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Influence of variations in the pressure distribution on the friction of the finger pad

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ABSTRACT

We investigated the influence of the contact pressure distribution on the friction of the index finger pad. The skin contact pressure distributions were characterised by round profiles for low forces. At higher loads, the pressure distributions of the finger pad became asymmetric and conical. Additional experiments with the knuckle revealed pressure distributions with sharp peaks. The friction coefficients of the finger pad and the knuckle indicated a common behaviour in accordance with the adhesion friction model. Varying pressure distributions were found to influence the friction coefficients of skin, contributing to the variation of measurement results at comparable normal loads.

1. Introduction

The contact and friction behaviour of human fingers is relevant in connection with the sense of touch and the gripping and manipulation of tools and objects. Recent studies on the tribology of the finger pad were related to the factors influencing friction [1–4] or to the tactile properties of materials and surfaces [5–7]. Knowledge about the contact and friction behaviour of the finger pad is also important in robotics, aiming at a realistic simulation of sensory tasks and object manipulation by means of artificial systems [8,9].

The glabrous skin of the human finger pad is characterised by the fingerprint ridges and a high density of sweat glands [10]. Results of Warman and Ennos [11] suggest that the primary role of the epidermal surface ridges is not to influence friction, but to improve tactile perception by amplifying mechanical stimuli for the excitation of mechanoreceptors located in the subsurface skin tissue. However, there is also evidence that the friction of the finger in contact with small, triangular ridged surfaces is enhanced by interlocking for ridge heights above 40 μm [2]. Such interlocking effects seem plausible due to the fingerprint pattern. The typical widths of the epidermal ridges and furrows are 200 μm and 120 μm, respectively [12], while the height difference between ridges and furrows is of the order of magnitude of 100 μm [13].

The sweat glands of the finger pad are distributed along the ridges with a density of 150–350 cm^{-2} [10]. A study of André et al. [14] indicated that sweat excretion changes the moisture of the fingertip during object manipulation such that the grip forces are minimised. Skin hydration and interfacial water due to sweating and occlusion influence skin-friction by softening the stratum corneum and by causing capillary bridges, leading to an increased real contact area and adhesion between the skin and the counter-surface [1,3]. The friction coefficient of the finger pad typically shows a maximum in the moist condition, while friction is reduced under both dry and wet conditions [1,3,15]. It was observed that lipids are transferred together with sweat in friction contacts of the finger pad, causing slightly decreasing trends in measured friction coefficients [10,12,16]. Because the skin of the finger pad itself is free of sebaceous glands, such lipids are believed to be transported from other body sites which were touched by the finger [3,12].

According to a recent review article on the tribology of human skin [17], the friction behaviour of the finger pad largely corresponds to that of other skin areas. In many cases, the friction coefficients of dry skin in contact with rough surfaces lie around 0.5, without exhibiting noticeable pressure-dependence. Against smooth surfaces, the friction coefficients tend towards higher values and show increased variations. This can be associated with sweating and occlusion effects, causing a damp interface [3]. Under moist and wet conditions, the friction coefficients of skin typically show a substantial increase on rough surfaces and a strong increase on smooth surfaces (factors between 1.5 and 7 compared to the dry condition). In addition, a pronounced

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pressure-dependence of the friction coefficient can normally be observed which is characterised by a strong increase with decreasing skin contact pressure [17].

In the majority of previous studies related to the human finger pad, the friction was measured at normal forces below 5 N, covering the typical range which is used for the tactile assessment of surfaces [17]. Within this range of normal forces, the apparent contact area of the finger pad increases nonlinearly up to values of about 2–3 cm^2 [13]. The order of magnitude of the resulting average skin contact pressure is 5 kPa for normal forces around 1 N and 17 kPa for normal forces around 5 N.

So far, it is unknown how the pressure distribution in the interface between the finger pad and the contacted surface depends on the normal force. A Hertzian contact pressure can be assumed for small contact forces [18,19], but it is unclear how the pressure distribution is influenced by increasing contact loads and how it is changed during dynamic friction. At high skin contact pressures, the soft tissue structures of the finger pad (skin and subcutaneous fat pad) are expected to be more and more compressed so that an influence of the distal phalanx might become important. If the friction coefficient of the finger pad depends on the mean contact pressure (as is the case for moist conditions), it is a question whether the interfacial pressure distribution has a measurable influence on the friction coefficient.

In the current study we investigated the friction between the index finger pad and a smooth pressure-sensitive film on a force plate as a function of the normal load, in order to investigate the effect of varying contact pressure distributions on the friction behaviour. As a contrasting case we additionally studied the knuckle of the index finger, characterised by a thin skin layer over a sharp bony prominence.

2. Methods

2.1. Friction measurements

The friction behaviour of the index finger pad was investigated in three subjects (three of the authors of this study, two females and one male). The subjects carried out series of unidirectional friction measurement series, in which they repeatedly rubbed the index finger of their dominant hand against a pressure-sensitive film (see Section 2.2) attached on a force plate (Kistler, type 9254). During the friction measurements, the index finger was held in a stretched position at an angle of about 45° to the horizontal (Fig. 1). In addition to the finger pad, the knuckle of the index finger (proximal interphalangeal joint) was investigated as a contrasting case, characterised by a thin skin layer over a sharp bony prominence.

Single friction measurement series included 10 individual friction cycles over a distance of 5 cm, distributed over the whole surface of the pressure sensitive film (5.6 cm × 5.6 cm). The sliding velocity of the finger was around 5 cm/s. It was controlled by conducting the friction measurement cycles according to the beats of a metronome. The subjects carried out up to 80 friction measurement series for each skin area, thereby varying the applied normal forces from about 0.03 N up to about 5 N, which includes the range of forces that is normally used for the tactile assessment of surfaces. The subjects controlled the normal load by means of an analogue voltage meter. The levels of the normal force were chosen in random order, covering the whole force range specified.

The normal and the friction forces transmitted to the force plate during the friction experiments were recorded with a resolution of approximately 25 mN at a sampling rate of 200 Hz using Dynoware software (Kistler, type 2825 A-02). A typical example of force–time curves measured in one friction experiment is shown in Fig. 2(a). Individual friction coefficients were determined for each single friction cycle by analysing the peaks of the force signals over intervals of about 0.5 s (Fig. 2b). The variation of friction coefficients within these time intervals was characterised by typical (median) standard deviations of 0.08 for measurements with the finger pad and by values of 0.03 in the case of the knuckle.

All friction experiments were carried out in a laboratory with a temperature of (23 ± 3) °C and a relative humidity of (50 ± 5)%. The subjects were acclimatised to the laboratory climate for at least 10 min prior to the measurements. The skin of the subjects was washed and dried before each measurement series. In the case of measurements under dry conditions, the surface of the pressure sensitive film was cleaned with ethanol after every five friction experiments. In the wet condition, the pressure sensor was covered by a film of deionized water with a thickness of approximately 1 mm. The superficial layer of the pressure sensitive film consists of polyester and is characterised by surface roughness parameters of $Ra = 0.91 \pm 0.24$ µm and $Rz = 3.39 \pm 0.83$ µm, measured by a mechanical profilometer (Perthometer M1, Mahr GmbH, Göttingen, Germany).

2.2. Measurement of skin contact pressure distributions

The pressure sensitive film (Tekscan, model 5051, 7 psi) used in combination with the force plate allowed measuring the skin contact pressure distribution during the friction measurements. The spatial resolution of the sensor was 1.27 mm^2 (62 sensor elements per cm^2). The sensor was calibrated using static loads and operated with a measurement range around 100 kPa, leading to a resolution of about 0.4 kPa for the sensor elements. The skin contact pressure distributions during friction contacts were recorded at a sampling rate of 100 Hz.

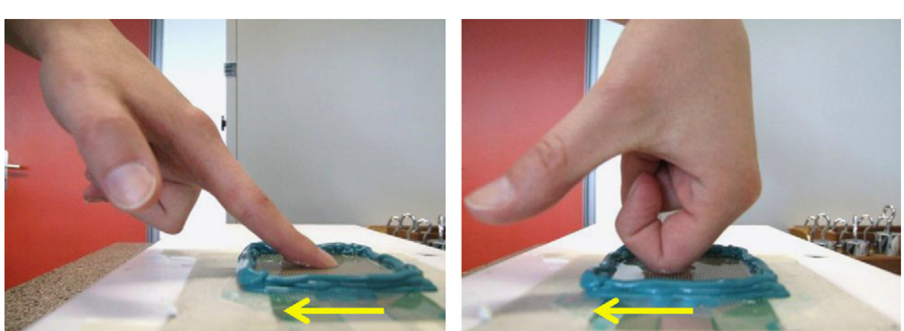

Fig. 1. Friction measurements for the skin of the index finger pad and the knuckle. The arrows indicate the direction of movement of the skin surface. Silicone material is used to trap water for measurements under wet conditions.