Prosthetics and Orthotics International, 1999, 23, 135–141

In vivo friction properties of human skin

M. ZHANG and A. F. T. MAK

Rehabilitaion Engineering Centre, The Hong Kong Polytechnic University, Kowloon, Hong Kong

Abstract

In vivo frictional properties of human skin and five materials, namely aluminium, nylon, silicone, cotton sock, Pelite, were investigated. Normal and untreated skin over six anatomic regions of ten normal subjects were measured under a controlled environment. The average coefficient of friction for all measurements is 0.46±0.15 ($p<0.05$). Among all measured sites, the palm of the hand has the highest coefficient of friction (0.62±0.22). For all the materials tested, silicone has the highest coefficient of friction (0.61±0.21), while nylon has the lowest friction (0.37±0.09).

Introduction

Frictional properties of human skin depend not only on the skin itself, its texture, its suppleness and smoothness, and its dryness or oiliness (Lodén, 1995), but also on its interaction with external surfaces and the outside environment. Investigation of skin frictional properties is relevant to several research areas, such as skin physiology, skin care products, textile industry, human friction-dependent activities and skin friction-induced injuries.

Frictional properties of the skin surface may become an objective assessment of skin pathologies. It has been shown that frictional properties can reflect the chemical and physical properties of the skin surface and thus depend on the physiological variations as well as pathological conditions of skin (Lodén *et al.*, 1992; Lodén, 1995; Comaish and Bottoms, 1971; Elsner *et al.*, 1990; Cua *et al.*, 1995). The measurement of skin friction may be useful in studying the progress of individual disease processes in skin (Comaish and Bottoms, 1971). Lodén *et al.* (1992) found experimentally that the friction of skin with dry atopic subjects was significantly lower than that for the normal skin.

Skin frictional data have been used to evaluate skin care and cosmetic products (El-Shimi, 1977). Friction of skin forms an integral part of tactile perception and plays an important role in the objective evaluation of consumer-perceptible skin attributes (Wolfram, 1983 and 1989). Cosmetic products, which aim at conferring smoothness to the skin, are thought to perform their function by depositing sufficient amounts of desirable ingredients leading to a perceptible change in the adhesion and friction properties of skin. Some experiments (Nacht *et al.*, 1981; El-Shimi, 1977; Gerrard 1987; Hills *et al.*, 1994; Highley *et al.*, 1977) investigated friction changes induced by hydration and emollient application and the correlation with perceived skin feel. The changes in skin friction coefficient immediately after product use are inversely proportional to the subjective after-feel of "greasiness", that is, the higher the increase in skin friction coefficient, the less greasy the product is perceived (Nacht *et al.*, 1981). In textile industry, skin friction to clothing materials may be related to sensation, comfort or fabric cling (Kenins, 1994).

Skin friction properties are also relevant to some friction-dependent functions, such as grasping, gripping and locomotion (Cua *et al.*, 1990; Johansson and Cole, 1994; Smith and Scott, 1996). An understanding of these properties is very important in the design of handles, tools, controls and shoes. Buchholz *et al.* (1988) investigated the frictional properties of human palmar skin and various

All correspondence to be addressed to Professor Arthur F. T. Mak, Rehabilitation Engineering Centre, The Hong Kong Polytechnic University, Kowloon, Hong Kong. Tel: (+852) 2766 7673 Fax: (+852) 2362 4365 E-mail: rcafmak@polyu.edu.hk

materials, using a two-fingered pinch grip and studying the effects of subjects, materials, moisture and pinch force. Taylor and Lenderman (1975) measured the coefficient of static friction between finger tips and aluminium (0.6) and found the value dropped by at least 75% when the surfaces were covered with soap. Foot-insole friction was investigated to study the characteristics of locomotion and damage to the foot skin.

The investigation of the skin frictional properties is also helpful in understanding skin friction-induced injuries (Naylor, 1955; Sulzberger *et al.*, 1966; Dalton, 1982; Armstrong, 1985; Akers, 1985). The injurious effects of friction on the skin and the underlying tissues can be divided into two classes, those without slip and those with slip. The former may rupture the epidermis and occlude blood and interstitial fluid-flows by stretching or compressing the skin. The latter adds an abrasion to this damage. Research showed that the skin shear force, produced by frictional force combining with pressure, is effective in occluding skin blood flow (Bennett *et al.*, 1979; Zhang and Roberts, 1993; Zhang *et al.*, 1994). Repetitive rubbing causes blistering and produces heat which may have uncomfortable and injurious consequences.

In lower-limb prosthetic socket and orthotic design, achieving a proper load transfer is the key issue since the soft tissues, such as those of the stump, which are not suited for loading, have to support the body weight as well as other functional loads. Skin and prosthetic device forms a critical interface, at which skin friction is an important determinant in the mechanical interactional properties. Friction plays significant roles in supporting the load and in causing discomfort or skin damage (Zhang, 1995; Zhang *et al.*, 1996). To optimise frictional actions, there is a requirement to understand adequately the friction properties between the skin and its contact surface.

Fig. 1 Skin friction meter.

In spite of its importance, there is however a paucity of knowledge about the frictional properties of skin and those materials used in prosthetic and orthotic devices. The objective of this study is to investigate the friction properties of skin in contact with those materials, and the variation of friction with load magnitudes, rotation speeds, anatomical sites and subjects.

Materials and methods

Skin frictional force was measured using Measurement Technologies Skin Friction Meter (Aca-Derm Inc., California), described in details by Elsnau (1995). The main part of the meter is a hand-held probe unit, including a DC motor, a rotating Teflon disk probe and rotary position transducer. When resting on the skin surface, the rotating disk probe contacts with skin and the torque resulting from frictional force can be measured. The normal force cannot be monitored, but depends on the relative position of the rotary probe to the base plate. The normal force applied to the probe is assumed to be constant, if only the weight of the probe unit is applied and the relative position of the rotary probe to the base plate is unchanged. However the weight supported by the base plate or by the sensing area depends on the geometry and stiffness of the soft tissue and the underlying bone in the measurement sites.

The Friction Meter is used in this investigation had two improvements. First, normal force was monitored by an additional spring balance. A critical factor in the accurate and consistent measurement of the coefficient of friction is the normal force applied. In this study, a spring balance (capacity 1kg) was connected to the hand-held probe, as shown in Figure 1. The base plate did not contact the skin surface. The weight applied to the skin surface can be read from the spring balance. A high accuracy electronic balance (AS200, OHAUS) was used to validate the accuracy of the spring balance reading. In 20 trials with application of an intended load of 100 grams, results showed that the weight recorded ranged from 93 to 108 grams, with an average 100.5±4.7 grams.

Table 1. Coefficients of friction measured at six sites (DH = dorsum of hand, PH = palm of hand, AF = anterior side of forearm, PF = posterior side of forearm, AL = anterior leg, PL = posterior leg) to five materials for 10 subjects.

Subject		sub 1	sub 2	sub 3	sub 4	sub 5	sub 6	sub 7	sub 8	sub 9	sub 10	Mean
Al	DH	0.37±0.04	0.27±0.02	0.47±0.04	0.50±0.05	0.45±0.03	0.58±0.02	0.35±0.06	0.38±0.02	0.36±0.03	0.48±0.05	0.42+0.09
	PH	0.57±0.04	0.40±0.03	0.55±0.02	0.58±0.02	0.58±0.01	0.57±0.02	0.58±0.11	0.32±0.06	0.75±0.06	1.00±0.11	0.59+0.18
	AF	0.36±0.02	0.34±0.03	0.39±0.02	0.43±0.04	0.44±0.03	0.52±0.04	0.32±0.02	0.46±0.06	0.47±0.08	0.32±0.03	0.40+0.08
	PF	0.32±0.02	0.33±0.03	0.40±0.01	0.39±0.04	0.32±0.03	0.58±0.03	0.28±0.02	0.37±0.03	0.29±0.03	0.29±0.02	0.36+0.09
	AL	0.24±0.03	0.24±0.02	0.40±0.03	0.45±0.04	0.32±0.01	0.50±0.03	0.31±0.02	0.32±0.02	0.32±0.03	0.33±0.06	0.34+0.09
	PL	0.27±0.01	0.26±0.02	0.32±0.04	0.37±0.03	0.29±0.02	0.51±0.04	0.29±0.02	0.32±0.02	0.37±0.02	0.41±0.04	0.34+0.08
	mean	0.36±0.11	0.32±0.06	0.42±0.08	0.45±0.08	0.40±0.11	0.54±0.05	0.36±0.11	0.36±0.06	0.43±0.16	0.47±0.25	0.42+0.14
Nylon	DH	0.37±0.03	0.30±0.02	0.43±0.03	0.47±0.02	0.41±0.03	0.45±0.03	0.29±0.01	0.29±0.08	0.43±0.02	0.31±0.03	0.38+0.08
	PH	0.42±0.02	0.38±0.03	0.49±0.04	0.43±0.03	0.46±0.02	0.49±0.03	0.40±0.02	0.36±0.06	0.58±0.01	0.70±0.08	0.47+0.10
	AF	0.40±0.02	0.32±0.02	0.38±0.05	0.40±0.01	0.39±0.01	0.37±0.02	0.33±0.04	0.32±0.02	0.37±0.02	0.42±0.07	0.37+0.05
	PF	0.35±0.03	0.31±0.02	0.30±0.02	0.33±0.01	0.34±0.02	0.43±0.03	0.31±0.04	0.33±0.03	0.29±0.02	0.34±0.01	0.33+0.04
	AL	0.30±0.02	0.30±0.03	0.42±0.02	0.32±0.01	0.36±0.03	0.35±0.03	0.28±0.01	0.23±0.02	0.27±0.02	0.38±0.02	0.32+0.06
	PL	0.33±0.02	0.26±0.02	0.41±0.04	0.34±0.02	0.29±0.02	0.39±0.04	0.28±0.01	0.24±0.04	0.27±0.02	0.38±0.02	0.32+0.06
	mean	0.36±0.05	0.31±0.04	0.40±0.06	0.38±0.06	0.38±0.06	0.42±0.06	0.32±0.05	0.29±0.06	0.37±0.11	0.42±0.14	0.37+0.09
Silicone	DH	0.44±0.03	0.40±0.03	0.75±0.07	0.66±0.04	0.54±0.02	0.60±0.02	0.86±0.22	0.44±0.05	0.50±0.06	0.51±0.04	0.57+0.16
	PH	0.80±0.04	0.67±0.05	0.98±0.05	0.98±0.04	0.88±0.05	0.84±0.07	1.26±0.11	0.63±0.03	1.16±0.11	1.06±0.09	0.93+0.20
	AF	0.48±0.02	0.46±0.02	0.65±0.03	0.61±0.02	0.57±0.04	0.58±0.03	0.68±0.01	0.41±0.02	0.61±0.12	0.47±0.05	0.55+0.10
	PF	0.38±0.04	0.44±0.03	0.50±0.03	0.51±0.05	0.56±0.04	0.63±0.03	0.64±0.13	0.60±0.04	0.43±0.04	0.43±0.05	0.52+0.10
	AL	0.39±0.04	0.44±0.03	0.46±0.04	0.68±0.02	0.45±0.01	0.59±0.02	0.57±0.02	0.40±0.06	0.37±0.04	0.42±0.03	0.48+0.10
	PL	0.46±0.04	0.53±0.01	0.44±0.03	0.51±0.03	0.45±0.03	0.62±0.03	0.51±0.06	0.41±0.07	0.35±0.04	0.40±0.09	0.47+0.09
	mean	0.49±0.15	0.50±0.09	0.63±0.19	0.66±0.17	0.58±0.15	0.64±0.10	0.75±0.27	0.48±0.11	0.57±0.29	0.55±0.24	0.61+0.21
Sock	DH	0.39±0.04	0.43±0.04	0.50±0.03	0.64±0.02	0.59±0.02	0.56±0.04	0.47±0.09	0.46±0.01	0.57±0.03	0.53±0.04	0.52+0.08
	PH	0.46±0.06	0.44±0.02	0.53±0.04	0.66±0.04	0.57±0.07	0.63±0.03	0.58±0.11	0.42±0.03	0.72±0.03	0.95±0.07	0.60+0.16
	AF	0.42±0.02	0.42±0.03	0.63±0.03	0.57±0.03	0.49±0.01	0.50±0.04	0.55±0.07	0.49±0.02	0.66±0.08	0.53±0.05	0.52+0.08
	PF	0.43±0.02	0.46±0.02	0.50±0.03	0.50±0.03	0.56±0.04	0.58±0.03	0.52±0.06	0.44±0.03	0.49±0.07	0.39±0.02	0.49+0.07
	AL	0.39±0.04	0.35±0.02	0.49±0.02	0.52±0.04	0.39±0.02	0.52±0.04	0.52±0.02	0.41±0.03	0.42±0.05	0.36±0.03	0.44+0.07
	PL	0.48±0.02	0.42±0.03	0.35±0.02	0.42±0.01	0.34±0.03	0.53±0.05	0.49±0.02	0.43±0.04	0.42±0.04	0.37±0.02	0.43+0.06
	mean	0.43±0.05	0.42±0.05	0.50±0.08	0.55±0.09	0.49±0.10	0.55±0.06	0.52±0.07	0.44±0.04	0.54±0.13	0.52±0.21	0.51+0.11
Pelite	DH	0.43±0.03	0.46±0.02	0.44±0.03	0.41±0.02	0.44±0.01	0.42±0.02	0.49±0.09	0.37±0.02	0.49±0.05	0.46±0.03	0.44+0.05
	PH	0.56±0.03	0.56±0.04	0.49±0.02	0.47±0.01	0.47±0.01	0.46±0.04	0.42±0.03	0.44±0.02	0.54±0.05	0.65±0.05	0.51+0.07
	AF	0.49±0.02	0.50±0.04	0.52±0.02	0.39±0.03	0.44±0.01	0.42±0.03	0.36±0.02	0.42±0.03	0.51±0.03	0.48±0.08	0.45+0.06
	PF	0.46±0.02	0.43±0.02	0.45±0.02	0.45±0.02	0.42±0.02	0.47±0.05	0.58±0.11	0.44±0.03	0.39±0.03	0.41±0.03	0.45+0.07
	AL	0.37±0.03	0.42±0.03	0.43±0.03	0.44±0.03	0.42±0.02	0.40±0.03	0.53±0.05	0.40±0.03	0.38±0.02	0.42±0.05	0.42+0.05
	PL	0.47±0.02	0.51±0.05	0.38±0.03	0.38±0.01	0.39±0.01	0.45±0.02	0.50±0.04	0.38±0.02	0.30±0.02	0.42±0.04	0.43+0.06
	mean	0.46±0.06	0.48±0.06	0.45±0.05	0.42±0.04	0.43±0.03	0.44±0.04	0.48±0.09	0.41±0.04	0.45±0.07	0.47±0.09	0.45+0.07
MEAN		0.42±0.11	0.41±0.10	0.48±0.14	0.49±0.14	0.45±0.12	0.52±0.10	0.49±0.21	0.40±0.09	0.47±0.18	0.49±0.20	0.46±0.15

Table 2. Mean coefficients of friction at the six anatomical sites (DH = dorsum of hand, PH = palm of hand, AF = anterior side of forearm, PF = posterior side of forearm, AL = anterior leg, PL = posterior leg) with all materials for all subjects.

Site	DH	PH	AF	PF	AL	PL
Coefficient	0.47±0.12	0.62±0.22	0.46±0.10	0.43±0.10	0.40±0.10	0.40±0.09

Table 3. Mean coefficient of friction with the five materials at all sites for all subjects.

Material	Aluminium	Nylon	Silicone	Sock	Pelite
Coefficient	0.42±0.14	0.37±0.09	0.61±0.21	0.51±0.11	0.45±0.07

The second improvement was made on the sensing surface, using a plane-ended annulus instead of a solid plane or a hemispherical shape. The pressure distribution in the sensing surface will affect the frictional torque – the product of the force and the distance to the centre.

In practice, the pressure distribution on the sensing surface varies with the geometry and the stiffness of the soft tissues and the underlying bone. An annular surface applying the load over the annulus can eliminate the error caused by the load distribution. In this study, all the probe sensing surfaces were annular with an outer diameter of 16mm and an inner diameter of 10mm.

Five (5) materials, namely, aluminium, nylon, silicone (soft liner material for trans-tibial suction sockets), cotton sock (often worn with a prosthesis) and Pelite (soft liner material for lower limb prostheses) were measured. The sensing surfaces of aluminium and nylon were machined with fine turning. An annular disk of silicone, cotton sock or Pelite was glued on the tip of the metal probe.

Ten (10) normal subjects, age from 19 to 40, with no visible signs of skin diseases, voluntarily participated in this investigation. For each subject, 6 anatomical sites, namely the palm of hand (PH), dorsum of the hand (DH), anterior side of the forearm (AF), posterior side of the forearm (PF), middle anterior leg (AL), and middle posterior leg (PL) were investigated. The skin was untreated but clean. Since the skin frictional properties may be affected by the ambient environment, all experiments were carried out in a room with controlled temperature of 20-24°C, and relative humidity of 55-65%. The subjects were required to enter the test room for at least 20 minutes before the tests. During the test period, they were asked to sit down and stay relaxed.

For each test, 5 trials were repeated. The coefficient of friction was calculated as the ratio of frictional force to the normal force (μ=F/N). The mean value and standard deviation were calculated with T-test statistical analyses.

Various normal forces were applied to investigate the effect of load on the coefficient of friction. Various probe rotation speeds from 25rpm to 62.5rpm were used to investigate the effect of speed.

Results

Table 1 gives the coefficients of kinetic friction at 6 skin sites with 5 materials for 10 subjects. Each datum comprises mean and standard deviation obtained from the 5 tests. The load applied was 100 grams (average pressure of 80kPa) and the probe rotation speed was 25rpm (average linear speed of 1m/min). The 'Mean' on the right column means the average coefficient of friction between one material and one site of skin for all subjects. The 'mean' on the bottom row for each material shows the average value of this material on all the measured sites for each subject. The 'MEAN' on the bottom row of the table means the average coefficient of friction between all the measured sites and all materials for each subject.

In all the measurements, the coefficient of friction ranged from 0.24 to 1.26, and the average value for all tests was 0.46±0.15 ($p<0.01$). The coefficients of friction with different materials and at different anatomical sites are shown in Tables 2 and 3. The highest coefficient of friction of skin was found over the site of the palm of the hand with the silicone. The palm of the hand has the highest coefficient of friction in all the sites measured. Of all the materials tested, the silicone shows the highest coefficient of friction.

Figure 2 shows the change in coefficient of friction with the normal force applied to the skin surface in the 10 trials. The results show there is a slight decrease in coefficient of friction with an increase of the load. When the load increases from 25 grams to 100 grams, the average coefficient of friction was decreased by 9.5±6% ($p<0.05$).

Figure 3 displays the effect of the probe rotation speed on the coefficient of friction in the 8 trials. The coefficient of friction increases slightly with an increase of the rotation speed. When the rotation speed increased from 25rpm to 62.5rpm, the coefficient of friction increased by 7±2% ($p<0.05$).

Discussion

Skin frictional properties have been reported by several groups, and the results show they varied with interface materials, subjects, anatomical sites, ambient environment and skin conditions (Naylor, 1955; Comaish *et al.*, 1971;

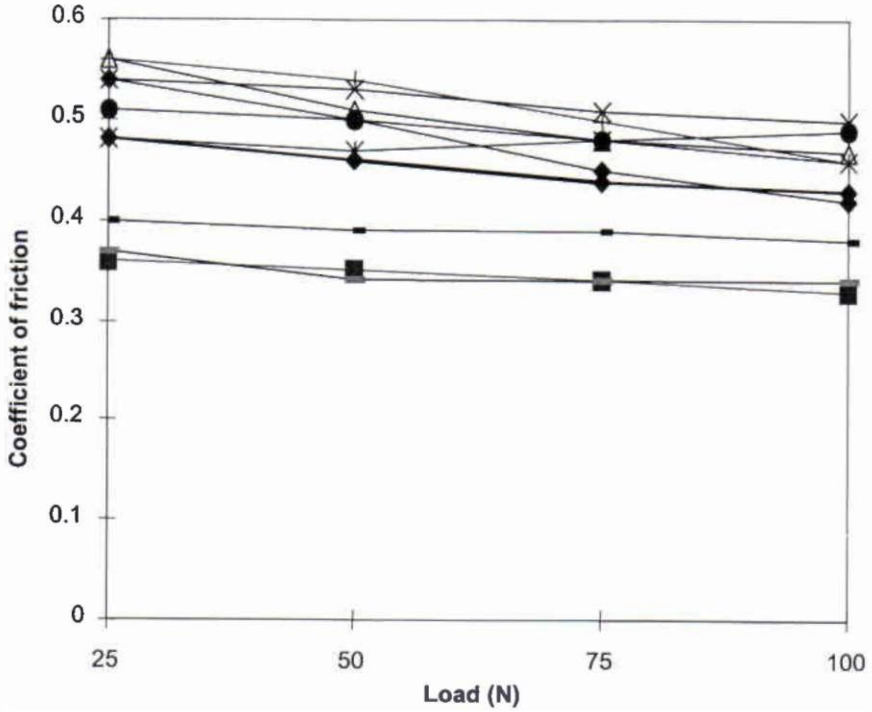

Fig. 2 Change in friction with normal load.

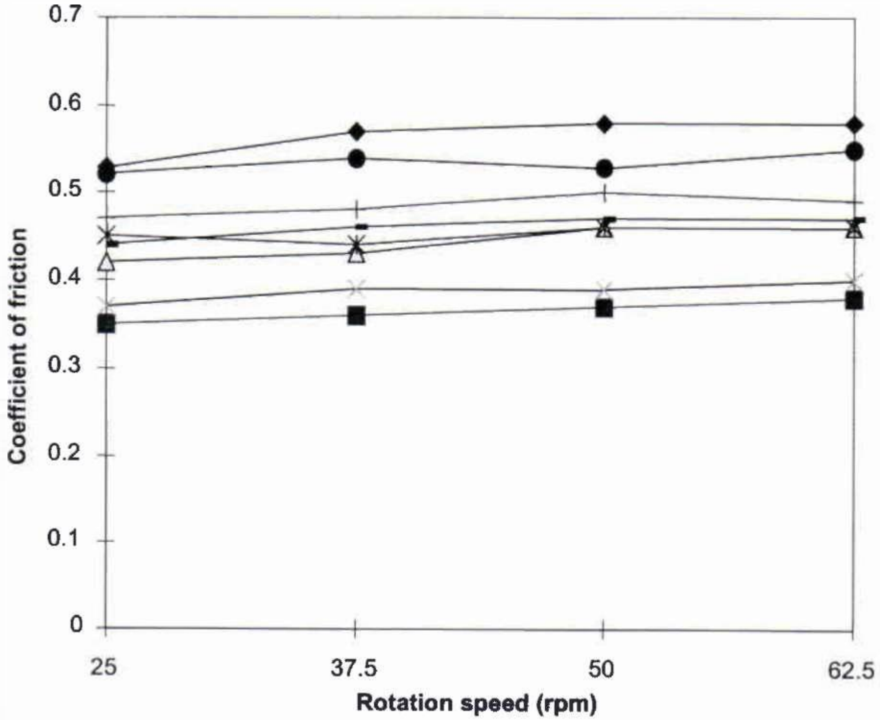

Fig. 3 Change in friction with rotation speed.

Highley *et al.*, 1977; El-Shimi, 1977; Nacht *et al.*, 1981; Cua *et al.*, 1990). The data reported in this study are particularly relevant to prosthetics and orthotics. These results provide the information needed for better understanding of the biomechanics of load transfer at the body support interface. The coefficient of friction obtained will be used in the computational biomechanical models of the load transfer characteristics between the human body and its supporting devices (Zhang, 1995; Zhang and Mak, 1996; Zhang *et al.*, 1997).

The findings in this investigation are in agreement with previous reports. The coefficients of friction reported for skin were generally within the range of 0.1-1.3 (Wolfram, 1989). In general, the coefficient of friction decreases with increasing load, especially in the range of a small load (El-Shimi, 1977; Comaish *et al.*, 1971). The effect of rotation speed was noted to be negligible over the range examined 3.6 - 585rpm (El-Shimi, 1977).

Frictional forces can be generated via two actions, one from the "ploughing" action, and the other one from the force required to overcome adhesion between the two surfaces. The former produces friction forces due to the mechanical interlocking of surface roughness elements. The latter generates friction forces due to dissipation when the atoms of one material are plucked out of the attractive range of their counter-parts on the material surface. The relative contribution from these two mechanisms depends on the physical and chemical properties of the contact surfaces. Generally speaking pairs of materials will compatible properties will have a larger friction if the second part is the major contributor. This may be the reason why silicone has the highest friction among the test materials.

The high coefficient of friction found in the palm of the hand may also be related to the fact that this is very rarely sweat free (Comaish *et al.*, 1971). Thus the physiological state of the skin at any one time must have a profound effect. Other geometric features such as the epidermal ridges may play an important part.

Acknowledgements

The first author thanks the Hong Kong Polytechnic University for a postdoctoral research fellowship. Help from the undergraduate students in the BSc (Hons) programme in Prosthetics and Orthotics is appreciated.

REFERENCES

AKERS CWA (1985). Measurements of friction injuries in man. *Am J Indust Med* **8**, 473-81.

ARMSTRONG TJ (1985). Mechanical consideration of skin in work. *Am J Indust Med* **8**, 463-72.

BENNETT L, KAVNER D, LEE BK, FRIEDA A, (1979). Shear vs pressure as causative factors in skin blood flow occlusion. *Arch Phy Med Rehabil* **60**, 309-314.

BUCHHOLZ B, FREDERICK LJ, ARMSTRONG TJ (1988). An investigation of human palmar skin friction and the effects of materials, pinch force and moisture. *Ergonomics* **31**, 317-25.

COMAISH JS, BOTTOMS E (1971). The skin and friction: deviations from amonoton's laws, and the effects of hydration and lubrication. *Br J Dermatol* **84**, 37-43.

CUA AB, WILHELM KP, MAIBAICH HI (1990). Frictional properties of human skin: relation to age, sex and anatomical region, stratum coreum hydration and transepidermal water loss. *Br J Dermatol* **123**, 473-9.

CUA AB, WILHELM KP, MAIBACH HI (1995). Skin surface lipid and skin friction: relation to age, sex and anatomical region. *Skin Pharmacol* **8**, 246-251.

DALTON B (1982). Friction, intermitted or otherwise, the exciting cause of corns and callous. *Chiropodist* **37**, 372-80.

EL-SHIMI AF (1977). In vivo skin friction measurements. *J Soc Cosmet Chem* **28**, 37-51.

ELSNAU WH (1995). Skin friction measurement. In: Bioengineering of the skin: methods and instrumentation./edited by Berardesca E, Elsner P, Wilhelm KP, Maibach HI. - Boca Raton: CRC Press. p121-124.

ELSNER P, WILHELM D, MAIBACH HI (1990). Frictional properties of human forearm and vulvar skin: influence of age and correlation with transepidermal water loss and capacitance. *Dermatolog* **181**, 88-91.

GERRARD WA (1987). Friction and other measurements of the skin surface. *Bioeng Skin* **3**, 123-39.

HIGHLEY DR, COOMEY M, DENBESTE M (1977). Wolfram LJ, Friction properties of skin. *J Invest Dermatol* **69**, 303-5.

HILLS RJ, UNSWORTH A, IVE FA (1994). A comparative study of the frictional properties of emollient bath additives using porcine skin. *Br J Dermatol* **130**, 37-41.

JOHANSSON RS, COLE KJ (1994). Grasp stability during manipulative actions. *Can J Physiol Pharmacol* **72**, 511-24.

KENINS P (1994). Influence of fibre type and moisture on measured fabric-to-skin friction. *Textile Res J* **64(12)**, 722-8.

LODÉN M, (1995). Biophysical properties of dry atopic and normal skin with special reference to effects of skin care products. *Acta Dermato-Venereolog* (Suppl.) **192**, 3-48.

LODÉN M, OLSSON H, AXELL T, WERNER Y (1992). Friction, capacitance and transepidermal water loss (TEWL) in dry atopic and normal skin. *Br J Dermatol* **126**, 137-41.

NACHT S, CLOSE JA, YEUNG D, GANS EH (1981). Skin friction coefficient: changes induced by skin hydration and emollient application and correlation with perceived skin feel. *J Soc Cosmet, Chem* **32**, 55-65.

NAYLOR PFD (1955). The skin surface and friction. *Br J Dermatol* **67**, 239-248.

SMITH AM, SCOTT SH (1996). Subjective scaling smooth surface friction. J *Neurophysiol* **75**, 1957-1962.

SULZBERGER MB, CORTESE T, FISHMAN L, WILEY HS (1966). Studies on blisters produced by friction, I results of linear rubbing and twisting technics. *J Invest Dermatol* **47(5)**, 56-65.

TAYLOR MM, LENDERMAN SJ (1975). Tactile roughness of grooved surfaces: a model and the effect of friction. *Percept Psychophys* **17**, 23-36.

WOLFRAM LJ (1983). Friction of skin. *J Soc Cosmet Chem* **34**, 465-76.

WOLFRAM LJ (1989). Frictional properties of skin. In: Cutaneous investigation in healthy and disease noninvasive methods and instrumentation./edited by JL Leveque. - New York: Maracel Dekker, p49-57.

ZHANG M, (1995). Biomechanics of the residual limb and prosthetic socket interface in below-knee amputees, *PhD dissertation,* University of London.

ZHANG M, MAK AFT (1996). A finite element analysis of the load transfer between a residual limb and its prosthetic socket - Roles of interfacial friction and distal-end boundary conditions. *IEEE Trans Rehabil Eng* **4**, 337-346.

ZHANG JD, MAK AFT, HUANG LD (1997). A large deformation biomechanical model for pressure ulcers. *ASME J Biomech Eng,* (Accepted).

ZHANG M, ROBERTS VC (1993). The effect of shear forces externally applied to skin surface on underlying tissues. *J. Biomed Eng* **15**, 451-456.

ZHANG M, TURNER-SMITH AR, ROBERTS VC (1994). The reaction of skin and soft tissue to shear forces applied externally to the skin surface. *J Eng Med* **208**, 217-222.

ZHANG M, TURNER-SMITH AR, TANNER A, ROBERTS VC (1996). Frictional action at residual limb/prosthetic socket interface. *Med Eng Phys* **18**, 207-214.