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A review of fingerpad contact mechanics and friction and how this affects tactile perception

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Abstract

In the sliding contact between the fingerpad and a rough surface when touching a product's surface, friction plays a role in the perception of roughness, slipperiness and warmth. For product engineers who aim to control and optimize the sensorial properties of a product surface interacting with the skin, it is essential to understand this frictional behaviour. However, the friction of skin is yet poorly understood. The variation that is observed within or between skin friction studies can be assigned to gender, age and orientation of the finger. Analysing data collected from literature shows some consistent trends. The coefficient of friction increases considerably with increasing hydration level of the skin, due to softening of the top layer of the skin. The coefficient of friction of the fingerpad decreases with normal load to a constant value, which can be attributed to effects of normal adhesion and the deformation behaviour of the fingerpad. There is no consistent effect of velocity on the coefficient of friction. Friction decreases with increasing R_a roughness. When the R_a roughness increases further, the contribution of deformation causes an increase in the friction after which it remains constant. Some influence of the finishing method is reported. The type of material has a smaller influence than the surface roughness of the sample or the condition of the skin. Even though the coefficient of friction of the fingerpad shows some consistent trends, examining the friction behaviour at a more detailed level might explain the contribution of friction to tactile perception. The measuring signal contains relevant information and should be analysed thoroughly as opposed to taking the average coefficient of friction of the steady state part of the signal. Future work should involve the study of local friction behaviour at the scale of the surface roughness.

Keywords

Skin, fingerpad, tactile perception, friction, tribology

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Introduction

When touching a product's surface, mechanical and thermal receptors in the skin of the fingerpad are stimulated and give rise to sensorial judgments such as soft, warm or rough. In combination with expectations, memories and personal background, the sensorial judgments lead to affective judgments, such as pleasurable or comfortable, thus creating a certain experience of the product.[1,2] In recent years, touch perception has gained increasingly interest from the field of engineering tribology. One of the first studies on touch properties of surfaces published in tribology literature was carried out at the University of Leeds by Barnes et al.[3] The main conclusion from their investigation of the sliding contact of a fingertip over glass surfaces with different roughnesses was that desirable feelings are generated when the finger slides over a surface which is less rough than the fingertip, whereas negative feelings are generated when the finger slides over a surface which is rougher than the fingertip. After this first publication, a number of studies have appeared in tribology journals. The relation between surface – and material – properties of consumer products and consumer's judgments was the subject of further research of the Leeds group.[2,4] Darden and Schwartz[5] investigated the relation between the tribological behaviour and the tactile attributes of polymer fabrics. Recently, several studies were carried out on the relation between friction properties and perceived surface properties, such as coarseness of paper[6] and grip.[7] Understanding the relationship between the perceptual responses and the properties of the material is the subject of affective

University of Twente, Enschede, the Netherlands

Corresponding author:
Julien van Kuilenburg, University of Twente, PO Box 217, Enschede, 7500 AE, the Netherlands.
Email: j.vankuilenburg@utwente.nl

engineering. From the viewpoint of the tribologist, it is the relation between the surface properties of the material and the sensorial and affective responses that is of most interest. The sensorial responses, also psychophysical responses, can be related almost directly to physical measurements of material and surface properties. Perceptions of roughness, warmth, softness and slipperiness can be related to measures of surface roughness, thermal conductivity, compliance and friction[8] using statistical techniques.

The senses of roughness, softness and slipperiness are mediated through mechanoreceptive afferents located in the skin. The different types of mechanoreceptors respond to spatiotemporal stimuli such as strains, or changes therein, and vibrations. This is where contact mechanics and, in case of sliding motion between the finger and a surface, the friction between the surfaces comes in. For instance, in a sliding contact, the maximum tensile stress at the surface and the maximum shear stress beneath the surface are proportional to the coefficient of friction.[9] The coefficient of friction μ, which is calculated as the quotient of the measured friction force F_μ and the applied normal load F, is commonly used in mechanical engineering to describe the friction behaviour of a system.

$$\mu = \frac{F_\mu}{F} \tag{1}$$

Numerous studies have reported on the friction behaviour of the human fingerpad. In their review paper Derler and Gerhardt[10] present a wide range of coefficients of friction as a function of countersurface material, surface roughness, normal load and skin condition. They further conclude that tactile perception and touch in relation to skin tribology is largely understudied and poorly understood. This paper aims at building an understanding of tactility and tactile friction from an engineering tribology background.

Tactile perception

Understanding product feel and the interaction of human skin and product surfaces requires a thorough knowledge of the tribological phenomena occurring at the interface between the human skin and the product surface. On the other hand, touch perception, which for the larger part starts with the stimulation of mechanoreceptors beneath the skin surface, can be explained from a mechanic point of view. When sliding the fingerpad over a surface, the characteristics of the surface and the material beneath will stimulate the skin senses, leading to sensorial judgments of softness, warmth, roughness and slipperiness. Figure 1 summarizes the physical stimuli and the psychophyiscal sensations in a schematical way.

Softness

In engineering, hardness refers to indentation hardness, which is basically the resistance of the surface and the underlying material against plastic deformation. In psychophysics, the 'softness' of an object is related to the compliance, or the lack of stiffness. The compliance can be expressed in terms of stiffness k, which gives the relation between the applied force and the resulting deformation, or by the elastic modulus E, which describes the relation between the applied stresses and the resulting strains. Obviously, stiffness and elastic modulus are related. Whereas the elastic modulus is a material property, the stiffness is a property of the object, also depending on the geometry. Whether the stiffness or the elastic modulus is the representative parameter of an objects softness depends on how soft or hard the object is perceived: It has been found that for the softer stimuli, the judgment of subjects is based on force–displacement information, thus stiffness, whereas for the harder stimuli the judgment is based on surface information, which is determined by the elastic modulus.[8] From a physiological point of view, this can be explained by the fact that part of the information comes from cutaneous stimuli caused by surface deformation and part of the information comes kinaesthetic stimuli combining force and displacement.[8]

In mechanical terms: From the point where the finger touches a surface and starts pressing, the relation between the applied force F and resulting displacement d_{finger} can be described as

$$F = k^* d_{finger} \tag{2}$$

where the reduced stiffness k^* of the contact can be defined as the product of the diameter of the contact $2a$ and reduced elastic modulus E^*

$$k^* = 2aE^* \tag{3}$$

The displacement of the fingerpad, the kinaesthetic stimulus, is composed of the deformation of the object δ_{surf} and the deformation of the fingerpad δ_{skin}, the cutaneous stimulus

$$d_{finger} = \delta_{surf} + \delta_{skin} \tag{4}$$

For softer objects $d_{finger} \rightarrow \delta_{surf}$, so the object is squeezed while there is no or little skin deformation. For hard objects $d_{finger} \rightarrow \delta_{skin}$, the displacement of the finger is accompanied by a significant deformation of the skin.

Warmth

The perception of warmth is related to the change in skin temperature through the rate and direction of

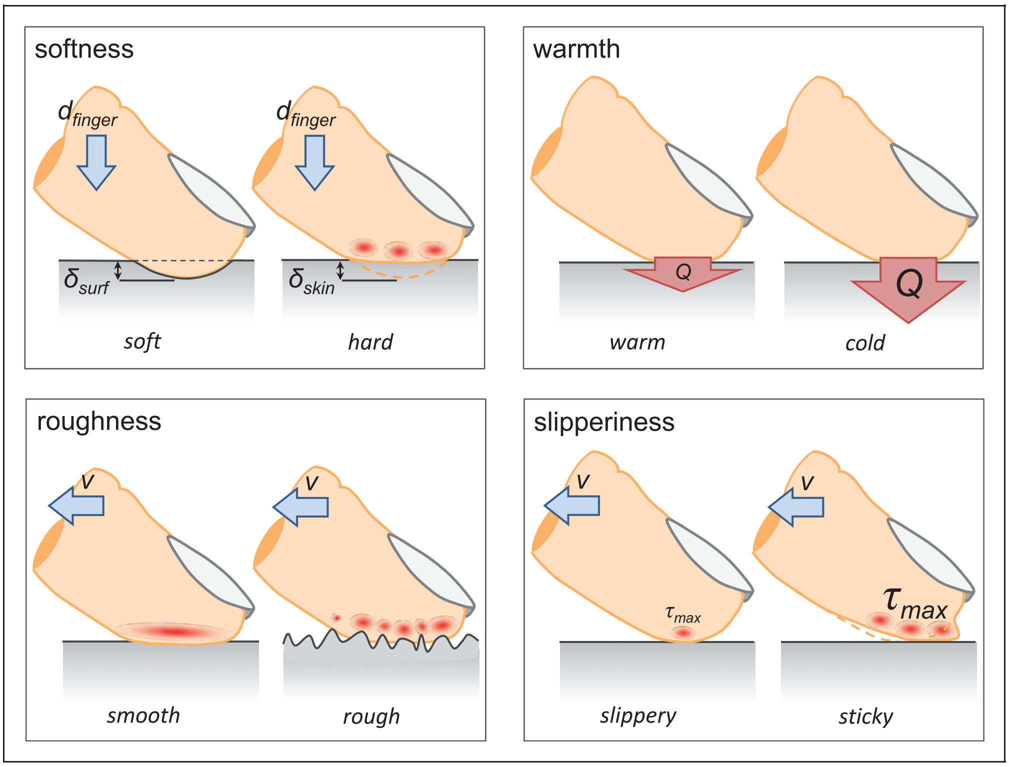

Figure 1. Schematic overview of the sensorial properties softness, warmth, roughness and slipperiness and used definitions. 'Soft' and 'hard' relating to surface and skin deformation; 'Warm' and 'cold' to small and large heat flux out of the skin; 'Smooth' and 'rough' to an uniform or irregular pressure distribution; 'Slippery' and 'sticky' to small and large strains in the skin.

heat flow between the finger and the surface. This depends on the bulk material's thermal properties such as thermal diffusivity and specific heat, the density and the geometry of the contact. Heat extraction from the fingers causes a perception of coldness, or coolness, whereas the conduction of heat into the skin results in a perception of warmth. Since in most cases the temperature of the surface is at room temperature, which is lower than that of the skin of the fingerpad, which ranges from 25 to 36°C,[11] it is the rate of heat extraction from the fingerpad skin that determines the perception of warmth. Ho and Jones[12] have shown that the cooling curves of the fingerpad can be modelled by exponential decay functions, characterized by a time constant. Different materials have different time constants, which are found to be inversely related to the logarithm of the material's thermal effusivity, which is the square root of the product of the material's thermal conductivity, specific heat and density. The thermal effusivity defines the material's ability to exchange heat with its surroundings. To be able to discriminate between two materials, the difference should at least vary a factor three in thermal effusivity, although it should be noted that the thermal effusivity does not take into account the geometry of the contact. In addition to the thermal properties of the material, the thermal contact resistance between finger and object, and the geometry of the object should be taken into account, as discussed by Bergmann Tiest.[8] The more compliant a material, the larger the contact area with the finger when the material is touched. An increase in contact area gives a larger heat transfer rate, so that softer materials feel colder. The real contact area is determined by the roughness of the material, and decreases with increasing roughness. The heat transfer rate is larger for smooth surfaces, so that smoother surfaces feel colder than rough surfaces. Ashby and Johnson[13] present the square root of the materials density ρ, thermal conductivity K and specific heat c_p as a measure of the coldness of the material. The quantity of heat leaving each unit of area of the fingerpad skin is proportional to this measure. The larger the quantity of heat Q leaving the skin, the colder a material feels.

In a rubbing contact, the contact temperature will increase proportional to the coefficient of friction following[14]

$$\Delta T = \frac{\mu F v}{a K_{eff}} \tag{5}$$

where the effective thermal conductivity is given as

$$K_{eff} = \frac{8}{3}\left(K_{stat} + K_{mov}\sqrt{K_{mov} + 0.4 a v \rho_{mov} c_{mov}}\right) \tag{6}$$

Equation (6) should be considered at various length scales. In the case of the fingerpad sliding against a smooth surface, the macro scale, the fingerpad is the stationary contact partner, whereas 'moving' applies to the countersurface. However, at the microscale, the scale of an asperity, it is the skin that is moving against the stationary asperity summit. In this case, it is the local friction behaviour, at the asperity level, that is of interest.

Roughness

The roughness of a surface, or rather its surface topography, is generally expressed in statistical measures which indicate the height differences of this topography measured with a profilometer, such as R_a, R_t or R_z roughess. Psychophysical roughness is related not to just one, but to a combination of these parameters, and also includes other mechanical properties of the surface, such as friction and compliance.[15,16]

When touching a rough surface, the roughness produces an uneven pressure distribution on the skin and vibrations when the fingerpad slides of the surface. Hollins and Bensmaïa[17] found that people spontaneously slide their finger over a surface, when asked to make judgments on its roughness. It was already reported by Taylor and Lederman[18] that when statically touching a rough surface, the perception of irregularities is diminished. When skin deformation changes are sufficiently rapid to prevent adaptation and the hand moves slowly enough so that skin deformation can occur, there is no influence of sliding velocity or type of motion.[15,18,19] The duplex theory of tactile texture perception[17,20] states that different mechanisms are responsible for tactile perception: a spatial code for coarse textures, with elements larger than about 100 µm, and a vibrotactile code for finer textures. The codes depend on the responses that arise in different types of mechanoreceptors. Hollins et al.[20] suggest that for relatively coarse surfaces, those with elements more than about 100 µm in size, information about the arrangement and density of surface features is carried from the finger to the brain primarily by slowly adapting type I (SAI) mechanoreceptors; the Merkel cells. For a textured surface, the SAI responses are found to be relatively sensitive to dot height and diameter,[17] which are spatial parameters. For finer surfaces, vibrotactile channels are involved, activated in part by vibrations set up when an exploring fingertip moves across a surface. Bergmann Tiest[8] argues that, since there is no direct relation between perceived roughness and sliding velocity, perceived roughness is associated with the amplitude of the vibrations, weighted with the frequency response of the Pacinian receptors.

A sample material commonly used to investigate perceived roughness is sandpaper. The perceived roughness of sandpapers is found to increase with particle diameter, or grit size, in the range 14–2000 µm, following a power law.[11,21] Results reported by several authors show that for textured surfaces the perceived roughness increases when the distance between elements, e.g. groove width increases: Lederman[19] found that perceived roughness increases with increasing groove width (0.175–1 mm) and increasing pressing force (0.27–2.2 N). Smith et al.[15] reported that perceived roughness increases with the distance between elements and height of the elements, whereas the size of the elements has a negligible effect. Kawasoe et al.[22] found that a change of height affects the perception of roughness less than a change of width does. With increasing distance between elements, the deformed volume of the fingerpad skin increases as can be shown by modelling.[18]

Although correlations were found between R_a roughness and perceived roughness,[23] for random rough surfaces it appears that peak values such as R_z and R_p are better descriptors to relate roughness to associated feelings.[2,3] Liu et al.[23] found a correlation of about -0.8 between surface kurtosis and perceived roughness, which indicates that the fingertip does not detect narrow large-amplitude surface features. Statistical roughness parameters such as the R_a or R_q are somehow related to asperity density and radius of curvature. Whitehouse and Archard[24] state that for many engineering surfaces the product of the density of summits η, their radius of curvature R and the standard deviation of the summit height distribution $\sigma = R_q$ is constant. Given the fact that η does not change vary much with changing roughness R and R_q are inversely proportional.[25] A dependence of perceived roughness on R_a or R_q roughness can thus be interpreted as a dependence on asperity radius of curvature, the equivalent of the particle diameter in sandpaper experiments.

Like there is no single parameter that uniquely represents a surface's roughness, there is no single physical roughness measure that best describes what is perceived as roughness. Bergmann Tiest and Kappers[16] report that when asked what they were paying attention to while assessing roughness, subjects mentioned the presence of irregularities, ridges or bits of fluff, whether they could depress the surface, the structure and size of the irregularities, the presence of fine or coarse bumps, whether the material was hard or soft, and whether the fingers slid easily over the surface. The definition of roughness perception has been found to be different for different people.

It may be concluded that there is not one single roughness parameter that correlates to perceived roughness, but that roughness is a multidimensional sensation that is determined by roughness amplitude, density or spacing of the asperities and friction between the surface and the fingerpad. Several studies report a positive correlation between roughness perception and friction (see for instance Refs. 8, 15, 18, 22 and 23). However, this may be assigned to the correlation between physical roughness and friction, which will be described later in this paper.

Slipperiness

Slipperiness is the psychophysical description that is related to the friction between the finger and the surface. It has been found that slipperiness correlates well to the coefficient of friction, as shown by for example Liu et al.[23] who measured a correlation of 0.79 between the measured coefficient of friction and perceived slipperiness rankings using aluminium samples within a range of roughnesses.

In the sliding contact between a sphere and a smooth flat, the maximum tensile stress σ_x at the surface is shown by Hamilton[9] to be proportional to the coefficient of friction following

$$\sigma_x = \frac{3}{2}\frac{F}{\pi a^2}\left(\frac{1-2\nu}{3} + \frac{4+\nu}{8}\pi\mu\right) \tag{7}$$

whereas the magnitude of the maximum subsurface shear stress τ_{vM} is proportional to the friction as well.

$$\tau_{vM} = \frac{3}{2}\frac{F}{\pi a^2}\left(\begin{array}{c}\frac{(1-2\nu)^2}{9} + \frac{(1-2\nu)(2-\nu)}{12}\pi\mu \\ + \frac{16-4\nu+7\nu^2}{192}\pi^2\mu^2\end{array}\right)^{1/2} \tag{8}$$

so that assuming a Poisson ratio $\nu_{skin} = 0.49$ gives $\sigma_x/p_0 \approx 1.76\mu$ and $\tau_{vM}/p_0 \approx 0.9\mu$, with p_0 the maximum contact stress. Furthermore, the location of the maximum shear stress beneath the skin surface changes with the magnitude of the friction. The different mechanoreceptors in the skin detect the variation and magnitude of these stresses when the fingerpad slides against a surface, creating a certain perception of slipperiness. Like with the perception of softness, Bergmann Tiest[8] argues that slipperiness is perceived through both kinaesthetic and cutaneous channels, detecting force and skin stretch, respectively. These phenomena can be considered at different levels: at the level of the fingerpad sliding against a smooth surface, and at the microlevel, where asperity summits are sliding against the smooth skin. The latter clarifies the importance of considering local coefficients of friction in the perception of roughness.

Bergmann Tiest[8] states that few studies have been carried out on the perception of slipperiness and that relatively little is known about the haptic perception of friction. It is suggested that this might be due to the fact that the friction behaviour itself cannot simply be quantified.

Tactile friction

Friction in contacts where the human fingerpad is one of the interacting surfaces is referred to as tactile friction. As opposed to grip, where contact loads up to 50 N may be applied, in tactile friction the touching force is low, generally in the order of several Newtons. The expressions presented in the preceeding paragraphs show that in the sliding contact between the fingerpad and a rough surface, friction plays a role in the perception of roughness, slipperiness and sometimes warmth. Statistical analysis confirm this statement, as shown by Chen et al.,[2] although the correlations may be direct or indirect. They concluded that cross-correlations arise from correlations between the physical measures, such as between friction and compliance, and friction and roughness.

In engineering, it is common to quantify friction and 'frictional behaviour' by the coefficient of friction, which is calculated by dividing the measured friction force by the applied normal load. Childs and Henson[4] found that it is not the mean coefficient of friction that is important, but the local peak values of friction coefficient within a contact. Smith et al.[15] found a significant correlation between the friction and perceived roughness of surfaces with arrays of raised dots. They concluded that the rate of change in the friction force seemed to be a more important parameter than the mean coefficient of friction.

Furthermore, the simplified representation of a mean coefficient of friction ignores the fact that the friction force that occurs in the contact is the result of different mechanisms. The so-called two-term model gives the friction force as the sum of an adhesion term and a deformation term[26,27]

$$F_\mu = F_{\mu,adh} + F_{\mu,def} \tag{9}$$

The first term in equation (9) can be calculated from the shear strength of the interface τ and the contact area A by[28]

$$F_{\mu,adh} = \tau \cdot A \tag{10}$$

Assuming that the interfacial shear strength τ between a probe sliding with velocity v and the fingerpad rises from shear in the lipid layer which covers the skin, the interfacial shear stress can be estimated from

$$\tau = \eta\frac{\mathrm{d}v}{\mathrm{d}t} \approx \eta\frac{v}{t} \tag{11}$$

where η is the dynamic viscosity and t is the thickness of the lipid film. The thickness of the lipid film can be obtained from the skin surface lipid content SSL, which can be measured using a Sebumeter (Courage + Khazaka GmbH, Germany). Typical values reported in literature range between 1.5 and $4\,\mu\mathrm{m/cm^2}$.[29–31] From the density $\rho \approx 0.9\,\mathrm{g/cm^3}$ and dynamic viscosity $\eta \approx 0.17\,\mathrm{Pa \cdot s}$ of the lipid film,[32] the layer thickness and shear stress can be calculated. Since sliding velocities in friction experiments are generally in the range 1 to 10 mm/s, an interfacial shear strength τ in the order of 10 to 100 kPa is expected.

Adams et al.[27] argue that, for countersurfaces on which there is a thin organic film, such as skin, the interfacial shear strength is a linear function of the contact pressure p following

$$\tau = \tau_0 + \alpha p \tag{12}$$

where τ_0 is the intrinsic interfacial shear strength, α is the pressure coefficient and p is the mean contact pressure, which is calculated as the quotient of the applied normal load and real contact area. For wet skin sliding against a spherical glass probe they found $\tau_0 \approx$ 4.8 kPa and $\alpha \approx 0.8$, whereas for polypropylene (PP) $\tau_0 \approx 6.1$ kPa and $\alpha \approx 2$ were found. Contact pressures in the experiments varied between 1 and 17 kPa, yielding interfacial shear strengths varying between 5 and 25 kPa at 8 mm/s sliding velocity. Hendriks and Franklin[33] adopted the same approach and estimated these parameters for dry and hydrated skin of the inner forearm. The intrinsic shear strength was found to have an order of magnitude $\tau_0 \approx 1$ kPa and tends to increase with increasing hydration. For dry skin $\alpha \approx 0.8$ was found, increasing to $\alpha \approx 1.7$ for hydrated skin.

When an asperity indenting the skin is moved forward, work is dissipated due to the viscoelastic nature of the skin. The deformation component equals the amount of work lost by viscoelastic hysteresis per unit sliding distance, thus being proportional to a viscoelastic loss fraction β and the indentation δ of the asperity into the skin.[26,34]

$$F_{\mu,def} = \frac{3}{16}\beta\frac{\delta}{a}F \tag{13}$$

For dry skin sliding against smooth surfaces, the deformation term can be neglected. However, when sliding against rough surfaces, and when the skin is hydrated, deformation should be taken into account. The viscoelastic loss fraction β can be obtained from static or dynamic indentation experiments. In a static indentation experiment, β is estimated from the area between the loading and unloading curve. Values varying between 0.24 and 0.27 are reported in literature.[26,35,36] In a dynamic indentation experiment, in which a sinusoidal deformation profile is applied, β is calculated from the viscoelastic loss tangent $\tan\delta$ following $\beta = \pi\tan\delta$. The viscoelastic loss tangent is defined as the ratio between the storage and loss modulus E''/E'. Boyer et al.[37] found that β increased with increasing age from ~0.35 to ~0.4 and ~0.43 for the age groups 18–30, 31–50 and 51–70 years, respectively. The viscoelastic loss fraction of isolated stratum corneum was measured by Yuan and Verma,[38] who obtained values of 0.31 and 0.79 for dry and wet skin, respectively.

It should be noted that β should be measured at a deformation rate which is comparable to the loading–unloading rate of the sliding contact. For a sphere in sliding contact with the skin, the loading–unloading rate v_z can be estimated from the contact dimensions and the sliding velocity following

$$v_z = \frac{a}{R}v \tag{14}$$

The reported data have been measured at indentation velocities between 0.06 and 2.5 mm/s, which is in accordance with the sliding velocity in tactile friction experiments, which is in general in the order of several mm/s. Figure 2 shows a schematic illustration of adhesion and deformation in a sliding contact between the fingerpad and a rough surface.

When in contact with a ridged surface, an additional term, the interlocking term, can be attributed to the fingerprint ridges climbing over the surface features of the countersurface. This third term is described in further detail by Tomlinson et al.[39]

Numerous studies have reported on the friction behaviour of the human fingerpad (see for instance Refs. 25 and 40–46). A wide range of coefficients of friction is found as a function of countersurface material, surface roughness, normal load and skin condition.

Contact mechanics of the fingertip

For engineering materials, Hertz's theory[47,48] provides us with expressions which describe the relation between radius of curvature R, normal load F and the contact radius a_H and deformation δ_H for a spherical contact as shown in equations (15) and (16).

$$a_{\mathrm{H}} = \left(\frac{3}{4}\frac{RF}{E^*}\right)^{1/3} \tag{15}$$

$$\delta_{\mathrm{H}} = \left(\frac{9}{16}\frac{F^2}{RE^{*2}}\right)^{1/3} \tag{16}$$

In which E^* represents the reduced elastic modulus, defined as

$$\frac{1}{E^*} = \frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2} \tag{17}$$

with E_1 and E_2 the respective elastic moduli and ν_1 and ν_2 the Poisson ratios of the contacting materials. In the case of contact between skin and a much stiffer counterbody, $E_{counterbody} \gg E_{skin}$ and the reduced elastic modulus depends solely on the properties of the skin so that $E^* \approx E_{skin}/\left(1-\nu_{skin}^2\right)$. Since the skin is composed of different layers, and the elastic modulus of these layers decreases with depth, at different length scales different layers determine the magnitude of the apparent elasticity E_{skin}. To account for the multilayered and nonhomogeneous structure of the skin, Van Kuilenburg et al.[49] adopted the concept of an effective elastic modulus $E = f(a)$,

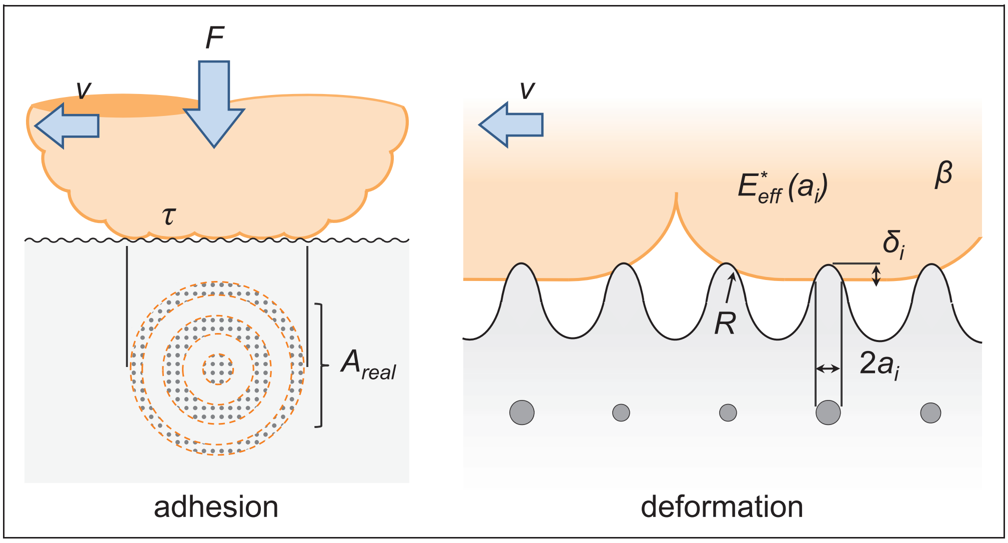

Figure 2. Schematic overview of the sliding contact between the fingerpad and a rough surface.

providing a closed form expression describing the elasticity of the skin of the volar forearm as a function of length scale. In the case of a spherical contact the length scale of the contact equals the contact radius a. Figure 3 shows that the effective elastic modulus of the volar forearm varies considerably with length scale. At different scales, the evolution of the effective modulus with length scale can be described by power laws. Although the anatomy of the fingerpad is different from the volar forearm and the skin differs in layer thickness and surface topography, the same trend is expected for the skin of the fingerpad. At the micro-scale, i.e. the scale of surface roughness, the effective elastic modulus is determined by the top layer of the skin, the stratum corneum. With increasing length scales, the lower, and more compliant, skin layers will determine the elastic behaviour, so that a decrease of the effective elastic modulus is expected. Finally, the much stiffer bone of the distal phalanx causes the elasticity to increase. The length scale effect determines the contact behaviour of the human skin, such as the growth of the fingerpad area with normal load.

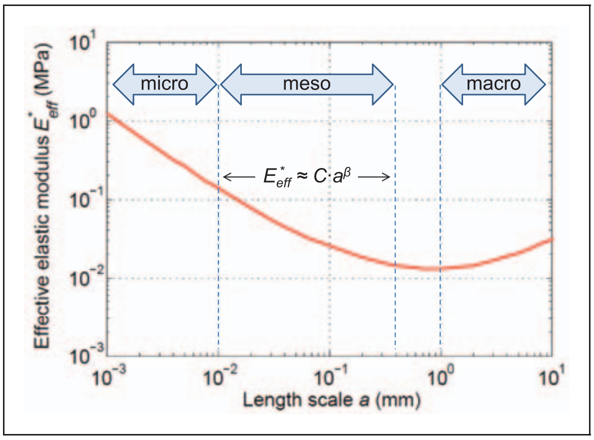

Figure 3. Effective elastic modulus of the skin of the volar forearm as a function of contact length scale. Figure adapted from Van Kuilenburg et al.[49]

Contact area

Different measuring methods have been used to measure the relation between the apparent contact area A_0 and applied load F. The main difference is the principle which is used for measuring the contact area for different values of the applied normal load. A relatively simple method is to use an inkpad and pressing the inked finger on a piece of smooth paper at different normal loads.[4,50–53] The normal load can be monitored using a load cell or even a kitchen scales. The size of the fingerprints can be measured using image analysis software.

To observe the contact area and applied load simultaneously, some researchers use a dedicated set-up to measure the contact area optically using microscopy[54–57] or optical coherence tomography.[58] An indirect method is the use of a pressure sensitive film.[59,60]

Analysis of data collected from the literature[4,18,40,50,52–57,59,60] shows that as a function of normal load the measured apparent contact area follows a power law

$$A_0 \propto F^n \tag{18}$$

with exponents ranging between 0.15 and 1.33. Obviously, the relation between the contact area of the fingertip and normal load deviates from the behaviour predicted by equation (15), which gives an exponent $n = 0.66$.

The exponent of the power law fitted through the measurement results depends on the range of applied normal loads. At higher loads, the effective elastic modulus increases with normal load. From equations

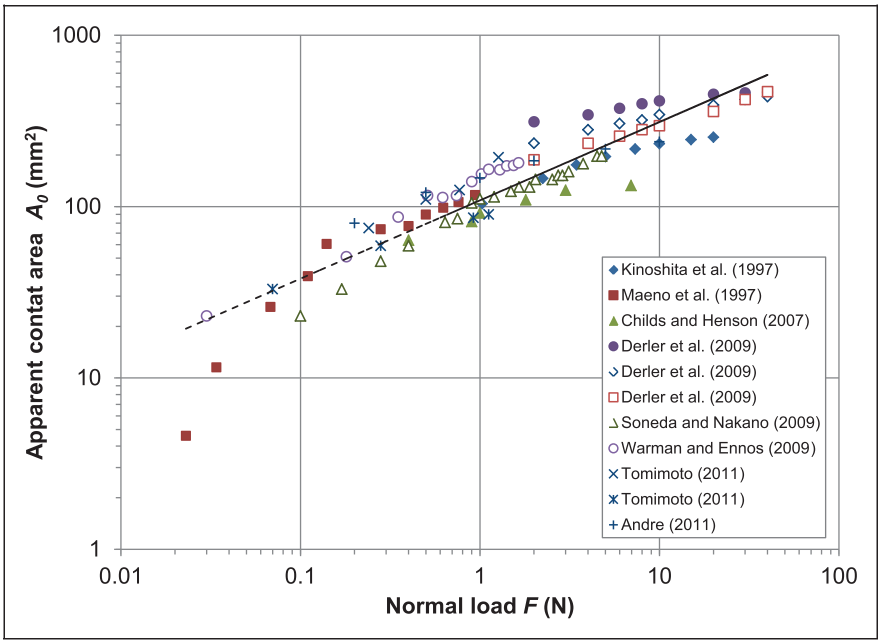

Figure 4. Apparent contact area of the fingerpad as a function of normal load. Data taken from Kinoshita et al.,[50] Maeno et al.,[54] Childs and Henson,[4] Derler et al.,[59] Soneda and Nakano,[56] Warman and Ennos,[52] Tomimoto[53] and André et al.[57]

(15) and (18), it can be seen that when the effective elastic modulus of the fingertip increases with normal load, an exponent $n < 0.66$ is expected. At low loads, the relation between normal load and apparent contact area follows a power law with an exponent larger than 0.66. The results obtained by Maeno et al.[54] illustrate those two regimes. To approximately 0.1 N, a steep increase of the apparent contact area with normal load is observed, characterized by $n \approx 1.33$, whereas from 0.1 to 1 N, a weaker decrease gives $n \approx 0.35$. Warman and Ennos[52] showed that, at loads between 0 and 1.6 N, the exponent n depends on the finger and the orientation of the finger. The middle and ring finger yield higher exponents (0.75 and 0.85) than the index finger (0.54). For the index finger, the fingerpad yields a higher exponent (0.54) than the tip of the finger (0.43). For the fingerpad and fingertip, respectively, exponents 0.55 and 0.36 were found by Tomimoto.[53]

Figure 4 shows an overview of data collected from literature for the apparent contact area measured as a function of normal load. At 1 N normal load, the contact area varies between approximately 80 and 200 mm^2. The contact area of the index finger decreases with increasing orientation angle, at 1 N normal load being approximately 155 mm^2 for the fingerpad, 40 mm^2 at intermediate orientation and 20 mm^2 for the tip as found by Warman and Ennos.[52] Kinoshita et al.[50] found that the thumb contact area was $\sim$1.5 times the area of the index finger regardless of the applied normal force for four subjects.

As well as the apparent contact area, the real contact area follows a power law with normal load. Soneda and Nakano[56] measured the real area of contact of the fingertip against smooth glass finding exponents between 0.58 and 0.81. At small loads, the contact ratio increases with normal load from 0.27 to 0.43,[61] whereas at higher loads the contact ratio was found to be independent of normal load and a contact ratio varying between 0.43 and 0.59 was found.[51] Assuming that the real area of contact increases by fresh ridges of the fingerprint pattern coming into contact rather than ridges increasing in width,[40] the real contact area can be calculated from the density and the width of the fingerprint ridges. The topography of the skin of the fingerpad, the fingerprint ridges, can be obtained from a three-dimensional surface topography measurement, e.g. using a silicone replica of the fingerprint skin.

Hydration

The fingerprint ridges contain sweat glands, which form single rows of pores of diameter 5–20 μm.[41] The number of pores per unit of area varies considerably between subjects. Liu et al.[58] measured between 310 and 1090 sweat ducts per cm^2 measured for seven subjects. The sweat ducts supply the skin of the fingerpad with a small amount of sweat to enhance grip by increasing adhesion. Besides, hydration of the top layer of the skin decreases its stiffness,[38,49,62] thus increasing the real contact area.

The hydration level of the skin can be measured using a Corneometer CM 825 (Courage + Khazaka GmbH, Germany). The Corneometer measures the changing capacitance of a precision capacitor in arbitrary units AU, which represent the change in the dielectric constant due to hydration of the skin surface, up to a depth of 10–20 µm. The Corneometer is an established equipment for measuring hydration in skin tribology studies.[63–65] Typical Corneometer readings are 20 AU for dry skin, 55 AU for normal skin and 85 AU for moist skin.[66] Another device to measure the amount of skin moisture is the Moistsense.[66]

Even when in the same environment or doing the same activity, the hydration level varies between subjects,[66] although no correlation has been found between the number of sweat ducts and the hydration level.[58]

The hydration level increases significantly when the subject is active, and with the duration of the activity.[66] Especially, when holding an object, such as a pen during writing, the moisture content at the interface is influenced by the occlusion time. Pasumarty et al.[67] suggest that the occlusion time is a critical factor that determines friction behaviour of skin.

Fingertip friction

In an early study on fingertip friction carried out using nearly 400 school children, Spurr[40] measured coefficients of friction ranging between 0.1 and 1.2. The average coefficient of friction obtained from measurements carried out on different days ranged between 0.42 and 0.54. Similar results were obtained on 30 adult subjects, where an average coefficient of friction of 0.48 was measured within a range 0.2–0.9. More recently, Liu et al.[58] measured the friction of the fingerpad sliding against steel for seven subjects. The coefficient of friction varied between 0.38 and 2.19 and an average of 1.03 was found with a standard deviation $\sigma = 0.64$. These panel studies clearly show that the friction measured between the fingertip and a certain countersurface is subject to various sources of variation.

Measuring

In tribology, it is common to measure friction and wear using a sphere-on-flat configuration, such as a pin-on-disk tribometer, under well-controlled conditions. The initial Hertzian contact stress is determined by the sample geometry and applied load, mostly applied using a dead weight. Friction and sometimes wear depth are measured instantaneously. A well-accepted method for measuring tactile friction is the principle of a stationary sample that is attached to a load measuring device over which the subjects slide their fingerpads. In several studies, researchers use a load cell,[5,15,25,45,46,59,68–71] although sometimes a custom made force plate is used.[22,23,41,43,44,53,58,72,73] As opposed to the subject applying a normal load and imposing a sliding motion, in a machine-controlled experiment, the fixated finger is in contact with a sliding probe.[67]

An important aspect in tribological research is the characterization of sample surfaces before and after testing, such as determination of the elastic modulus, hardness, surface topography and surface chemistry. In skin tribology, some dedicated equipment is used to evaluate the condition of the skin surface. The hydration level of the skin, which interacts with the mechanical and surface chemical properties of the skin, is measured using an apparatus such as the Corneometer, whereas the lipid content can be measured using a Sebumeter.

Variation

The frictional behaviour of two surfaces that are in sliding contact depends on the surfaces, any lubricant and the environmental conditions as well as the operational conditions.[74] Any changes in these contact conditions will inevitably lead to a noticable variation in friction results. The variation which is observed when analysing skin friction data, whether those data are collected from literature or obtained from an experimental program, can be attributed to several sources. Considering operational conditions such as the normal load, the sliding velocity and the hydration level of the skin as the experimental parameters still leaves several variables which may influence the results. An overview of studies which report on the influences of subject gender and age, orientation angle of the finger and type of motion is given in Table 1.

Most authors observed a lower friction for adult females than for adult males. Below a certain age it the friction observed for female subjects, or rather girls, is higher than for boys.[40,42] In a study on the friction between the fingerpad and different textiles, Savescu et al.[70] measured a lower friction for females than for males, although against some materials this effect was reversed. When sliding against relatively hard surfaces such as steel or glass, the lower friction observed for females can be explained from the contact behaviour of the fingertip. Generally, women have a smaller fingertip than men, so the contacting area between the finger and the countersurface will be smaller, hence the lower friction. Sasada[42] further reports the influence of age: for both males and females a decrease of the coefficient of friction was observed when the age increases from 0 to 80 years.

After receiving instructions, in most studies the subject controls the position and motion of the fingertip. The orientation of the finger is often referred to as ‘pad’, ‘tip’ or ‘intermediate’. It has been shown that the orientation angle has a significant influence on the coefficient of friction, the friction decreasing with increasing orientation angle.[4,53,72] As discussed earlier in this paper, Warman and Ennos[52] showed that the contact area, and its relation to applied load, depends strongly on the orientation angle. No significant

Table 1. Sources of variation.

Study	Variable	Range	Countersurface	Coefficient of friction
Spurr[40]	Gender		Metal cooking foil	Girls > boys
Sasada[42]	Gender		Steel	Female > male (<20 years)
				Female < male (>20 years)
Ramalho et al.[68]	Gender		Glass	Female < male
Savescu et al.[70]	Gender		Sandpaper, silk, polyester	Female > male
			Cotton, rayon	Female < male
Derler et al.[59]	Gender		Glass	Female < male
Sasada[42]	Age	0–80 years	Steel	Decreases
Han et al.[72]	Orientation angle	30°, 45°, 60°	Acrylic (PMMA)	Decreases
Childs et al.[4]	Orientation angle	0°, 45°	Textured polymer	Decreases
Tomimoto[53]	Orientation angle	0°, 80°	Acrylic (PMMA)	Decreases
Gee et al.[43]	Sliding direction	Left–right	Miscellaneous	Constant
Skedung et al.[45]	Sliding direction	Back–forth	Paper	Constant

differences have been reported whether sliding from left to right,[43] nor between back and forth.[45]

Before carrying out an tribological experiment, it is common to clean the sample material in an ultrasonic bath using solvents such as ethanol or acetone. In most studies involving the fingerpad as one of the contacting partners, before the experiments the hands are is washed with soap and air dried to achieve a condition which can be referred to as 'untreated normal skin.'[23,25,41,44–46,58,60,66,70–72,75] To achieve a condition that more closely resembles practical applications, Derler et al.[69] applied no cleaning or treatment of the skin at all.

The thin lipid layer which may be present on the skin alters the friction behaviour. It could increase the friction through its adhesive properties, but this same lipid layer might also act as a lubricating layer on the interface, which against a smooth counter surface forms a friction reducing layer. To remove the lipid layer on the skin, it can be cleaned with ethanol,[42,53,59,60,73] propanol[43] or another surfactant.[67] Sasada[42] found that after cleaning the skin with ethanol, the measured friction is very low. However, after 10 min, a gradual generation of sweat was observed at the finger surface and the friction increased. Spurr[40] observed oily contamination which remained after sliding a clean finger over glass and found that only a little contamination can reduce the measured friction. Sliding the finger over a previously used part of the surfaces resulted in significantly lower friction. This same effect was observed by Skedung et al.,[45] who measured a decrease in coefficient of friction against paper with the number of repetitions. XPS measurements showed that lipid material was transferred to the paper. The effect was stronger for smoother papers. A layer of transferred lipid material was observed by Dinç et al.[41] as well.

Hydration

Consistent results have been reported over the years showing that the coefficient of friction increases considerably with increasing hydration level of the skin.[25,41,58,66,67,69]

Masen[25] found an influence of the countersurface roughness on the effect of hydration: whereas for intermediate roughness (R_q between 0.005 μm and 1 μm) a two- to threefold increase in the coefficient of friction was measured, for surfaces that are relatively smooth or relatively rough the increase in the coefficient of friction for hydrated skin is only moderate.

The hydration level of the skin increases as a result of ambient relative humidity, occlusion or application of water onto the skin. Pasumarty et al.[67] found that the coefficient of friction increases with increasing contact time, or occlusion time, until it reaches a steady-state value.

Tomlinson et al.[66,75] showed that friction increases with increasing hydration level of the skin, whereas above a certain level the presence of moisture at the skin surface reduces friction again.

Normal load

In engineering applications, the real contact area of the tribological contacts grows proportional to the normal load so that Amontons' law of friction applies, which states that the friction force is proportional to the normal load: The coefficient of friction has a constant value. Some authors report a linear dependence of the friction force on normal load. In one of the earliest studies on fingertip friction, Spurr[40] found that the friction force was approximately proportional to the load. Against a smooth glass surface Ramalho et al.[68] measured that the friction force is proportional to the normal load within a large load range from 0 to 70 N. Also at lower loads against textured polymers,[4] different types of textiles[70] and paper[45] a linear relation was observed. In a comparative study Tomlinson et al.[44] found that the friction force and normal load showed a linear relation between 0 and 40 N normal load for different types of materials; metals, plastics as well as elastomers.

However, for materials such as elastomers and skin, the real contact area is a function of normal load. The friction force and the coefficient of friction are expected to depend on the applied normal load. Several authors report that the coefficient of friction decreases with normal load following a power law with exponents between -0.68 and -0.24.[42,46,60,70,72,73]

Masen[25] found a more complex friction behaviour as the measured coefficient of friction varied strongly with normal load. At low loads (1 N), the coefficient of friction is relatively high ($\mu \approx 1$). At a load in the order of 2.5 N, it reaches a minimum ($\mu \approx 0.3$) after which it increases with increasing load ($\mu \approx 0.4$ at 5 N load). Seo and Armstrong [71] report that the coefficient of friction decreased when the normal load increased from 1 to 10 N. A further increase to 20 N normal load had no significant effect. An increase at higher normal loads was found by Liu et al.[58] who reported a linear increase of the coefficient of friction when the normal load increases from 7.5 to 25 N.

The behaviour might depend on the countersurface material. Dinç et al.[41] report that the coefficient of friction against polymers, such as acrylic (PMMA), polyamide (PA) and polycarbonate (PC), decreases with friction when the normal load increases from 1 to 20 N. The same trend was observed independent of roughness and ambient humidity. However, when sliding against polytetrafluorethylene (PTFE), the coefficient of friction remained constant.

Tomimoto[53] showed that for the fingerpad ($\varphi \approx 0^\circ$), the coefficient of friction decreases with increasing normal load, whilst for the fingertip ($\varphi \approx 90^\circ$) it remains approximately constant.

Derler et al.[59] report friction as a function of normal load in the range 0 to 50 N against smooth and rough glass. They found that the coefficient of friction decreases with increasing normal load when the fingertip is sliding against smooth glass, for both dry and wet skin. The decrease with increasing load was larger for females than for males, and against the wet glass the decrease was larger than against the smooth glass. When sliding against rough glass, the coefficient of friction in the dry state is almost independent of normal load.

Figure 5 shows data for the coefficient of friction of the fingerpad obtained from literature. Although the data are obtained from different studies, carried out in different laboratories, using different subjects and against different surfaces, the data show a consistent trend of a coefficient of friction decreasing with increasing normal load. The figure points out that the strongest decrease occurs at relative low normal loads. This can be explained from the evolution of the contact area with increasing normal load following a power law with exponent n. Assuming that the friction force is proportional to the contact area gives for the relation between the coefficient of friction and normal load

$$\mu \propto F^{n-1} \tag{19}$$

A fit through all data shown in Figure 4 gives $n = 0.54$, so that $n - 1 = -0.46$. A line representing this relation is drawn in Figure 5.

Calculating the measured coefficient of friction by dividing the measured friction force by the applied normal load does not take into account the effect of adhesion on the contact load. What is actually measured is the friction force which results from the real normal load F_{real}, which is the applied load plus the adhesion force between the two surfaces

$$\begin{aligned} F_\mu &= \mu_{real} \cdot F_{real} \\ &= \mu_{real} \cdot (F + F_{adh}) \end{aligned} \tag{20}$$

When the measured coefficient of friction μ is calculated by using equation (1), what is actually calculated is

$$\mu = \mu_{real} \cdot \left(1 + \frac{F_{adh}}{F}\right) \tag{21}$$

Equation (21) shows that the effect of adhesion becomes important when the normal load is of the same order of magnitude as the adhesion force, i.e. at relatively low normal loads. A line representing this relation is drawn in Figure 5.

Velocity

Only few studies report on the influence of sliding velocity on the measured friction. A decrease of the coefficient of friction with increasing sliding velocity (6–60 mm/s) was observed by Dinç et al.[41] for different plastics at normal and high humidity. An exception was PTFE for which the friction remained constant. Fagiani et al.[73] found that the friction between the fingerpad and aluminium was only slightly affected by the sliding velocity (10–30 mm/s), the coefficient of friction decreasing with increasing velocity. When sliding against different types of textile, they found that the coefficient of friction tends to decrease when the sliding velocity increases within the range 10–50 mm/s. Recently, Derler et al.[60] found that when sliding against wet smooth glass the coefficient of friction decreases with sliding velocity (0–1500 mm/s) following a power law with exponent

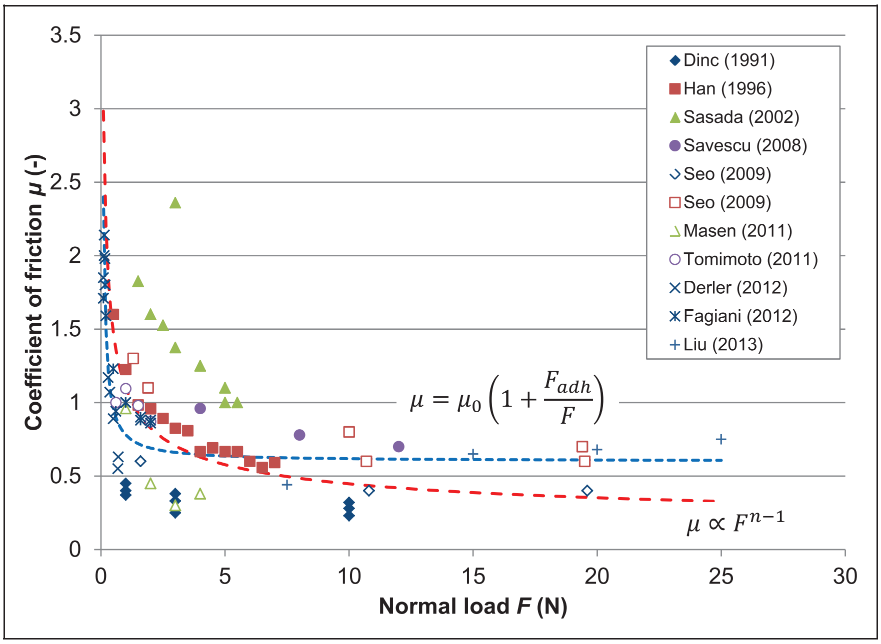

Figure 5. Coefficient of friction of the index finger as a function of normal load. Data taken from Dinç et al.,[41] Han et al.,[72] Sasada,[42] Savescu et al.,[70] Seo et al.,[71] Masen,[25] Tomimoto,[53] Derler et al.,[59] Fagiani et al.[73] and Liu et al.[58]

−0.37. Although, in general, the coefficient of friction of the fingerpad tends to decrease with increasing sliding velocity, Pasumarty et al.[67] observed different trends depending on the type of material and condition of the skin. Within the velocity range between 3 and 24 mm/s, the coefficient of friction against glass was almost independent of sliding velocity, whereas against PP a slight decrease was observed and friction against steel was found to increase with velocity. Against hydrated skin the coefficient of friction for these materials was found to be independent of sliding velocity.

Material

The data collected from literature cover a wide range of materials, but differences in test conditions make it difficult to compare between studies. Only few studies provide a comparison of the friction behaviour of different materials.

Sasada[42] measured the friction as a function of R_a roughness for PMMA and a ceramic. For a roughness between 4 and 12 μm, R_a the coefficient of friction against PMMA is lower than against the ceramic. Results of an experimental program using different types of materials are reported by Liu et al.[23] Comparing the results obtained using samples having a comparable roughness in terms of R_a shows that the coefficient of friction against aluminium is larger than against wood and ABS. The friction measured against PP is higher than measured against aluminium. These results correspond to observations by Tomlinson et al.[75] who found higher coefficients of friction for PP than for metal. The friction they observed against different soft elastomers is even higher. Pasumarty et al.[67] measured a coefficient of friction between 0.2 and 0.24 between the fingerpad and smooth glass ($R_a = 0.01$ μm) which is considerably lower than the coefficient of friction they measured against smooth steel ($R_a = 0.05$ μm), between 0.5 and 1.

Roughness

In most studies, the surface topography of the sample is characterized by the centre line average roughness, in other words the R_a roughness. A measure commonly used in mechanical engineering. This parameter basically is the arithmetic mean of the surface heights relative to the mean line and in general gives an acceptable indication of the roughness of a test surface.

Dinç et al.[41] found that the coefficient of friction between the fingerpad and PMMA decreased when the R_a roughness increased from 0.033 to 1.55 and 6.15 μm. This effect was found to be independent of load (1–20 N) and sliding velocity (6–60 mm/s) and was observed for dry as well as hydrated skin. The results correspond to the observations by Sasada[42] who found a decrease in friction when the R_a roughness of the PMMA countersurface increased from 0.2 to 10.5 μm. In the same study, a decrease was observed when sliding against porous ceramics ($R_a =$ 4.1–22 μm). The same trends were observed against metals such as aluminium, when the roughness increased from 0.3 to 13 μm R_a^{23} and steel, when the roughness increased from 0.003 to 1.44 μm R_a.[25] When sliding against different types of paper, Skedung et al.[45] found that rougher papers tend to result in lower coefficients of friction than smoother papers ($R_a = 1$–$4\,\mu$m).

A completely different behaviour is reported for very rough surfaces by Tomlinson et al.,[44] who report for different metals an increase of the coefficient of friction with roughness, from 0.46 μm R_a onwards. For roughness values exceeding approximately 26 μm R_a, the friction did not increase any further. An increase of the friction of dry skin was also measured against glass when the R_a roughness increased from 0.01 to 4.2 μm by Pasumarty et al.[67] On the contrary, when sliding against hydrated skin they observed a considerable decrease of the friction with roughness.

Amplitude parameters such as the R_a roughness are in fact statistical parameters describing the height distribution of the measured profile. Those parameters do not contain any information about size, shape or density of the asperities. It is beyond doubt that these properties also influence the surface topography and the frictional behaviour. The surface topography is the result of the finishing method that is used. Gee et al.[43] compared samples with roughness amplitudes, in terms of R_a roughness, of 0.8, 3.2 and 25 μm, finished using different techniques. It was found that the coefficient of friction decreased with R_a roughness when the surfaces were spark eroded and increased when the surfaces were grit blasted or ground. For planed surfaces the friction showed a minimum at intermediate R_a roughness, being higher for both smoother and rougher surfaces. Smith et al.[15] investigated the friction behaviour of the fingerpad against macro-textures build up from 1.8 mm amplitude truncated cones. They found that the coefficient of friction increased when the spatial period between the cones increased from 1.5 to 8.5 mm. The friction behaviour between the fingerpad and rectangular ridged metal surfaces was investigated by Tomlinson et al.[76] They found that the coefficient of friction increased with increasing ridge height (0.5–2.5 mm) and increasing spacing (2–12 mm). The coefficient of friction decreased with increasing ridge width (1–4 mm), whereas from 4 to 8 mm no change was observed.

Summarising conclusion

When touching a product's surface, mechanical and thermal receptors in the skin are stimulated and give rise to sensorial judgments of softness, warmth, roughness and slipperines. The phenomena occurring in the contact between the fingerpad and the surface, which give rise to these perceptions, can be understood by considering deformations, subsurface stresses and vibrations in the skin. Contact mechanics theory shows that the friction against the skin influences the magnitudes, locations and gradients of subsurface stresses and strains and temperatures, thus influencing the perception of roughness, slipperiness and sometimes warmth.

For product engineers who aim to control and optimize the sensorial properties of a product surface interacting with the skin, it is essential to understand this frictional behaviour. However, the friction of skin is yet poorly understood. In literature, a wide range of coefficients of friction as a function of countersurface material, surface roughness, normal load and skin condition is reported. The variation that is observed within or between studies can be assigned to gender, age and orientation of the finger. Together with the skin condition, these parameters should be taken into account when comparing between different studies. Despite these sources of variation, which are intrinsic to tactile exploration, analysing data collected from literature shows some consistent trends:

- The coefficient of friction increases considerably with increasing hydration level of the skin, mainly due to softening of the top layer of the skin.
- Measurements show that the contact area of the fingerpad changes with normal load following a power law. Since the friction force is proportional to the contact area, the coefficient of friction changes with normal load. Although there is a large variation in geometry and properties of the fingerpad between different people, measurements of the mechanical behaviour of the fingerpad show a consistent trend. The relation between contact area and normal load can easily be evaluated using a load measuring device and an inkpad in combination with image analysis software.
- The coefficient of friction of the fingerpad decreases with normal load to a constant value. The decrease, which is most clear at relatively low loads, below 5 N, can be attributed to the effect of normal adhesion and to the contact behaviour of the fingerpad. At low normal loads, the contribution of the adhesion force between the skin and the countersurface becomes apparent, leading to an increase in friction with decreasing normal load.
- The coefficient of friction changes with surface roughness. Data collected from literature show that for low values of R_a roughness, friction decreases with increasing roughness, caused by a decrease in the real contact area. When the R_a roughness increases further, the contribution of deformation causes an increase in the friction after which the coefficient of friction remains constant. Although it is arguable whether the R_a roughness is a suitable parameter to describe surface roughness, the trends found in literature are consistent. However, some influence of the finishing method is reported. It should be noted that when investigating roughness perception, alternative roughness parameters should be included as well.

Analysis of the tactile qualities described from a tribological point of view shows that in the sliding contact between the fingerpad and a rough surface, friction plays a role in the perception of warmth, roughness and slipperiness. In a rubbing contact the contact temperature increases proportional to the coefficient of friction. The relation between perceived roughness and friction is less obvious and may be assigned to the correlation which exists between physical roughness and friction. The perception of slipperiness has been show to correlate to the frictional properties of the surface. Slipperiness can be related to the magnitude and location of (sub)surface stresses and strains in the skin, which are proportional to the coefficient of friction.

Even though the coefficient of friction of the fingerpad shows some consistent trends, examining the friction behaviour at a more detailed level might further explain the contribution of friction to tactile perception. The measuring signal contains relevant information, such as local peaks in friction and friction versus time gradients, and should be analysed thoroughly as opposed to taking the average coefficient of friction of the steady state part of the signal. Furthermore, future work involves the study of local friction behaviour at the scale of the surface roughness.

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Conflict of interest

None declared.

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Appendix

Notation

A	contact radius (m)
A	contact area (m^2)
A_0	apparent contact area (m^2)
A_{real}	real contact area (m^2)
C	specific heat (J/K)
D	displacement (m)
E	elastic modulus (Pa)
E^*	reduced elastic modulus (Pa)
E^*_{eff}	effective elastic modulus (Pa)
F	normal load (N)
F_{adh}	adhesion force (N)
F_μ	friction force (N)
k	stiffness (m/N)
K	thermal conductivity (W/mK)
K_{eff}	effective thermal conductivity (W/mK)
p	contact pressure (Pa)
R	radius of curvature (m)
R_a	centre line averaged roughness (m)
R_p	roughness, maximum peak height (m)
R_q	root mean squared roughness (m)
R_z	roughness, average distance between the highest peak and lowest valley in a given length (m)
t	time (s)
t	thickness (m)
T	temperature (K)
v	sliding velocity (m/s)
α	thermal diffusivity (m^2/s)
β	viscoelastic loss modulus (-)
δ	indentation depth, deformation (m)
φ	orientation angle (°)
η	surface density (-/m),(-/m^2)
μ	coefficient of friction (-)
ν	Poission ratio (-)
ρ	density (kg/m^3)
σ	stress (Pa)
T	shear stress (Pa)