression model enables an estimation of the relative contribution of the independent variables to the dependent variables over the velocity range 0-12mm/s. The regression model in Experiment 3 is as follows:

Main effect:

$Yi = B_0 + B_1 * X_1$ (surface pressure) + $B_2 * X_2$ (velocity) + $B_{3\text{-}6} * X_{3\text{-}6}$ (surface topographies) + $B_{7\text{-}12} * X_{7\text{-}12}$ (contaminants and skin conditions) + E

- and the additional three interactions

$B_{13\text{-}17}$*contaminations * X_2(velocity) + $B_{18\text{-}22}$*Contaminations * X_5 (surface topography T5)+ $B_{23\text{-}27}$ contaminations * X_6 (surface topography H5)+ E

Where:

Y_i = dependent variables μ_s, μ_k

X_1 to X_{12} = original variables (Table 3 in Appendix 3)

B_0 = intercept

B_1 to B_6 , and one of B_7 to B_{12} = regression coefficients for main effects (Table 1 in Appendix 3)

B_{13} to B_{27} = regression coefficients for interactions (Table 2 in Appendix 3)

E = error term

Main effect. Regression coefficients (Bi)	
Intercept, B_0	0.55
	Regression coefficient, Bi
(B_1) Surface pressure	-0.00390 *
(B_2) Velocity	0.08700 *
(B_3) Del.q	-0.00021*
(B_4) Sm	-0.00013
(B_5) T5	0.01450 *
(B_6) H5	-0.00220 *
(B_7) Glycerol	-0.09940
(B_8) Hydraulic fluid	-0.15200
(B_9) Engineering grease	-0.16200
(B_{10}) "Normal" clean skin	0.05750
(B_{11}) "Sweat"	0.04000
(B_{12}) Hydration	Reference level 0.00000

Table 4. Estimated regression coefficients (Bi) for the main effect. * = significant, $p < 0.05$

		Contamination/skin condition interactions					
	Interactions	**"Sweat"**	**Glycerol**	**"Normal" clean skin**	**Hydraulic fluid**	**Engineering grease**	**Hydration**
(X_2)Velocity	*Contamination/ skin condition	-0.08000*	-0.08500*	-0.07800*	-0.09300*	-0.09900*	Reference level 0
(X_5) T5	*Contamination /skin condition	-0.0083*	-0.01600*	0.00750*	-0.01300*	-0.01400*	Reference level 0
(X_6) H5	*Contamination /skin condition	0.00380*	0.00520*	0.00110	0.00660*	0.00500*	Reference level 0

Table 5. **Regression coefficients for three interactions in the presence of contaminants/skin conditions.**
***= significant, $p<0.05$**

Original variable (X_i)	Range and nominal data	Ratio
(X_1) Surface pressure	7 – 70 kPa	10
(X_2) Velocity	0, 6 and 12 mm/s	12
Surface topography (X_3) Del.q.	6.00-43.40	7.23
(X_4) Sm	0.65-512.7	788
(X_5) T5	3.75-14.00	3.73
(X_6) H5	6.25-117.00	18.72
Surface energy, total	Polycarbonate 47.6 mJ/m2	
Contaminations Nominal	(X_7) Glycerol (X_8) Hydraulic oil (X_9) Engineering grease	
Skin conditions Nominal	(X_{10}) "Normal" clean skin (X_{11}) "Sweat" (X_{12}) Hydrated skin	

Table 6. **The original variables (X_i) in the linear regression model, ranges and the ratio they cover.**

(X_i)	(B_j) per texture								
	No. 202	No. 203	No. 204	No. 9004	No. 9006	No. 9050	No. 9057	No. 9078	Ratio Max./Min.
Del.q	-0.00508	-0.00760	-0.09320	-0.00240	-0.00330	-0.00100	-0.00760	-0.00130	93.2
Sm	-0.00019	-0.00022	-0.00021	-0.00018	-0.07820	-0.03630	-0.05170	-0.06400	434.2
T5	0.20300	0.05800	0.18900	0.06540	0.18200	0.14500	0.40000	0.05450	7.7
H5	-0.09510	-0.25900	-0.21000	-0.02100	-0.01380	-0.01490	-0.06080	-0.01880	18.8
Summary. B_j per texture No.	0.10300	-0.20900	-0.11400	0.04180	0.08670	0.09280	0.28500	-0.02960	

Figure 7. **Regression coefficients (B_i) and the Summary contribution of the surface topography variables in the regression model (Del.q, Sm, T5 and H5) to coefficient of friction μ.. The last column shows the ratio between the largest and smallest coefficients.**

No.	Sample details	R_p	R_a	Del.q	S	S_m	T5	H5
201	Non-textured	0.56	0.015	0.61	59.72	125.24	42.50	3.50
202	Coarse 0.1mm	76.27	18.96	24.18	170.27	1.538	14.00	43.00
203	Coarse 0.3mm	143.94	54.15	35.04	539.64	1.751	4.00	117.00
204	Coarse 0.5mm	178.80	79.64	43.40	398.162	1.683	13.00	95.00
9004	"wide striped"	28.75	21.18	11.09	244.01	1.40	4.50	9.50
9006	"fine striped"	33.29	22.71	15.56	276.11	0.65	12.50	6.25
9050	"small dots"	7.23	2.75	4.64	121.0	290.42	10.0	6.75
9057	"large dots"	31.43	11.23	12.32	264.52	413.10	6.50	27.5
9078	"small dots and flat spots"	16.77	6.55	6.00	157.44	512.70	3.75	8.5
	Range	7.23 - 178.80	2.75 –79.64	6.00 - 43.40	121.0- 539.64	1.538- 624.7	3.75- 14.00	6.25- 117.00

Table 8. **Original variables of surface topography of the evaluated samples**

Parameter	**Original variable (X_i)**	**Regression coefficient (B_i)**	**Contribution to the estimated coefficient of friction (x_i x B_i)**
Intercept			*0.55*
Environmental conditions			
"Sweat" (X_{11} = 1)	*(X_{11} = 1)*	*B_{11} = 0.04*	*0.04*
Surface pressure, (X_1 = 7) kPa	*(X_1 = 7)*	*B_1 = - 0.0039*	*0.0273*
Velocity (X_2 = 0) mm/s	*(X_2 = 0)*	*B_2 = 0.087*	*0*
Texture No. 202 - Surface topography			
Del.q. (X_3 = 24.18)	*(X_3 = 24.18)*	*B_3 = -0.00021*	*-0.0052*
Sm (X_4 = 1.54)	*(X_4 = 1.54)*	*B_4 = (-0.00013*	*- 0.00019*
T5 (X_5 = 14.00)	*(X_5 = 14.00)*	*B_5 = 0.01450*	*0.203*
H5 (X_6 = 43.00)	*(X_6 = 43.00)*	*B_6 -0.0022*	*-0.0951*
Interactions			
Velocity (X_2 = 0) multiplied by "sweat",(B_{13} =-0.08)	*(X_2 = 0)*	*(B_{13} =-0.087*	*0*
T5 (X_5 = 14.00) multiplied by "sweat" (B_{16} = -0.0083)	*(X_5 = 14.00)*	*(B_{16} = -0.0083)*	*- 0.1162*
H5 (X_6 = 43.00) multiplied by "sweat" (B_{19} = 0.0038)	*(X_6 = 43.00)*	*(B_{19} = 0.0038)*	*0.1634*
			0.71

Table 9 **Example of how original variables and regression coefficient are used in the main and interaction model to estimate the static coefficient of friction (velocity is 0 mm/s) for Texture No. 202 under "sweat " conditions and 7 kPa surface pressure. The respective contribution to the estimated coefficient of friction according to the main an d interaction effects are presenter in the right column.**

Friction interface characteristics	Texture specifics				Environmental factors		Skin condition			Contamination		
Intercept Bo= 0.55	Del.q	Sm	T5	H5	Velocity	Surface pressure	"Normal" clean skin	'Sweat"	Hydrated	Glycerol	Engineering grease	Hydraulic oil
Range	6.00-43.40	0.65-512.7	3.75-14.00	6.25-117.00	0, 6 and 12 mm/s	7 – 70 kPa						
Main effect - coefficients, (B_i)	- 0.00021*	-0.00013	0.01450*	-0.00220*	0.08700*	-0.00390*	0.05750	0.04000	Reference level 0	-0.09940	-0.15200	-0.15200
Keys	-	-	++	-	++	-	++	++		--	---	---
Interactions (keys)												
"Normal" clean skin			++	+	--							
"Sweat"			-	+	--							
Hydrated			0	0	0							
Glycerol			--	++	--							
Hydraulic oil			--	++	--							
Engineering grease			--	++	--							

- Note : The main effect is presented on the row "Main effect." The contributions from interactions to the main effect (ie. ++, -- etc) are found at the intersections between the variablesand T5, H5, and velocity. For significant interactions se Table 11.13 in Appendix 3 * = significant. $p<0.05$

Keys (regression coefficient values)

---	Bi < - 0.1	0 = Reference level	+++	Bi > 0.1
--	Bi = -0.005 to –0.1		++	Bi = 0.005 to 0.1
-	Bi = 0 to – 0.005		+	Bi = 0 to 0.005

Table 10. Regression coefficients (B_i), the interactions and their contribution to μ for velocities 0-12 mm/s

Contaminations and skin conditions	Surface pressure kPa	Velocity mm/s	Texture							
			No. 202	No. 203	No. 204	No. 90046	No. 9006	No. 9050	No. 9057	No. 9078
"Normal" clean skin	7	0	0.84	0.53	0.67	0.67	0.77	0.76	1.10	0.59
		3	0.86	0.55	0.69	0.69	0.80	0.78	1.13	0.62
		12	0.94	0.63	0.77	0.77	0.87	0.86	1.21	0.69
	70	0	0.59	0.28	0.42	0.42	0.52	0.51	0.85	0.34
		3	0.61	0.3	0.44	0.45	0.55	0.54	0.88	0.37
		12	0.69	0.38	0.52	0.52	0.62	0.61	0.96	0.45
"Sweat"	7	0	0.71	0.77	0.71	0.61	0.57	0.60	0.73	0.54
		3	0.74	0.79	0.73	0.63	0.59	0.62	0.75	0.56
		12	0.80	0.85	0.79	0.69	0.65	0.68	0.81	0.62
	70	0	0.47	0.52	0.46	0.36	0.32	0.35	0.48	0.29
		3	0.49	0.54	0.48	0.38	0.34	0.37	0.50	0.31
		12	0.55	0.61	0.54	0.44	0.41	0.43	0.56	0.37
Hydration	7	0	0.62	0.32	0.41	0.57	0.61	0.62	0.81	0.50
		3	0.89	0.58	0.67	0.83	0.87	0.88	1.07	0.75
		12	1.67	1.35	1.45	1.61	1.65	1.66	1.85	1.53
	70	0	0.37	0.07	0.16	0.32	0.36	0.37	0.56	0.25
		3	0.69	0.33	0.42	0.58	0.62	0.63	0.82	0.51
		12	1.42	1.11	1.20	1.36	1.40	1.41	1.60	1.29
Glycerol	7	0	0.53	0.76	0.60	0.44	0.34	0.39	0.41	0.38
		3	0.53	0.76	0.60	0.45	0.35	0.40	0.41	0.38
		12	0.54	0.78	0.61	0.46	0.36	0.41	0.43	0.39
	70	0	0.28	0.51	0.35	0.20	0.10	0.14	0.16	0.13
		3	0.28	0.52	0.35	0.20	0.10	0.15	0.17	0.13
		12	0.29	0.53	0.36	0.21	0.11	0.16	0.18	0.15
Hydraulic fluid	7	0	0.58	0.88	0.72	0.42	0.34	0.38	0.49	0.35
		3	0.56	0.86	0.70	0.40	0.32	0.36	0.47	0.33
		12	0.50	0.81	0.64	0.34	0.27	0.31	0.41	0.28
	70	0	0.33	0.63	0.47	0.17	0.09	0.14	0.24	0.10
		3	0.31	0.61	0.45	0.15	0.07	0.12	0.22	0.08
		12	0.26	0.56	0.39	0.10	0.02	0.06	0.16	0.03
Engineering grease	7	0	0.50	0.70	0.56	0.40	0.32	0.36	0.42	0.34
		3	0.46	0.66	0.52	0.36	0.28	0.33	0.38	0.30
		12	0.35	0.55	0.41	0.25	0.17	0.21	0.27	0.18
	70	0	0.25	0.45	0.31	0.15	0.07	0.12	0.17	0.09
		3	0.22	0.41	0.27	0.12	0.03	0.08	0.14	0.05
		12	0.10	0.30	0.16	0	0	0	0.02	0

Table 11. **Predicted μ for textures * contamination's * surface pr4essure * velocity and their interactions according to the regression model. Bold figures illustrates which texture provides the highest μ for each skin condition and contaminant.**

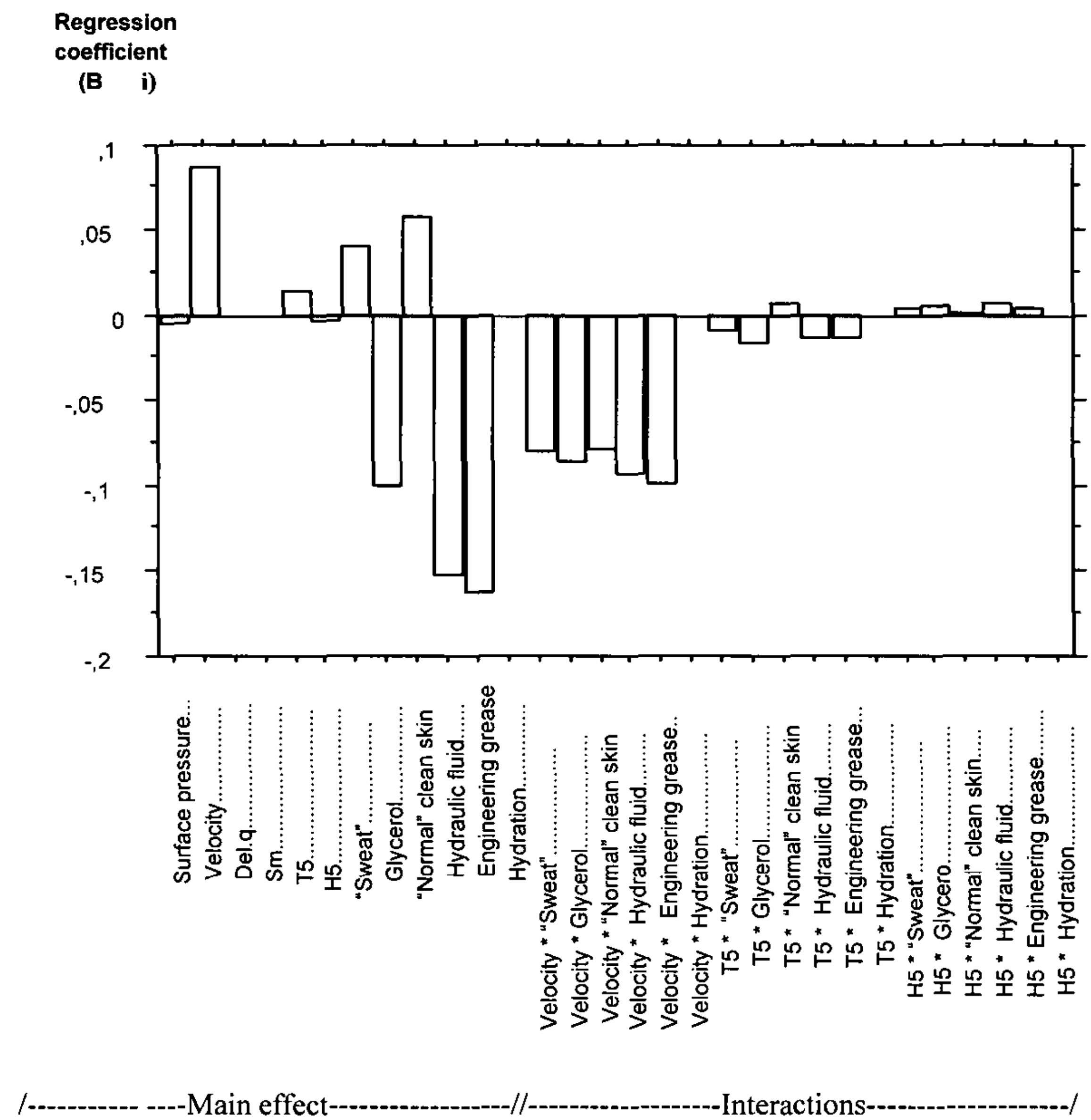


Figure 12. Illustration of the coefficients in the regression model. Three skin conditions, three contaminants surface pressure, velocity and surface topographies (Del.q, Sm, T5, H5). Reference level (0) is the hydrated condition.

Appendix 4 A research approach to the design of ergonomic hand tools

The Bahco 11-point program for the development of ergonomic hand tools.

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Background

The program's scientific content was presented at PREMUS 95, the international scientific conference on the prevention of work-related injuries. The conference took place in Montreal, Canada, in September 1995.

Contents

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

1. Market analysis

Which tools are most popular and why?

Now it's time to take a look at the tools that professionals prefer. We take a keen interest in tools that claim to be the best technically, and those that claim to be the best ergonomically.

Why do users think that certain tools are better than others? What characteristics do these tools share? How durable are they? How are they maintained? Which design solutions are most popular? Which tools are easiest to handle? Give the best results? Reduce the pressure exerted on users' hands? Which tools are the correct size? Weigh just enough and no more? Provide the right friction? Which tools actually reduce the risk of injury?

And finally: How are the best tools marketed? How much do they cost? Are they so much better that user are willing to pay a premium?

2. Preliminary specifications

Factors that we take into consideration.

It sounds easy, but this first step is much more comprehensive than you think.

We start by raising key questions. What is the tool supposed to do? How often will it be used? For how long? With one hand, or two? How refined is the end-result? Should the tool be capable of performing several tasks, or just one? Who will use the tool? What build will the user have? How strong? What work skills will he or she have? What experience? Will the user have large hands? How much will user hands vary? How is this type of tool usually used? In which working postures? For what kinds of jobs? Are protective clothes worn? Or gloves? What are the typical working conditions? What positions will users have while they are using the tool? Is the tool usually fixed in place, or does it move about?

What about the work environment? Temperature? Humidity? Visibility? Vibrations? Noise? Dirt? Are additional accessories required? If so, when are they used? What kinds of demands will be made on the tool? How large should the tool be? Should it come in different sizes? What would be the ideal shape? Maximum weight? Minimum weight? Which materials are most suitable? And which are unsuitable? What are the appropriate performance parameters? What kind of force should the tool resist? Do any international standards apply? Does legislation vary from one country to another? We find the answers by interviewing users and observing the way they work, and by drawing on our own experience. Using this data, we develop the specifications for the new tool. But this is only the beginning. At this stage, nothing is final. Our preliminary specifications may change at any time if new and better ideas emerge later in the development process

3. Background research

We look into and learn from other sources

Research on work-related injuries caused by hand tools is published worldwide on an ongoing basis. We can learn a lot from the work of others. So we read books, reports and analytical studies. We examine international medical databases. What are the risks associated with this particular type of tool? Which factors exacerbate the risk of work-related injuries? What are the statistics on accidents and injuries? Which injuries are described in detail? What can we learn from the technical performance tests that have been carried out? What can we learn from user experience that has been documented? What experience have we at Bahco Saws and Tools had with this type of tool? What can we learn from it?

4. Prototype design

A dozen prototypes, all ergonomically designed.

On the basis of the information gathered during steps one, two and three, we now develop the first working prototypes. Each prototype is designed to conform to the latest ergonomic findings by researchers. Hand and handle must work together in harmony. The user must be able to exert precise manual control over the tool's working parts - the jaws of an adjustable wrench, for example, or the tip of a pair of pliers. We pay special attention to the fact that users' hands come in all shapes and sizes. Other key factors that influence material selection for the prototype are climate, temperature and typical industrial applications.

We make prototype tools out of the same materials and in the same colors, so that user tests will provide us with as much realistic feedback as possible.

5. User test #1

We select, measure and film hundreds of hands at work.

This crucial step takes a long time. Because we sell our tools worldwide, we must test their suitability for many different kinds of hands. We start by choosing professional users who rely heavily on the tools. We choose them from the industrial sectors and target countries in which the given tool is most widely used. We then take exact measurements of each user's hand. We record each hand's length, width and strength. We use a gripping cone to measure gripping diameter: between thumb and forefinger, thumb and middle finger, and thumb and ring finger. Then we make a paper tracing of each hand.

Now for the test itself. The test must be performed exactly the same way every time. So the tool is delivered to each test user in the same way, in identical packaging. The explanation accompanying the test is the same for each user. And then the users try each prototype in turn, under realistic circumstances, according to a routine worked out by our researchers.

We document the performance of each tool with the help of video recordings, interviews and questionnaires. We also collect information on the way each user actually employs the tool and what he or she thinks of it. We seek both spontaneous reactions as well as opinions that have been thought-through. If a user feels pain, or unnecessarily high pressure at certain points, these points are carefully noted on the sketch of the user's hand.

We use a variety of methods to establish which tool the users prefer. Ranking, individual grading and eliminating prototypes by comparing pairs of tools are the most common. The shape, ease of manipulation and "graspability" of each tool are recorded and graded. In many cases, we also have to use other measuring methods. Thus we use EMG - electromiography - to measure muscular tension, and a goniometer to measure the position of users' hands.

The test period is an intense and critical time for our product developers, as well as for our ergonomists and industrial designers

6. Prototype evaluation and modification

User preferences give us the clues we need

Step six is exciting. This is when we modify the best prototypes to make them even better. Improvements are based on in-depth analysis of the preceding user tests. This phase takes two to three months. We are now laying the foundations for the finished design. We begin by improving the size and shape of the handle. We decide whether to make the tool in several sizes, or whether the same tool should be suitable for use by hands of many different sizes and shapes. We decide which materials to use, and what surface friction these materials should possess.We complete this phase by producing a limited number of refined prototypes.

7. User test #2

The new prototypes are tested by an even wider selection of users.

The total number of new prototypes is smaller, but we ask an even larger number of users in even more countries to test them. Once again, we involve users who took part in our first tests, but we also extend our testing to cover a significant number of new users

To make sure we capture as many viewpoints as possible, we also select a group of highly-qualified users who provide us with especially good comments.

8. Final design recommendations

Manufacturing the true-to-life prototype.

Analyzing user test #2 is quick and painless - if the results indicate that we are on the right track. But this is also the moment at which certain key decisions have to be made. For example, the majority of users may prefer a particular technological solution. But there may be a sizable minority who dislike this solution intensely. Do we go back to step 6 and attempt to find a solution that appeals to both groups? Or do we develop the tool preferred by the majority? And if we go for the latter option, do we also develop a tool for the minority?

In most cases, we find we're on the right track. And that's when we decide on the final design criteria, based on the prototype that turned out to be most popular during user test

#2.

We decide on precise radii for all the curves and contours on the tool. We determine the design of corners and edges. We finalize the different positions the tool can take. Materials, colours and graphics are specified in detail. Finally, we manufacture a tool that is identical in every way to the tool that will eventually be sold to professional users worldwide. A true-to-life prototype.

9. Product specifications

We produce manufacturing specifications

The new tool is based on new ideas, so it rarely resembles existing tools. Which means we can't simply re-use existing manufacturing specifications. Almost everything must be specified from scratch. Over a few months of frenetic activity, our designers and production engineers prepare all the necessary CAD drawings and specifications for the new tool. Based on these specifications, we manufacture a small run of "finished" tools for our final user test.

This limited production series also allows us to test our new manufacturing equipment and machine-tool setups.

10. User test #3 Preparation for launch

The new tool is approved and marked with our Ergo symbol.

We want to make absolutely sure that our new tool satisfies the needs of users worldwide. So we perform one final user test. The test is performed with about 200 tools. Afterwards, our ergonomists evaluate user feedback on the tool's performance and handling over an extended period of time. If this final test shows that the tool works as it should, the tool is approved for mass production and marked with our Ergo symbol. While the test is under way, we prepare for the tool's launch by producing a demonstration pack for sales representatives. We decide on the design of the packaging and produce printed promotional material, advertising and press releases. The entire process of tool development, from specification to approval, lasts between two and three years.

11. Follow-up

Five years later: What do users think?

It isn't easy to prove scientifically that one hand tool is better than another. Even a tool that has been correctly and ergonomically designed can be used in the wrong way. If users often apply excessive force or adopt inefficient working postures, the inherent quality of the tool is negated and the risk of work-related injuries rises accordingly.

Appendix 5 Experimental studies <u>not</u> presented in this thesis

Experiment 4 Palm friction for 89 different materials

This experiment investigated the dynamic friction, μ_k, for 89 different materials without textures. They belong to 10 categories of thermoplastic, viscoelastic, construction polymers, steel, non-ferrous metals, textiles, paper, sandpaper, suede and leather. Several samples of the same material were provided with different surface treatments e.g. varnished, chrome plated, phosphated. They were investigated under moderate to high surface pressure. Investigations were made on a "normal" and a hydrated hand. Some materials were researched when contaminants such as glycerol, hydraulic fluid and grease were present on the friction interface.

Experiment 5 Coefficient of dynamic palm friction in white and blue collar workers

The experiment investigated the differences in coefficient of dynamic skin friction at low and high exposed groups. Seven of the subjects were office office workers. Ten subjects performed daily hand intensive work. They were professional bricklayers, carpenters, mechanics, labourers, plumbers and gardeners. Different materials and textures, but also two skin conditions were investigated, "normal" and "sweat" skin.

Experiment 6 Palm friction in different palm locations.

This research investigated the friction in the pad of all fingers but also the skin centrally in the palm and locations in the tenar and hypotenar area respectively.

Experiment 7 Palm friction in dry, normal and moist hands

This experiment focused on the moisture of palm skin and the association with friction. Subject's hands were normal and moist but also dry.

Experiment 8 Perception of palm friction in textured and not textured surfaces.

The objective of this experiment was to find whether the true palm coefficient of friction in partnership with five samples could be determined by touch. 60 subjects took part in the experiment. 20 were heavy manual workers in a steel works. 20 were office workers and 20 performed light, hand intensive industrial work. The true coefficient of friction against palm skin had already been established in another experiment (Bobjer et al 1993). The subjects were asked to touch the sample by pulling their fingers across their grooves. Their task was to rank the five samples for perceived friction from highest to lowest.