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Friction of human skin against smooth and rough glass as a function of the contact pressure

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ABSTRACT

The friction behaviour of human skin was studied by combining friction measurements using a tri-axial force plate with skin contact area measurements using a pressure sensitive film. Four subjects carried out friction measurement series, in which they rubbed the index finger pad and the edge of the hand against a smooth and a rough glass surface under dry and wet conditions. The normal loads were varied up to values of 50 N, leading to skin contact pressures of up to 120 kPa. The analysis of the pressure dependence of friction coefficients of skin for contrasting sliding conditions allowed to determine the involved friction mechanisms on the basis of theoretical concepts for the friction of elastomers.

Adhesion was found to be involved in all investigated cases of friction between skin and glass. If adhesion mechanisms predominated (skin against smooth glass in the dry condition and skin against rough glass in the wet condition), the friction coefficients were generally high (typically >1) and decreased with increasing contact pressure according to power laws with typical exponents between -0.5 and -0.2. Contributions to the friction coefficient due to viscoelastic skin deformations were estimated to be relatively small (<0.2). In those cases where the deformation component of friction played an important role in connection with adhesion (skin against rough glass in the dry condition), the friction coefficients of skin were typically around 0.5 and their pressure dependence showed weak trends characterised by exponents ranging from -0.1 to $+0.2$. If hydrodynamic lubrication came into play (skin sliding on smooth glass in the wet condition), the friction coefficients were strongly reduced compared to dry friction (<1), and their decrease with increasing contact pressures was characterised by exponents of <-0.7.

1. Introduction

The friction behaviour of human skin is determined by the complex interplay of material and surface properties of the skin as well as the contacting material, and strongly depends on the contact parameters (e.g. pressure and sliding velocity) and the presence of substances such as water, sweat or skin surface lipids at the interface [1–3].

To a large extent, the current knowledge on the tribology of skin resulted from dermatological studies on the effects of skin care products [4–7]. However, the frictional properties of skin are of general importance in connection with mechanical contacts of the human body with external materials, e.g. when touching and handling objects or when wearing clothes and accessories. In several recent studies on skin tribology, specific practical cases such as friction contacts between hand and object [8–10] or between skin and textiles [11,12] were analysed by *in vivo* measurements. The typical experimental set-up in these studies was to rub the skin against objects and surface samples attached to a multi-axial force plate or a force transducer in order to measure normal and friction forces and to determine friction coefficients. An alternative approach consists in the use of a tribometer with which (mostly spherical) probes made of different materials are slid over the skin of subjects [13,14]. This measurement technique was applied to characterise the general friction properties of skin [15,16] and to study the contribution of the *stratum corneum* to the friction of skin [17].

Human skin shows viscoelastic material properties similar to those of a soft elastomer [2,18,19]. Therefore, theoretical concepts for the friction of elastomers [20,21] were applied to interpret experimental data for the friction of skin. Under dry conditions, adhesion at the skin/material interface as well as deformation of the skin and the soft sub-surface tissue contribute to the coefficient of friction (two-term model of friction) [1]:

$$\mu = \mu_{adhesion} + \mu_{deformation} \quad (1)$$

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The friction of skin is considered to be mainly determined by adhesion, while deformation is normally believed to be unimportant [2,22,23]. Applying the contact theory of Hertz [24], Wolfram derived the following expression for the adhesion component of friction

$$\mu_{adhesion} \propto N^{-1/3} \cdot E^{-2/3} \quad (2)$$

where N denotes the normal load and E the elastic modulus of skin [23]. A decrease of friction coefficients with increasing normal load according to $\mu \propto N^{-1/3}$ is consistent with experimental studies in which the friction of dry skin was investigated using solid probe materials [25–27]. Friction coefficients that decreased with increasing load were also observed in experiments, in which spherical probes were slid on wet skin [22].

In order to estimate the contribution of viscoelastic skin deformations to friction (hysteresis), Johnson et al. [2] applied the approach of Greenwood and Tabor [28]. In contrast to the adhesion component of friction (Eq. (2)), the contribution due to hysteresis is expected to increase with normal load:

$$\mu_{hysteresis} \propto N^{+1/3} \cdot E^{-1/3} \quad (3)$$

It is usually experienced in everyday life that the friction of skin increases with hydration, e.g. due to sweating. This was explained by the fact that moist skin becomes softer and is characterised by a lower elastic modulus so that adhesion is increased (Eq. (2)) [23]. In addition, human skin swells due to water uptake, leading to a smoothing of the skin surface and an increased microscopic contact area in friction contacts [22]. In a recent study, Gerhardt et al. systematically varied the hydration state of the skin of the volar forearm in 22 subjects and found a highly positive linear correlation between skin moisture and friction coefficients against textiles [29].

When the skin is saturated and excess water accumulates in the interface, capillary bridges between the skin and the countersurface might be relevant to a certain degree, but with further increasing amounts of water lubrication phenomena will become more and more important. Dowson [1] described various types of lubrication that are relevant in connection with human skin. Hydrodynamic lubrication is characterised by the complete separation of the sliding surfaces by a liquid film. Under these conditions, the adhesion component of friction is replaced by a contribution due to viscous friction

$$\mu_{viscous} = \frac{1}{N} \cdot \eta \cdot \left(\frac{V}{h}\right) \cdot A = \eta \cdot \left(\frac{V}{h}\right) \cdot p^{-1} \quad (4)$$

where N denotes the normal load, η the viscosity of the fluid, h the film thickness, V the sliding velocity, A the apparent contact area and p the contact pressure [1]. Depending on contact conditions as well as fluid film thickness in relation to the surface roughness of the skin and the contacting material, mixed lubrication or boundary lubrication can take place. The former lubrication regime is characterised by the coexistence of dry and wet contact zones, the latter by molecular surface films influencing the friction behaviour.

It is a common empirical approach to express measurement data for the friction force F in the form $F = k \cdot N^n$, where k corresponds to the conventional friction coefficient at unit normal load, N denotes the normal load and n is termed the load index [22]. The friction coefficient as a function of the normal load is then given by

$$\mu(N) = k \cdot N^{n-1} \quad (5)$$

In the logarithmic form $\log(\mu) = \log(k) + (n-1) \cdot \log(N)$, this equation can be used to determine the exponent $n-1$ (and the load index n) by linear regression and to test if the friction measurement data can be attributed to a predominant friction mechanism. According to Eqs. (2)–(4), friction mechanisms such as adhesion, deformation or hydrodynamic lubrication should be indicated by distinctive exponents of $-\frac{1}{3}$, $+\frac{1}{3}$ and -1, respectively.

In this study, the friction behaviour of human skin was studied as a function of the contact pressure by combining friction measurements using a tri-axial force plate with contact area measurements using a pressure sensitive film. Four subjects carried out compression tests and friction measurement series, in which they rubbed the skin of two different anatomical sites against a smooth and a rough glass surface under dry and wet conditions. The objectives were (1) to analyse the pressure dependence of the friction of skin for contrasting cases (dry/wet, smooth/rough) and to determine the involved friction mechanisms and lubrication regimes and (2) to test how far theoretical concepts developed for the friction of elastomers are applicable to describe the experimental data found for human skin.

2. Experimental

2.1. Friction measurements

The friction behaviour of the human skin was investigated for two anatomical sites, namely the pad of the index finger and the edge of the dominant hand. Two females and two males with ages between 23 and 45 y (four of the authors) carried out friction measurement series, in which they repeatedly rubbed their skin against a smooth and a rough glass surface using normal loads of up to 50 N. The skin slid over distances between 5 and 8 cm within periods of 0.5–1.5 s, leading to sliding velocities between 5 and 10 cm/s. Two subjects carried out the experiments with a pulling motion and the other two with a pushing motion, holding the finger and the hand in a stretched position (Fig. 1). When measuring friction coefficients for the skin of the finger pad, the index finger was inclined at angles between 30° and 45° to the counterface. The glass plates were attached to a quartz 3-component dynamometer Kistler, type 9254 (dimensions 15 cm × 10 cm). The normal and the friction force were measured using charge amplifiers (Kistler, type 5011), and Dynoware software (Kistler, type 2825A-02) was used to acquire the friction and normal force with a resolution of approximately 25 mN at a sampling rate of 125 Hz.

Measurements were carried out over periods of 20 s, allowing a subject to conduct a sequence of friction movements at varied normal loads. In the process, the subjects controlled the applied normal load by means of an analogue voltage meter. Figs. 2a and b show typical results measured in one friction experiment. Individual friction coefficients were determined for each single friction movement by analysing the peaks of the normal and friction force signals over intervals of 0.1 s. The variation of friction coefficients within these time intervals was characterised by typical (median) standard deviations of 0.02.

For each glass surface and each anatomical site, the subjects carried out at least 10 friction measurements under dry and wet conditions. In the wet condition, the glass surfaces were covered by a film of deionised water with a thickness of approximately 1 mm.

All friction experiments took place at a temperature of (23±1) °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 cleaned with ethanol before each measurement series. In addition, the dry glass surfaces were cleaned with ethanol before each friction experiment.

2.2. Contact area measurements

In order to measure the apparent contact area between the skin and a flat surface as a function of the normal load, a pressure