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Research paper

A systems based experimental approach to tactile friction

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ABSTRACT

This work focuses on the friction in contacts where the human finger pad is one of the interacting surfaces. This 'tactile friction' requires a full understanding of the contact mechanics and the behaviour of human skin. The coefficient of friction cannot be considered as a property of the skin alone, but depends on the entire tribo-system. In this work, frictional forces were measured using a commercially available load cell. Parameters such as the hydration of the skin, the normal load on the contact and the roughness of the contacting surfaces were varied, whilst keeping the other parameters constant. The tests were performed under controlled environmental conditions. The total friction force is a combination of forces related to adhesion and to deformation.

A commonly made assumption is that, to describe the friction of human skin, the deformation component can be ignored and only the adhesive behaviour has to be taken into account. However, in this study it was found that the forces related to the (micro-scale) deformation of skin can have a significant contribution to the total friction force; this is valid both for dry conditions and in the presence of water, when hydration of the skin causes softening.

1. Introduction

The frictional behaviour of contacts in which the human finger pad is one of the interacting partners (often referred to as 'tactile friction') is of interest for a wide variety of applications. Examples include tactile perception, grip and haptic control when wearing disposable gloves for clinical use, as described by Burke et al. (1989) as well as the 'design for touch' of consumer products and packaging as discussed by Barnes et al. (2004).

A fair amount of literature is available describing the frictional behaviour of human skin. Two noteworthy overviews of results presented in literature are those by Sivamani et al. (2003) and Dowson (2009). Sivamani reports experimental values for the coefficient of friction μ ranging between 0.12 and 0.7, while Dowson reports significantly higher values, between 0.31 and 1.20. These values are obtained using a wide variety of test set-ups, ranging from small handheld devices (see e.g. Comaish et al., 1973 and Cua et al., 1990) to larger laboratory based set-ups (Sivamani et al., 2003; Asserin et al., 2000; Adams et al., 2007) that sometimes require more than one operator (Polliack and Scheinberg, 2006).

It needs to be noted that the coefficient of friction, as such, is not a material property but rather a system-parameter, meaning it depends on the combination of the two contacting materials, their surfaces and micro-geometry, any lubricants and the environmental conditions, as well as the operational conditions of the contact (Czichos, 1978). Thus, the large variation in values for the coefficient of friction that are reported in the literature is not surprising, considering the wide range of system properties under which they have been obtained.

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(a) Rotating probe. (b) Sliding probe. (c) Moving skin.

Fig. 1 – Measurement principles for skin friction.
***Source:* Veijgen et al. (2010), used with permission.**

The total friction force that occurs in a contact is a combination of the forces required to break the adhesive bonds between the two surfaces and the forces related to the deformation of the bodies in contact. Wolfram (1983) concludes in a review of the experimental results of Naylor (1955), Comaish and Bottoms (1971) and El-Shimi (1977) that the adhesive part of the friction force is usually dominant, whilst the deformation component can be ignored.

1.1. *Measuring the friction behaviour of human skin*

Measuring the friction behaviour of human skin is not as straightforward as it initially appears. Most existing friction testers are designed and optimised for use on traditional engineering materials such as steels and ceramics, meaning that typical contact pressures are of the order of hundreds of MPa to several GPa. The high modulus of elasticity of these materials means that the deformations are usually several orders of magnitude smaller than the geometrical sizes of the used specimens. Therefore, the deformations will not affect the measurement of the friction force and can be ignored, enabling the use of relatively straightforward set-ups. In the case of human skin and other compliant materials such as elastomers, deformations are relatively large and the geometrical deformation of the specimens needs to be taken into account. Furthermore, as a material, skin behaves in a complex manner; it has a layered structure with highly changing properties through the layers, its behaviour is viscoelastic, anisotropic and there may or may not be an influence of underlying tissue and bones. The properties of the skin vary with anatomical location and with subject, age, gender, level of care and hydration.

1.2. *Principles for measurement of the skin friction*

Basically, three types of measurement principles are utilised when measuring the frictional forces in skin-object interactions. These are schematically illustrated in Fig. 1.

The rotating probe shown in Fig. 1(a) is essentially an adapted viscometer. Usually, the resulting torque is measured and translated into a coefficient of friction. This type of measurement averages out the in-plane anisotropic behaviour of skin. Furthermore, because the frictional behaviour of human skin depends strongly on velocity, an important issue in these measurements is that the velocity inside the contact between the probe and the skin is not constant, but is zero in the centre and maximum at the edge. This is sometimes solved by using a ring instead of a full disk, so that the zero-velocity centre is removed and the velocity variance within the contact is limited.

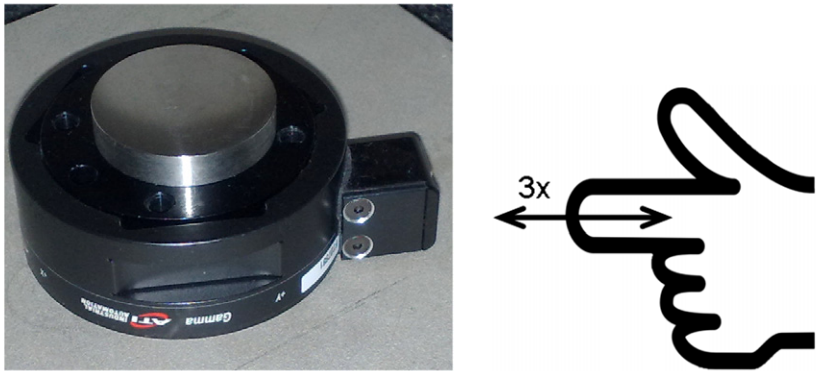
The sliding probe or reciprocating probe, as schematically shown in Fig. 1(b), is an often used concept in tribology. It is, therefore, also applied in a large number of laboratory set-ups for measuring the friction forces in skin contacts. Usually, such measurements are done on the ventral forearm, for reasons of ease of access and the limited amount of hair growth on that part of the body. In such a reciprocating set-up, the turning points, where the velocity of the sample equals zero, can affect the results. Another typical point of attention in these measurements is the alignment of the skin surface with the moving sample. Poor alignment can cause an offset in the friction signal, which can be accounted for with relative ease, but can also cause stability issues in the control of the applied normal load. To prevent this from happening, the arm of the subject is often immobilised by strapping it tightly. The perceived loss of control can cause unease, discomfort and even fear in the subject, possibly resulting in a change of skin properties due to sweating or cutis anserina (goose bumps).

By using the principle of a stationary sample over which the skin moves, as illustrated in Fig. 1(c), the issue of alignment is solved and the perceived unease is reduced as in this case the subject is controlling the experiment. This comes, however, at the cost of reduced control over the applied load and the speed of motion, but these can be measured. Furthermore, subjects can be trained, in order to reduce the variation in force and velocity, as discussed in more detail by Skedung et al. (2010). The experimental set-up can be relatively simple, using e.g. a table with flexure elements, such as the one introduced by Gee et al. (2005), or a force cell, see for instance Derler et al. (2007) and Smith and Scott (1996).

2. Materials and methods

2.1. *Measurement principle*

All three discussed measurement principles have their strengths and weaknesses. In this work, the principle shown in Fig. 1(c) – the stationary sample over which the skin moves – is used primarily because of its inherent simplicity. In the setup, a sample is attached to a load cell (ATI Gamma three-axis force/torque transducer, ATI Industrial



(a) Sample attached to the load cell. **(b) Movement.**

Fig. 2 – The setup.

Table 1 – Test matrix.

Sample	Roughness Rq [µm]	Normal Load [N]			
		1.0	1.5	2.5	5.0
Polished	0.004	Dry and Hydrated	Dry	Dry	Dry
	0.006	Dry and Hydrated			
Blasted	0.034	Dry and Hydrated			
	0.089	Dry			
	0.4	Dry and Hydrated			
Tumbled	0.8	Dry			
	1.8	Dry and Hydrated			

Automation, Apex, NC, USA) using double sided adhesive tape. The sample is touched by the index finger of the non-dominant hand of the subject (M, 33 years of age). The finger is moved three times back and forth in the horizontal plane, as indicated in Fig. 2(b).

The ATI force transducer measures the forces with six degrees of freedom. This means that the normal force (z-direction) and the two forces in the tangential or xy-plane are measured, as well as the torques around the x, y and z axes. The resolution of the force measurements is 25 mN in normal direction and 12.5 mN in tangential direction, with a sampling frequency of 100 Hz. From the measured dataset, the coefficient of friction is calculated as the ratio of the total tangential load and the normal load. The sliding velocity of the finger is calculated from the change of the location for each time step, i.e. for each measurement point the torque around the axis perpendicular to the sliding direction is divided by the normal load.

2.2. *Samples*

The samples are stainless steel disks with a diameter of 40 mm. To obtain a range of surface roughness values, initially all disks were polished to a roughness Rq of 0.006 µm. Subsequently, the surfaces were altered by either further polishing using a finer grit diamond paste, by blasting using Ø1 mm hardened steel balls or by tumbling. An overview of the samples and the applied test conditions is given in Table 1. The roughness values were measured using an optical interference microscope (Micromap Corp. Tucson, AZ, USA).

2.3. *Preparation*

The stainless steel disks were cleaned using ethanol and then air-dried for at least 15 min. The finger was cleaned using soapy water, followed by a rinse with water and dried in air for 30 min prior to the start of the experiment. For the hydrated tests, the finger was soaked for 5 min in water at room temperature immediately before each test. Excess water was shaken off, rather than being wiped.

3. Theory

As stated before, Czichos introduced the concept of friction as a system parameter in 1983. In the following, some relations between the friction and the properties of the tribological system are discussed.

3.1. *Relation between friction force and normal load*

The friction force in the contact between human skin and a counter surface is a combination of forces due to both adhesion and deformation, see e.g. Wolfram (1983). Johnson et al. (1993) and Adams et al. (2007) presented relations for the adhesive and deformation components in the friction force, as shown in Eqs. (1) and (2) respectively.

$$F_{f,\mathrm{adh}} = \pi \cdot \tau_0 \cdot \left(\frac{3 \cdot R}{4 \cdot E^*}\right)^{\frac{2}{3}} \cdot N^{\frac{2}{3}} \quad (1)$$

$$F_{f,\mathrm{def}} = 0.17 \cdot \beta_{ve} \cdot \left(\frac{1}{R^2 \cdot E^*}\right)^{\frac{1}{3}} \cdot N^{\frac{4}{3}}. \quad (2)$$

In which $F_{f,i}$ represents the respective friction forces, τ_0 the shear strength of the interface, R the reduced radius of the two bodies in contact, β_{ve} the viscoelastic hysteresis loss fraction, N the applied normal load and E^* the reduced Young's modulus, which in the case of contact between skin and a rigid counter body depends solely on the properties of the skin. The coefficient of friction μ is defined as:

$$\mu = \frac{F_f}{N}. \quad (3)$$

Combining Eqs. (1)–(3) shows that the adhesive component in the coefficient of friction reduces with increasing load N, whilst the deformation component in μ increases with increasing load:

$$\mu \propto C_{adh} \cdot N^{-\frac{1}{3}} + C_{def} \cdot N^{\frac{1}{3}}. \quad (4)$$

3.2. *Hydration, the Young's modulus of skin and the influence on the friction force*

The Young's modulus of hydrated skin is significantly lower than that of dry skin, see e.g. Papir et al. (1975), who reported a 700 fold decrease in the Young's modulus of the stratum corneum, the most upper layer of the skin, when the relative humidity increases from 26% to 100%. The influence of hydration on the friction behaviour of skin is described by Adams et al. (2007); the respective expressions for the friction force due to adhesion, Eq. (1), and deformation, Eq. (2), show inverse relations between the Young's modulus E and the friction force. This means that hydration of the skin is expected to result in increased friction forces. It is, however, questionable whether a 'simple' elastic parameter such as the Young's modulus can be used to accurately describe the behaviour of a complex material such as the human skin. In this respect, van Kuilenburg (submitted for publication) collected Young's modulus data for human skin on various anatomical locations, as reported in literature. Fig. 3 shows the reported value of the Young's modulus on the y-axis and the length scale at which the value was measured on the x-axis. It can be seen that there is a significant effect of the length scale, with the Young's modulus decreasing over several orders of magnitude when the length scale increases. To account for the multi-layered and non-homogeneous structure of the skin and the influence of humidity, as well as the relatively large deformations and any non-linear effects in a relatively straightforward manner, it is suggested to use the Effective Young's modulus E_{eff}, see also Pailler-Mattei et al. (2008). The appropriate value of E_{eff} to be used should be determined at the correct length scale and under representative conditions.

3.3. *The relationship between the roughness of the counter surface and the friction force*

Generally, it is accepted that there is only a negligible influence of the surface roughness on the friction force (see e.g. Bowden and Tabor, 1950). According to (Williams, 2005) this holds, as long as the (macroscopic) apparent contact area is significantly larger than the real contact area, the real contact area being the summation of the localised spots inside the contact where actual micro-scale contact occurs. For steel-on-steel contacts this is usually the case, but when

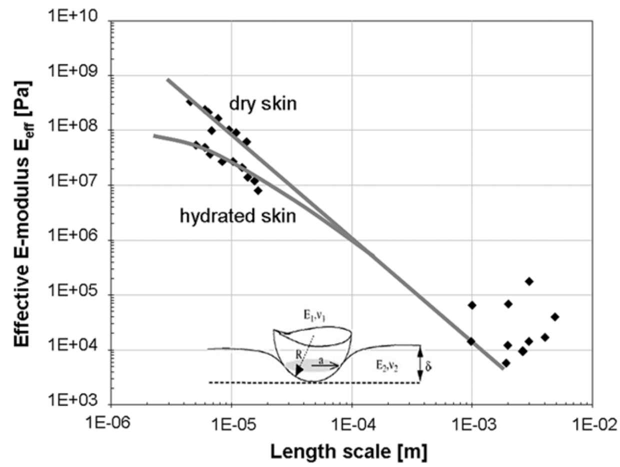


Fig. 3 – Effective Young's modulus as a function of length scale for dry and hydrated skin.
Source: **Taken from van Kuilenburg et al. (submitted for publication), used with permission.**

one of the contact partners is a compliant material, such as an elastomeric material or skin, the area of real contact may approach the area of apparent contact. In that case, an increased surface roughness will result in a larger separation between the mean planes of the two contacting surfaces, causing a reduction in the amount of adhesion. When friction is dominated by adhesion, this means that an increase of the surface roughness will result in a reduced friction force in the contact.

However, (Peressadko et al., 2005), showed that is an over-simplification and that not only the height of the surface roughness should be taken into account but that the lateral geometry such as the wavelength or the spacing between the individual asperities plays an important role. Similar to this, (van Kuilenburg et al., submitted for publication) presented a theory for the friction behaviour of human skin in contact with well-defined regular patterned surface textures in which the determining parameter is the ratio of the asperity size and the inter-asperity distance. As yet it is not clear how this theory translates to the multi-scale surface roughness observed on most product surfaces.

One could visualise the influence of the height and spacing of the micro-geometry by imagining the skin surface wrapping itself around the roughness asperities of the rigid surface, meaning that full surface-to-surface contact also occurs inside the valleys of the rough surface. When the asperities are too high, or positioned too close to each other, the valleys will not be filled and only partial contact occurs. This is schematically illustrated in Fig. 4(a) and (b).

As discussed above, it is commonly accepted that the friction behaviour of human skin is dominated by adhesive phenomena and that effects due to deformation may be ignored. The relationship between the surface roughness Rq and the adhesive component of the friction force can be described by Eq. (5), in which the value of k needs to be established.

$$F_{f,adh} \propto Rq^{-k}. \quad (5)$$

Based on experiments and an analytical model, (Fuller and Tabor, 1975; Briggs and Briscoe, 1976) showed an inverse

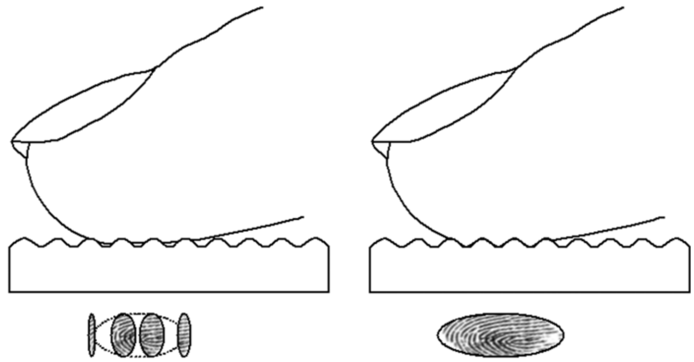


Fig. 4 – Partial contact and full contact depends on the surface micro-geometry and loading conditions.

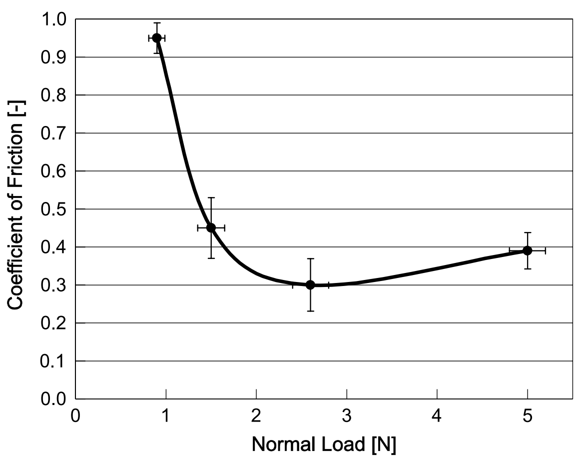


Fig. 5 – Measured coefficient of friction as a function of normal load for a polished surface in dry conditions.

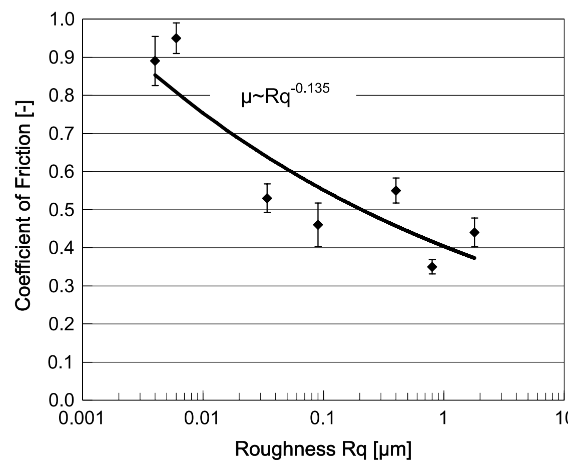


Fig. 6 – Measured coefficient of friction as a function of surface roughness for a dry surface.

linear relation between the adhesion between two surfaces and the surface roughness, $F_{f,\mathrm{adh}} \propto \mathrm{Rq}^{-1}$. Greenwood and Williamson (1966) modelled rough surfaces as a collection of spherically tipped asperities, all with equal radius R and a Gaussian asperity height distribution. This enables the use of Hertz' theory (Hertz, 1881, see also Johnson, 1985) for use on rough surfaces. Whitehouse and Archard (1970) deducted that for many engineering surfaces the product of the density of asperities η, their radius of curvature β and the standard deviation of the asperity height distribution σ is constant. In symbols:

$$\eta \cdot \beta \cdot \sigma = C. \tag{6}$$

The asperity density η is a spatial or lateral parameter, i.e. describing surface micro-geometry in the xy-plane, whilst the height distribution σ only contains data in the z-direction. Therefore, there is no direct relation between these two parameters and, as a first approximation, η does not vary much with changing roughness (see e.g. de Rooij, 1998). By 'translating' the Greenwood–Williamson parameters, $\beta = R$ and $\sigma \sim \mathrm{Rq}$, it follows from Eq. (6) that R and Rq are inversely proportional. Substituting this into Eq. (1) gives $F_{f,\mathrm{adh}} \propto \mathrm{Rq}^{-0.66}$.

From the above, it can be concluded that when the friction behaviour is dominated by adhesion, the value for k in Eq. (5) ranges somewhere between 0.66 and 1.0.

3.4. *Interaction of parameters*

The aforementioned parameters load, hydration and surface roughness are only discussed here as independent parameters. It is, however, known that these parameters can also interrelate; e.g. the load can have an influence on the surface roughness as the surface of compliant materials deforms under loading and the required spacing between asperities in order to obtain full contact will be affected by the Young's modulus and hence, by the hydration level of the skin.

4. Experimental results

The obtained experimental results are shown in Figs. 5–7. The error bars show the standard deviation of the coefficient of friction during the steady state part of the reciprocating motion, as calculated from the measured force signals according to Eq. (3). Steady state means that data around

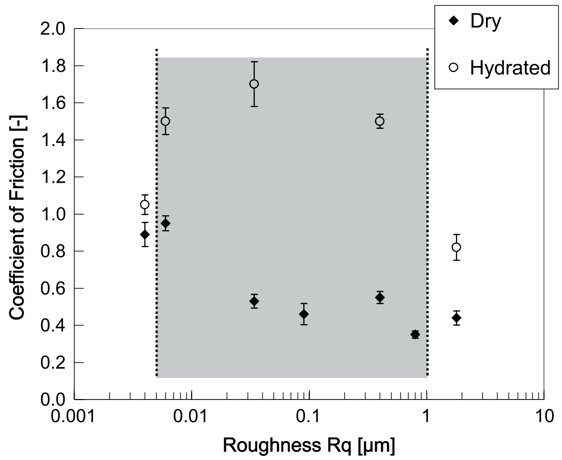


Fig. 7 – Measured coefficient of friction as a function of surface roughness for dry and hydrated skin at a normal load of 1 N.

the turning points of the motion, where the velocity is not constant or zero, is omitted.

Fig. 5 shows the measured coefficient of friction as a function of the normal load. At low loads the coefficient of friction is high and shows a strong decrease with increasing normal load. At higher loads the coefficient of friction tends to increase with load. In the figure, the horizontal error bars show the standard deviation of the applied normal load as measured during the reciprocating motions.

Fig. 6 shows the coefficient of friction as a function of the surface roughness Rq at a normal load of 1 N for dry skin. For smooth, polished surfaces, the coefficient of friction is approximately 0.9. This value reduces to between 0.35 and 0.55 for the samples with higher roughness.

Fig. 7 shows the same data as Fig. 6, but also contains the obtained results for hydrated skin. Hydration leads to an increase of the coefficient of friction, but the amount of this increase varies largely with the roughness. Note the changed scale of the y-axis, which now ranges to a maximum coefficient of friction $\mu = 2.0$.

5. Discussion

The coefficient of friction varies strongly with the normal load. At low loads the coefficient of friction is relatively high. At a load in the order of 2 N it reaches a minimum after which it increases with increasing load. This indicates that at high loads, the friction force contains a deformation component which should not be ignored. As the polished surface has a mirror-like finish, the deformation will be a macroscopic phenomenon rather than a roughness-based microscopic deformation of the finger pad.

The coefficient of friction shows a decline with increasing surface roughness. A curve fit through the data points shown in Fig. 6 indicates $\mu \propto \mathrm{Rq}^{-0.135}$. This might seem a rather weak relation, but the roughness can vary over a wide range – in the current study the Rq spans almost three orders of magnitude – so the effect can be quite pronounced. The value of -0.135 is far off the above discussed theoretical range of -0.66 to -1.0 for the case of pure adhesive friction. It, therefore, seems justified to conclude that next to adhesion, deformation plays a significant role and should not be neglected.

In the case of hydrated skin in comparison to dry skin, for intermediate roughness (Rq between 0.005 μm and 1 μm, shaded grey in Fig. 7) a substantial increase in the coefficient of friction is observed. This increase is less prominent on both the lower and upper end of the tested roughness range, i.e. for surfaces that are either relatively smooth, or relatively rough, the increase in the coefficient of friction for hydrated skin is only moderate.

A possible explanation for this is that very smooth, mirror-like surfaces have no significant roughness asperities to indent the skin. In that case, the softening of the skin due to hydration will result in an increased contact area between the finger and the sample and, hence, a larger contribution of adhesion to the friction forces. The fact that the increase is only moderate can be explained by the development of a plasticised low shear strength layer (Johnson et al., 1993; Adams et al., 2007), which effectively reduces the value of τ_0 in Eq. (1).

For surfaces with a relatively high roughness, the observed increase in the coefficient of friction due to hydration is also moderate. In this case, the roughness protuberances form localised micro-contact spots against the skin and the contact behaviour is governed by the mechanical properties of the outer-most layers of the skin. As shown before, hydration will cause softening of these layers, resulting in an increased contact area, but Eq. (2) shows that the effect of softening (i.e. a reduction of the Young's modulus) on the coefficient of friction is rather low ($\mu \propto E^{-1/3}$). Furthermore, any effects might be counter-balanced by the hydration-induced change of the viscoelastic hysteresis loss fraction β_{ve} as mentioned in Eq. (2) as well as the changing shape of the ridges on the finger tips due to hydration, as suggested by Adams et al. (2007), represented by the parameter R in Eq. (2).

A possible explanation for the more substantial increase at intermediate roughness values might be that both the adhesion and the deformation are significant and they interact. As discussed before, softening of the skin causes an increased contact area and depending on the micro-geometry of the surface, this softening might result in either partial contact between skin and surface or full contact, as was schematically illustrated in Fig. 4(a) and (b). The combination of a favourable surface micro-geometry, softened skin and deformation might cause folding of the skin around the surface asperities, resulting in increased adhesion. This adhesion causes the contact area to grow even further, i.e. that adhesion and deformation interact and reinforce each other. The result would be an over-proportional increase in the friction force with increasing skin hydration. The occurrence of this effect will depend on the micro-geometry of the surface roughness in the normal (height) as well as the lateral (wavelength) direction.

6. Conclusions

Using a relatively simple setup with a load cell, measurements of the friction forces on the human finger pad can be performed. Even though the applied method does not allow the control of parameters such as the normal load and the sliding velocity, these parameters can be accurately measured. The applied setup is particularly suited for research in which friction, surface roughness and touch-perception are linked.

The obtained results for smooth surfaces show a friction force that initially drops sharply with increasing load and subsequently shows a slow increase. This increase is attributed to (macro-) deformation of the finger due to the high normal loads.

With increasing surface roughness of the counter body, the coefficient of friction reduces due to a decrease in adhesion. However, for high roughness values ($Rq \gg 1$ μm) the deformation component starts to significantly influence the frictional behaviour. Deformation should, therefore, not be ignored.

When comparing the coefficient of friction of hydrated skin to that of dry skin, an increase is observed for all tested surfaces. The increase is most substantial for intermediate roughness values (0.01 μm < Rq < 1 μm). It can be concluded that under hydrated conditions the deformation component in the coefficient of friction should also not be ignored.

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