*Friction* **1**(2): 130–142 (2013)
DOI 10.1007/s40544-013-0015-1 ISSN 2223-7690
**REVIEW ARTICLE**

# Skin tribology: Science friction?

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*Received: 01 February 2013 / Revised: 30 March 2013 / Accepted: 23 May 2013*



**Abstract:** The application of tribological knowledge is not just restricted to optimizing mechanical and chemical engineering problems. In fact, effective solutions to friction and wear related questions can be found in our everyday life. An important part is related to skin tribology, as the human skin is frequently one of the interacting surfaces in relative motion. People seem to solve these problems related to skin friction based upon a trial-and-error strategy and based upon on our sense for touch. The question of course rises whether or not a trained tribologist would make different choices based upon a science based strategy? In other words: Is skin friction part of the larger knowledge base that has been generated during the last decades by tribology research groups and which could be referred to as Science Friction? This paper discusses the specific nature of tribological systems that include the human skin and argues that the living nature of skin limits the use of conventional methods. Skin tribology requires *in vivo*, subject and anatomical location specific test methods. Current predictive friction models can only partially be applied to predict *in vivo* skin friction. The reason for this is found in limited understanding of the contact mechanics at the asperity level of product–skin interactions. A recently developed model gives the building blocks for enhanced understanding of friction at the micro scale. Only largely simplified power law based equations are currently available as general engineering tools. Finally, the need for friction control is illustrated by elaborating on the role of skin friction on discomfort and comfort. Surface texturing and polymer brush coatings are promising directions as they provide way and means to tailor friction in sliding contacts without the need of major changes to the product.

**Keywords:** friction; bio-tribology; skin; soft tissue; surface texture; brush coatings

## 1 Skin friction in daily life

The application of tribological knowledge, i.e., knowledge on the science and technology of interacting surfaces in relative motion, is not restricted to optimizing mechanical and chemical engineering problems. In fact, effective solutions to tribology related questions are evident in our everyday life, as illustrated in fascinating examples described by D. Dowson's "A tribological day" [1]. An important part of the effective solutions in daily life situations is related to skin tribology, as the human skin is frequently one of the interacting surfaces in relative motion. These questions are typically related to optimizing friction and lubrication problems in skin–product interactions, rather than to optimising wear. Take for example the swimming pool or bathroom where material selection and application of anti-slip coatings prevent us from falling when the floor gets wet. Yet, if such coatings do not sufficiently increase friction, one will optimize the tribological system, e.g., by pressing our full foot to the floor and subsequently increasing the true area of contact or by changing the operational conditions, e.g., by minimising the sliding velocity, in order to prevent falling. Another striking example of optimising the frictional response of a skin–product interaction

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in the bathroom is found in shaving. The application of tailored operational conditions during shaving, i.e., person specific pressure and sliding velocity during the shaving action, combined with tailored boundary layers—shaving soap—gives a close shave. Another modern-day typical aspect of our current lifestyle is the interaction with touch screens, which are dominantly present around us world-wide, especially among the younger generation of consumers. Touching screens with the index finger clearly illustrates the relative importance of skin friction: reduced control over friction during the interaction, e.g., because of the environmental conditions, will reduce the ability to manipulate the device. People will change the operational conditions, i.e., sliding velocity or contact pressure, in such a situation to regain control based on a trial-and-error strategy. This probably holds for more skin–product interactions such as selection of clothing and textiles. People seem to solve these problems related to skin friction based upon a trial-and-error strategy and based upon on our sense for touch. The question rises whether or not a trained tribologist would make different choices based upon a science based strategy? In other words: Is skin friction part of the larger knowledge base that has been generated during the last decades by tribology research groups and which could be referred to as Science Friction? This paper tries to formulate an answer to this question by elaborating on the specific nature of the tribological system, by elaborating on the feasibility of current friction models to skin tribology, and by the possibilities to influence friction in skin–product interactions by surface texturing and polymer coatings.

## 2 Friction in skin–product interactions

### 2.1 The systems approach and living materials

A well accepted method for analysing the tribological performance is based upon the so-called systems approach [2, 3]. Basically this means that a tribological contact situation is separated from the application studied, by using a hypothetical system envelope. The contact situation separated by this envelope is regarded as a system, that is, a set of elements interconnected by structure and function. Hence, the structure of contact situations is reduced in the case of skin tribology to the interaction between a product surface and a skin surface in the presence of a possible "lubricant" and surrounded by a specific environment (see Fig. 1).

In product–skin interactions, the function of the systems is related to the application, i.e., sports or personal care with a process that depends on the selected product, like for example making a sliding on artificial turf or wet-shaving, respectively. The connections between the system and the rest of the application can generally be reduced to input: the operating variables, and output: friction and wear. In the case of skin tribology one of the contacting surfaces is a living material. The implication of this condition is only limitedly explored in current engineering practise [4]. Emphasis is put on the connection with the human somatosensory system, see Refs. [5–9] for touch related literature and on the characteristics of individual subjects [10] in relation to best practises in panel testing.

The human somatosensory system has a tribological aspect. In fact, the exploratory procedure that is used to touch a surface is similar to experimentally determining friction in a reciprocating test. By pressing your finger(s) at the surface of interest and sliding to feel specific features, friction is generated in the contact.


**Fig. 1** Schematic presentation of the tribological system in skin–product contacts, showing the interaction of the product's surface with the top layer of the human skin, in the presence of a lubricant and surrounded by the environment. The input, i.e., the operating variables and the output, i.e., friction and wear, connect the tribo system with the rest of the application. Histology by P. van Erp, Dermatology, Nijmegen, NL.

Pressure in this contact is linked to the applied normal force of for example the finger that "feels" the surface and sliding velocity is related to the exact exploratory procedure that is selected for feeling. A key aspect of the human sense for touch is formed by a group of sensory cells, an assortment of morphologically and functionally distinct mechanosensory cell types that are tuned to selectively respond to various mechanical stimuli, such as vibration, stretch and pressure. In glabrous skin of the palms and fingertips, Pacinian corpuscles, rapidly adapting Meissner's corpuscles, Merkel cell-neurite complexes, Ruffini corpuscles make up the majority of touch receptors [11, 12]. From the tribological action, signals are produced by the sensory cells that are transmitted by the nerve system, through the spinal cord, to the thalamus and from there to the somatosensory part of the brain. Next, the sensory information is processed by the brain, i.e., organised, identified, and interpreted in order to fabricate a mental representation, which essentially determines the touch perception or tactility of a surface. The relation between finger ridges, vibrations, friction and surface texture is subject of research in Refs. [13, 14], yet a straightforward translation to comfort during use [15] or an application to for example touch perception of robotic fingers is at the very beginning of development [9].

The set of operating variables, involved in tribological contact situations in skin–product interactions and their relative importance strongly depends on the actual application. Sliding velocity and the load or interfacial pressure are usually taken as main operating variables.

The loss-output of a tribo-system is described by measuring and classifying the friction and wear characteristics of the system. Wear is typically discussed in terms of removal of the stratum corneum, the presence of scratches or wounds or by indirect measures such as trans epidermal water loss, skin irritation and redness or the occurrence of blisters [16, 17]. Friction data and models are presented by Refs. [13, 18–20] and are discussed in more detail in Section 2.

The systems approach is designed to handle complex processes that influence wear or unexpected friction levels in industrial practice and shows a way to simulate critical aspects of the operation at a laboratory scale. By changing the operating variables and studying the tribological characteristics it becomes possible to optimise the function of the system, without necessarily understanding the structure of the system in detail. Secondly, it is possible to study the structure of a system by varying the elements and comparing the performance at given operational conditions. Both techniques are used in skin tribology.

### 2.2 Modeling and predicting friction

The science of friction typically starts with theempirical rules formulated by Amontons and Coulomb for elastically deforming, dry contacts, i.e., the force of friction is directly proportional to the applied load, the force of friction is independent of the apparent area of contact and the force of dynamic friction is independent of the sliding velocity. These empirical rules are summarized by Eq. (1) in which $\mu$ is the coefficient of friction, $F_f$ the friction force and $F_n$ the normal force.

$$\mu = \frac{F_f}{F_n} \tag{1}$$

The coefficient of friction given by Eq. (1) can be determined experimentally, maintaining a sliding contact with the contacting surfaces of interest and using a limited range of operating variables.

*In vivo* experimental research on skin friction is conducted basically with four contact set-ups, i.e., the contact material moves with respect to skin linearly, the contacting material rotates with the axis of rotation parallel to the skin or rotates with the axis of rotation perpendicular to the skin, or the skin moves linearly in contact with a non-moving surface. A summary of the experimental research on skin friction, given by Derler and Gerhardt [21], and recently by Veijgen [4] reveals a large range of values for the coefficient of dynamic friction [4], i.e., from 0.07 [22] to 5.0 [23]. This is also found for the coefficient of static friction [4] that ranges from 0.11 [24] to 3.4 [25]. Based on these results it is concluded that the coefficient of friction in skin–product interaction is not constant and depends greatly upon the operational conditions, the environmental conditions, materials selection and possibly upon the type of motion that is used for the study, see Table 1 for an overview extracted from Ref. [4]. This

**Table 1** Coefficient of (a) dynamic friction and (b) static friction from experimental research, extracted from Ref. [4].

(a)

| Reference used in Ref. [4] | Location at human body* | Counter surface | $\mu_{dynamic}$ | Remarks |
|---|---|---|---|---|
| Asserin et al. [26] | Forearm (V) | Ruby | 0.7 | – |
| Bobjer et al. [27] | Finger | PC | 2.22 | 1 N normal load |
| | | | 0.85 | 20 N normal load |
| | | | 0.61−1.21 | Sweat |
| | | | 0.11−0.30 | Glycerol |
| | | | 0.09−0.28 | Paraffin oil |
| | | | 0.10−0.72 | Lard |
| Comaish & Bottoms [28] | Hand (D) | PTFE | 0.20 | |
| | | PA, sheet | 0.47 | |
| | | PE | 0.30−1.3 | |
| | | Wool | 0.40 | |
| | | PA, knitted | 0.37 | |
| | | Terylene | 0.40 | |
| Cua et al. [29, 30] | Forehead | PTFE | 0.34 | |
| | Upper arm | | 0.23 | |
| | Forearm (V) | | 0.26 | |
| | Forearm (D) | | 0.23 | |
| | Postauricular | | 0.34 | |
| | Hand (P) | | 0.21 | |
| | Abdomen | | 0.12 | |
| | Upper back | | 0.25 | |
| | Lower back | | 0.19 | |
| | Thigh | | 0.15 | |
| | Ankle | | 0.21 | |
| Derler et al. [31] | Finger | Wool | 0.27−0.71 | |
| El-Shimi [22] | Forearm (V) | Polished steel | 0.31 | Untreated |
| | | | 0.07−0.38 | Silicone oil, velocity |
| | Forearm (D) | Polished steel | 0.37 | Dry |
| | | Rough steel | 0.12 | Dry |
| Gee et al. [32] | Finger | Rubber | 2.4 | |
| | | PC | 2.7 | |
| | | Steel | 1.8 | |
| | | Glass | 1.2 | |
| | | PE | 1.6 | |
| | | Paper | 0.6 | |
| Li et al. [33, 34] | Scar tissue | PE | 0.8 | 0.1 N normal load |
| | | | 0.6 | 0.7 N normal load |
| | Prosthetic / healthy skin | | 0.72 | 0.1 N normal load |
| | | | 0.47 | 0.7 N normal load |
| | | | 0.17 | 8.0 N normal load |
| Naylor [35] | Lower leg (V) | PE | 0.5−0.6 | |
| | | | Max 1.1 | Wweating |
| | | | Max 1.1 | Cleaned skin |
| Pailler-Mattei et al. [23] | Forearm (V) | Steel | 1.1−1.4 | |
| Ramalho et al. [36] | Forearm (V) | Glass | 0.15−1.07 | Standard |
| | | | 0.17−0.87 | Washed |
| | | | 0.10−0.84 | Alcohol |
| | | | 0.5−1.35 | Glycerine |
| | | | 0.8−1.4 | Petrolatum |
| | Palm | | 1.21 | Standard |
| | | | 0.90 | Washed |
| | | | 1.24 | Alcohol |
| | | | 0.45−0.7 | Glycerine |
| | | | 0.8−1.4 | Petrolatum |
| Sivamani & Maibach [37] | Finger (D) | Stainless steel | 1.1 | 0.05 N normal load |
| | | | 0.55 | 0.45 normal load |
| | | | 0.3−0.9 | Cream |

* (V) ventral, (D) dorsal and (P) palmar side

(b)

| Reference used in Ref. [4] | Location at human body* | Counter surface | $\mu_{static}$ | Remarks |
|---|---|---|---|---|
| Comaish & Bottoms [28] | Hand (D) | PTFE | 0.25 | |
| | | PA, sheet | 0.55 | |
| | | PE | 0.43 | |
| | | Wool | 0.45 | |
| | | PA, knitted | 0.42 | |
| | | Terylene | 0.45 | |
| | Hand (P) | PE | 0.62.1 | |
| | Lower leg | PE | 0.6−1.3 | 0.03−10 N normal load |
| Lewis et al. [24] | Finger | Al (lacquered) | 0.26 | Dry |
| | | | 0.54 | Wet |
| | | | 0.11 | Oil |
| | | Label paper | 0.29 | Dry |
| | | | 0.41 | Wet |
| | | | 0.13 | Oil |
| Mossel & Roosen, adapted from Ref. [4] | Finger | Stainless steel | 0.35−1.13 | |
| Mossel, adapted from Ref. [4] | Finger | Stainless steel | 0.35−0.94 | |

* (V) ventral, (D) dorsal and (P) palmar side

dependence of friction on the system characteristics is consistent with the non-linear, visco-elastic mechanical behavior of the skin and with the strong dependence of the mechanical properties of the outermost layers of the skin with the environmental conditions [21].

An explanation for the nonlinear relation between the friction force and the normal force in skin–object interactions could be found in analyzing the frictional response with the two term (non-interacting) model of friction [13, 18–21]. The friction force in skin–object interactions is seen as the sum of the forces required to break the adhesive bonds between the two surfaces at the asperity level, $F_{\mathrm{f,\,adh}}$, and the forces related to the deformation of the bodies in contact, $F_{\mathrm{f,\,def}}$. This concept was recently applied to the contact of a regularly patterned surface in contact with *in vivo* skin by van Kuilenburg et al. [13]. The regular pattern consisted of an array of summits of equal height with a common radius $R_{\mathrm{summit}}$ at a distance $\lambda$ in both $x$ and $y$ direction, made by direct laser texturing. The term related to adhesion in the contact between the summits and the skin, is assumed to be proportional to the real area of contact for each summit individually, $A_{\mathrm{real,\,summit}}$, see Eq. (2).

$$F_{\mathrm{f,adh}} = \tau A_{\mathrm{real,summit}} \tag{2}$$

The interfacial shear strength, $\tau$, depends on subject specific or anatomical location specific "lubricating" properties of the skin, like the sebum content, hydration of the skin, the amount of sweat, any effects due to treatments of the skin, such as the use of creams and conditioners [26] and possibly the hair density [4]. The deformation related term is assumed to be determined by the indentation of an individual summit into the skin, see Eq. (3) [38],

$$F_{\mathrm{f,adh}} = \frac{3}{16}\beta\frac{\alpha}{R}F_{\mathrm{n}} \tag{3}$$

in which $\beta$ is the visco elastic loss fraction, $\alpha$ the radius of the contact area and $R$ the radius of the individual summit present at the textured surface.

Expressions for the area of contact $\alpha_{\mathrm{H}}$ and the indentation depth $\delta_{\mathrm{H}}$ in the Hertzian case for an individual summit–skin contact are depicted in Eqs. (4) and (5), respectively.

$$\alpha_{\mathrm{H}} = \left[\frac{3}{4}\frac{RF_{\mathrm{n}}}{E^{*}}\right]^{1/3} \tag{4}$$

$$\delta_{\mathrm{H}} = \left[\frac{9}{16}\frac{F_{\mathrm{n}}^{\,2}}{RE^{*2}}\right]^{1/3} \tag{5}$$

in which $E^{*}$ equals the reduced elastic modulus given by Eq. (6):

$$\frac{1}{E^{*}} = \frac{1-\upsilon_{\mathrm{skin}}^{\;2}}{E_{\mathrm{skin}}} + \frac{1-\upsilon_{\mathrm{product}}^{\;2}}{E_{\mathrm{product}}} \tag{6}$$

with $E_{\text{skin}}$, $E_{\text{product}}$, $\upsilon_{\text{skin}}$, and $\upsilon_{\text{product}}$ the Young's moduli and Poisson's ratios of the skin and product surface, respectively at the asperity level. As the elastic moduls of skin is not a material property but a system property—values depend e.g., on the indentation depth and the indentors radius, see Ref. [39] —it is necessary to use values that are measured with indenter that have equal or similar dimensions as the summits of interest. Values for $E_{\text{skin}}$ and $\upsilon_{\text{skin}}$ could therefore be taken from representative experimental research presented in Ref. [40]. Although the viscous character of skin is not incorporated in this contact model yet, it is possible to improve the quality of the model greatly by adding adhesion to the Hertzian contact model. As demonstrated by Ref. [13], the normal force acting on an individual summit must be corrected to an effective normal force, $F_{\text{eff,summit}}$ to correctly estimate the increased contact area for that specific summit–skin contact.

$$F_{\text{eff,summit}} = F_{\text{n}} + 2F_{\text{adh}} + 2\sqrt{F_{\text{adh}}(F_{\text{n}} + F_{\text{adh}})} \tag{7}$$

with the adhesive force $F_{\text{adh}}$ based on the JKR theory of adhesion [41],

$$F_{\text{adh}} = \frac{3}{2}\pi R W_{12} \tag{8}$$

The work of adhesion at the asperity level, $W_{12}$, gives the opportunity to fine tune the overall contact by tailoring individual summits to the presence of specific layers. The feasibility of this approach however, is to be validated by future research. From Eqs. (3)−(8) one can construct an expression for the real or true area of contact, as a function of the material properties of the skin and product, as a function of the two controlling roughness parameters and the nominal contact area $A_0$, see Eq. (9):

$$A_{\text{real}} = \pi\left(\frac{3}{4E^*}\right)^{\frac{2}{3}}\left(\frac{R}{\lambda}\right)^{\frac{2}{3}}\left(\frac{E_{\text{eff}}}{A_0}\right)^{\frac{2}{3}} A_0 \tag{9}$$

Similarly, an expression for the deformation related term of friction for an individual summit–skin contact with radius $a_{\text{summit-skin}}$ relative to the radius of that specific summit $R$ can be constructed, see Eq. (10).

$$\frac{a_{\text{summit-skin}}}{R} = \left(\frac{3}{4E^*}\right)^{\frac{1}{3}}\left(\frac{\lambda}{R}\right)^{\frac{2}{3}}\left(\frac{E_{\text{eff}}}{A_0}\right)^{\frac{1}{3}} \tag{10}$$

Equations (9) and (10) can be used as building blocks for predicting skin-friction, as shown in more detail in the work of Van Kuilenburg et al. [13].

The presented approach , although developed for a specific texture, could possibly be extended to rough product surfaces in general, as it is based on the contact behavior of individual summits.

An alternative approach that circumvents these issues has been followed by Veijgen et al. [4, 10], who used multivariable statistical analyses to develop a quantitative model for the friction of human skin based on a large dataset composed of several hundred friction measurements and recording the associated tribo- system properties, including contact conditions and the environment, but also subject characteristics, and dietary habits.

However, a complete physics-based model describing the friction behaviour of human skin is still a subject of debate and research and is not expected to be ready for engineering purposes at short notice. In the meantime a power law expression given by Eq. (11) is frequently suggested as simplified model for the coefficient of friction:

$$\mu = c_1 \cdot F_{\text{n}}^{c_2 - 1} \tag{11}$$

One could start with $c_2$ = 2/3 for contact situations where adhesion is dominant, compare Eqs. (9) and (1), and with $c_2$ = 4/3 for situation where deformation is dominant, compare Eqs. (10) and (2) and fine-tune with $c_1$.

# 3 Engineering skin friction

## 3.1 The role of skin friction in comfort perception

Materials selection by manufacturers of sports and care products includes optimising the complex interaction of manufacturing costs, functionality, durability and product specific aspects like colour. The degree of comfort or the degree of discomfort, important from the user's point of view, is incorporated as well in this selection process. Analysis of comfort and discomfort in skin–product interactions that involve sliding actions—thinking of making a sliding on artificial turf—clearly reveals the relative importance of skin friction in relation to comfort and discomfort.

Deformation of the skin during sliding could cause discomfort. A threshold for that is given by Xu et al. [42] as the threshold for stress at the nociceptor location and is assumed to be 0.2 MPa. The depth of the nociceptor varies in the range of 75 to 200 μm below the skin surface. Below the threshold values for mechanical damage, $\sigma_{crit}$, tactile sensation is determined by the subsurface stresses and strains at the locations of the mechanoreceptors in the skin:

- Merkel cells—points, edges and curvatures;
- Meissner corpuscles—slip, friction and vibrations (10–200 Hz);
- Ruffini endings—(direction of) motion;
- Pacinian corpuscles—surface roughness, vibrations (70–1000 Hz).

A linear relation between the firing rate of the nerve endings and the subsurface stress and strain distribution in the skin is known to exist as shown by Sripati et al. [43]. Innervation density and psychophysical thresholds of defined stimuli at the skin surface have been investigated thoroughly within the scope of for example haptics and plastic surgery [44].

The subsurface stress and strains within the skin are influenced by skin friction. For estimation of the influence of friction load at the surface on the magnitude of stresses within the skin explicit equations are available [45]. For example, the maximum tensile stress beneath a sliding spherical contact occurs at the skin surface at the back edge of the contact and contains a term that increases linearly with the coefficient of friction and with the maximum contact pressure, $p_{max}$. In other words, the absolute stress value at the skin surface could rise an order of magnitude if friction changes from $\mu$ = 0.1 to $\mu$ = 1, e.g., due to changes in environmental conditions. As such, it is important to characterize the mechanical intensity of a contact, e.g., by defining a dimensionless mechanical intensity number MI given by

$$\mathrm{MI} = \frac{\mu p_{max}}{\sigma_{crit}} \quad (12)$$

Secondly, frictional heating during sliding is strongly associated with discomfort. Temperature and exposure time determine to a great extent of the severity of skin burns [46]. From pathologic examination a reciprocal relationship between temperature and exposure time was found and modelled successfully using an Arrhenius equation by Tropea and Lee [46]. Tissue specific values are found experimentally by calibration. Non-invasive tests with a thermal imager confirmed that the temperature of the skin surfacs rises after friction testing [47]. A solution for local surface temperature rise presented in Ref. [48] and summarized by Eq. (3) can now be used to predict skin temperature rise by frictional heating in real asperity contacts.

$$T_f = \frac{\mu \cdot F_n \cdot v}{a \cdot K_{eff}} \quad (13)$$

with $K_{eff}$ the effective thermal conductivity that takes into account the operational conditions and the thermal properties of the contacting materials. From Eq. (13) it is clear that the local temperature increases linearly with the coefficient of friction and is equally sensitive for an increase in sliding velocity. In other words, higher sliding velocities require low friction forces in skin–product interactions. From Eq. (3) one can construct a thermal intensity number given by

$$\mathrm{TI} = \frac{\mu \cdot F_n \cdot v}{T_{crit} \cdot a \cdot K_{eff}} \quad (14)$$

in which $T_{crit}$ represents the critical contact temperature.

Combining the MI and TI parameters with a measure that represents comfort during use, enables the construction of a skin comfort map, which can serve as a design diagram. A conceptual version of such a diagram is given in Fig. 2. No experimental evidence exists yet for this diagram, but nevertheless

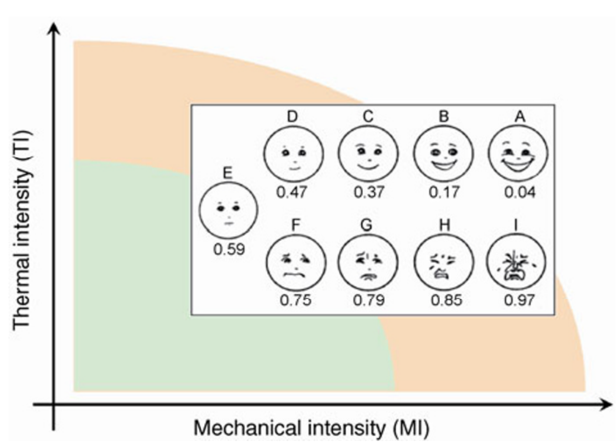


**Fig. 2** Conceptual version of a comfort diagram based on the mechanical and thermal intensity of a sliding contact.

it clearly illustrates the need to predict and control friction. Two promising directions to influence friction in a controlled way are the use of surface textures and the use of brush coatings.

### 3.2 Changing friction by surface texture

In "hard" tribological contacts, the (macroscopic) apparent area of contact is significantly larger than the real area of contact and there is only a negligible influence of the surface roughness on the friction force. When 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, which means that the adhesion component of friction can be quite substantial, particularly when the surface has a low roughness. Indeed, in describing the friction behaviour of human skin, any effects due to deformation (e.g., viscoelastic losses and mechanical interlocking) are often ignored, and only adhesion phenomena are taken into account, see Ref. [22].

The relation between the surface roughness and the adhesive component of the friction force has been be described as

$$F_{\mathrm{f,adh}} \propto \mathrm{Rq}^{h} \tag{15}$$

in which Rq represents the root mean square roughness of the counter surface and the exact value of the exponent $h$ is, as yet, unknown. Hendriks and Franklin [49] reported a factor 5 decrease in the coefficient of friction measured on skin when the roughness of the counter material was increased from 0.1 to 10 μm, from which the exponent $h$ can be estimated to be approximately −2. In contrast, based on a fully elastic approximation combined with a Greenwood-Williamson-like statistical approach, Masen [50] estimated $h$ to range between −0.66 and −1. However, this latter estimate is an over-simplification because the mechanical properties of skin vary with the size of the contact [39], and a deterministic approach to account for the effects of surface roughness seems more appropriate.

For surfaces with a roughness Rq in the order of micrometres and more, the adhesive model gives rather low coefficients of friction, and such low values are not obtained in experiments. The 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, provided that the lateral spacing between the asperities is small enough so that the skin does not fill the valleys, which would result in an increased area of contact and, hence, high friction. Indeed Peressadko et al. [51] showed that the lateral geometry such as the wavelength or the spacing between the individual asperities can play an important role. One could visualise the influence of the 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.

The deformation component of friction in skin-object interactions is often neglected. For surfaces with high roughness and waviness, the ploughing of the roughness asperities through the skin causes viscoelastic losses as well as mechanical interlocking between the asperities and the friction ridges of the finger pad. This contribution can be substantial and provide an opportunity to create high friction and increased grip. The viscoelastic loss factor $\beta$ is often estimated to amount to about 24% of the total energy involved in the deformation process and, as a general guideline, for skin interactions with surfaces with a roughness Rq in the order of several micro-meters and more, the deformation component can be used to change the frictional response of a product–skin interaction substantially.

### 3.3 Changing friction by brush coatings

Brush coatings, a relatively new and promising strategy for boundary lubrication, is a way to control the friction in skin–product interactions. Brush coatings represent polymer layers developed on a supporting surface by tethering long polymer chains with a sufficiently high grafting density. A schematic illustration of a polymer brush coating in an aqueous solution is shown in Fig. 3. When in good solvent, the end-grafted polymer chains allow the fixation of a large number of solvent molecules to form brush-like structure [52]. Many experimental and computer-simulation studies

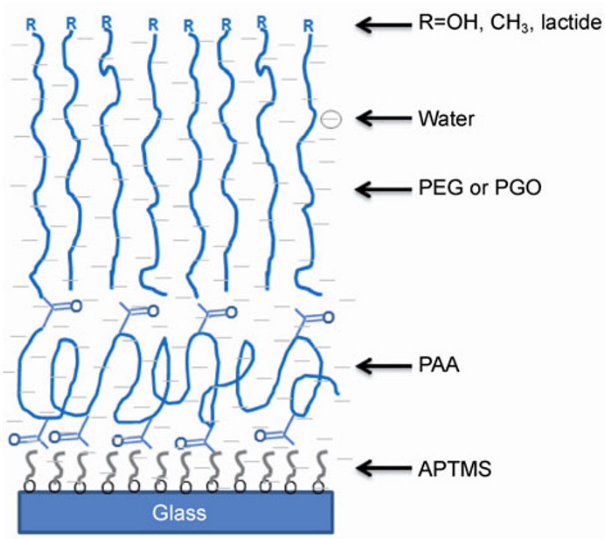


**Fig. 3** Schematic illustration of a polymer brush coating on a glass surface in an aqueous solution.

have been performed to investigate the lubrication mechanism of polymer-bearing surfaces and it was thought that the origin of the low frictional forces between brush-bearing surfaces is attributed both to the steric repulsion between the polymers supporting high normal loads and to intermolecular interactions between the polymer brushes and the solvent molecules which maintain a lubricating fluid layer at the sheared interfacial region [52, 53]. By varying the polymer architecture, such brushes can profoundly modify interfacial properties and change surface properties like wettability, surface energy, adhesion and friction to desirable state [54–57].

Friction and lubrication of skin play a major role in product development for cosmetics, textiles, artificial turf, medical devices, floor, etc. Some of these systems are in aqueous environment, like wet shaving, showering in bathroom, playing football on artificial turf after raining, etc. To enhance skin comfort during these activities, hydration lubrication by hydrophilic polymer brushes can be applied. Most tribological studies concerned with brush coatings have been performed at the nano-scale in a very low-load regime [58–60]. A translation of these results to engineering applications is one of the challenges of current skin tribological research.

Application-oriented studies on macroscopic scale contacts have been conducted to develop appropriate surfaces for the control of skin–product interactions [61, 62], in which the contact pressures applied were higher than 0.004 MPa, reported as clinically realistic for supine person on a foam mattress, and lower than 0.23 MPa, measured for highly stressed local contact at the forefoot during walking. A study on the effect of polyacrylic acid (PAA) grafted with poly(ethylene glycol) (PEG) (PAA-g-PEG) on friction was carried out using a reciprocating flat-on-flat test setup involving silicone skin L7350 [63]. The result shows that effective lubrication by water is able to reduce friction coefficient from above 1 to below 0.01 at low sliding velocities. The great friction reduction of more than one order of magnitude is contributed to the change of the hydrophobic-hydrophobic tribopair to the hydrophobic-hydrophilic tribopair with PAA-g-PEG brush coating, which can bind water in its structure and result in a lubricating water layer to remain in the contact. Thus, the sliding between two surfaces can be accommodated by shearing of a thin water film that is created in the contact area by applying a normal load. Such a layer is able to effectively separate the two tribological surfaces during sliding contact and as a consequence minimize the high adhesive contribution to friction that occurs for dry contact. Another study with hydrophilic brush coatings was conducted using a rotating pin-on-plate test setup involving polyurethane as mechanical skin equivalent. In this study, the influence of end group type (hydroxyl, methyl, lactide) and hydrophilicity (PEG, polyglycerol (PGO)) was evaluated. Result indicates that the friction coefficient is in the order of methyl>lactide>hydroxyl and PGO<PEG, which correlates to the hydrophilicity, that is, the higher the hydrophilicity, the lower the friction coefficient in aqueous environment. In addition, with the increasing of normal load, the friction coefficient increases and the difference is more obvious for brush coating with hydrophobic end group. This may be because the hydrophobic end group makes the polymer chains less densely packed, leading to weak steric repulsion, which cannot support high normal load. Therefore, under high normal load, the bound water molecule can be easily squeezed out, causing the increasing of friction. Further studies on the effect of skin temperature, the interactions between brush coatings and emulsions are under investigation.

## 4 Conclusions

This paper shows the relative importance of skin friction, not only for everyday situations but also in the design process of consumer products. Skin friction has a clear and distinct role in the perception of discomfort and comfort. For that, modelling of skin friction is important. Current friction models can only partially be applied to predict *in vivo* skin friction and are not ready yet to serve as general engineering tools. The specific nature of the tribological system limits furthermore, the use of conventional methods and stresses the need for *in vivo*, subject and anatomical location specific test methods. The need to control friction especially in product–skin interactions with a sliding component is evident. For that, surface texturing and polymer coatings are promising directions.



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