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REVIEW

Tribology of Skin: Review and Analysis of Experimental Results for the Friction Coefficient of Human Skin

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Abstract In this review, we discuss the current knowledge on the tribology of human skin and present an analysis of the available experimental results for skin friction coefficients. Starting with an overview on the factors influencing the friction behaviour of skin, we discuss the up-to-date existing experimental data and compare the results for different anatomical skin areas and friction measurement techniques. For this purpose, we also estimated and analysed skin contact pressures applied during the various friction measurements. The detailed analyses show that substantial variations are a characteristic feature of friction coefficients measured for skin and that differences in skin hydration are the main cause thereof, followed by the influences of surface and material properties of the contacting materials. When the friction coefficients of skin are plotted as a function of the contact pressure, the majority of the literature data scatter over a wide range that can be explained by the adhesion friction model. The case of dry skin is reflected by relatively low and pressure-independent friction coefficients (greater than 0.2 and typically around 0.5), comparable to the dry friction of solids with rough surfaces. In contrast, the case of moist or wet skin is characterised by significantly higher (typically >1) friction coefficients that increase strongly with decreasing contact pressure and are essentially determined by the mechanical shear properties of wet skin. In several studies, effects of skin deformation mechanisms contributing to the total friction are evident from friction coefficients increasing with contact pressure. However, the corresponding friction coefficients still lie within the range delimited by the adhesion friction model. Further research effort towards the analysis of the microscopic contact area and mechanical properties of the upper skin layers is needed to improve our so far limited understanding of the complex tribological behaviour of human skin.

Keywords Biotribology · Human skin · Friction coefficient · Adhesion friction · Deformation friction · Skin hydration

1 Introduction

The tribology of human skin is a research topic that has continuously attracted scientific studies over the past years. Typically, tribological studies on skin were related to cosmetics and the effects of skin care products [1–4] or dealt with dermatological questions concerning skin condition, ageing, skin injuries, wound healing and prosthetics [5–14]. Another category of studies investigated the role of skin friction, especially of the finger pad, in connection with the sense of touch [15–17]. There seems to be a new trend in materials development, taking more and more into account human factors such as skin compatibility, tactile perception, touch properties and ergonomics [18–21]. Knowledge on the contact mechanics and friction behaviour of human skin is a prerequisite to improve and optimise surfaces and materials which come in contact with the skin.

Recent tribological studies on materials contacting the skin comprise medical and sports applications [22, 23],

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textiles [24, 25] as well as appropriate surfaces for consumer products [20, 26, 27] and automotive applications [28, 29]. The friction and surface properties of materials and objects are known to be essential for their tactile properties. It is possible to assess friction and tactile properties in human subject tests, but instrumental tribological measurements are an efficient alternative, providing objective and more reproducible results (no inter- and intra-subject variations) [30–33]. This is why there are attempts to use mechanical skin models in combination with tribological tests where mechanical contacts between skin and external materials are simulated close to practical conditions [34–40].

A specific high-tech application is the development of artificial skin with material behaviour and sensory function (e.g. tactile feedback) similar to those of human skin in order to enable the dexterous handling of objects by robotic hands and prostheses [41–46]. It is known that friction governs the forces that are applied by the fingers when grasping and manipulating objects [47]. The friction of skin strongly depends on the moisture content in the *stratum corneum* (SC) [4, 48–50] as well as on the presence of water in the interface between skin and a contacting surface [51, 52]. Interestingly, it was found in a recent study of André et al. [53] that the moisture of the fingertip during object manipulation is modulated in such a way that the forces to grip an object are minimised. On the other hand, results of Warman and Ennos [54] suggest that the primary function of fingerprints is not to influence friction, but rather to improve tactile perception by amplifying mechanical stimuli for the excitation of mechanoreceptors located in the subsurface skin tissue.

In a very informative and enjoyable review article about tribology in everyday life, Dowson [55] described the practical aspects of skin tribology in connection with bathing and washing, shaving, skin care, tactile response to external surfaces, selecting textiles and wearing clothes. Also the question of walking barefoot safely versus slipping on a wet floor represents an ergonomic topic that is closely related to the tribology of human skin [56–58]. There have been approaches to complement experimental investigations by numerical simulations, e.g. in connection with the formation of friction blisters [59], the friction between feet and socks [60], contacts between fingertip and textured surfaces [61] and the ageing and wrinkling of human skin [62]. Due to reduced skin thickness and viscoelastic recovery, aged skin becomes more vulnerable and susceptible to injuries such as abrasions and bedsores [63, 64], for which friction and shear forces are believed to be important risk factors [65–67].

So far, the literature conveys an intricate picture of skin tribology, which is largely due to the fact that human skin is a soft biomaterial with a complex anatomical structure

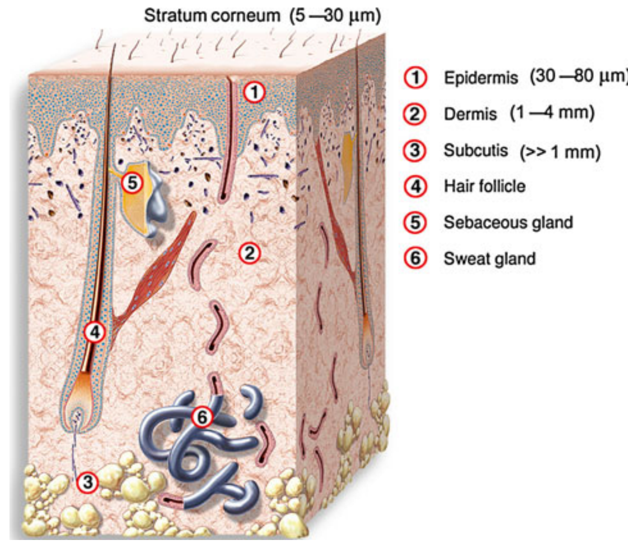


Fig. 1 Structure of human skin showing the functional layers as well as skin appendages (by courtesy and with permission of Beiersdorf AG, Hamburg, Germany). Blood vessels and sensory receptors are mainly located in the dermis, but not shown in the figure

[68] (see Fig. 1), being characterised by nonlinear viscoelastic material behaviour [52, 69] and showing a friction behaviour that strongly depends on the contact conditions. Because the tribology of skin was investigated in different fields and in connection with diverse applications, various measurement techniques were independently developed and applied in the past. Consequently, the direct comparison of measurement results is difficult in many cases.

Early reviews [70, 71] discussed the friction mechanisms of human skin and presented basic theoretical concepts for the interpretation of experimental data. In a subsequent series of review articles, Sivamani and colleagues [72–76] gave an overview on skin tribometrology, friction coefficients measured for skin, factors influencing skin friction as well as on the effects of skin care products. Tomlinson et al. [17] reviewed the friction properties of fingers when gripping objects. Interesting aspects of biotribology and biomimetics, e.g. in connection with skin and lubrication phenomena in oral and ocular tribology were highlighted and reviewed by Dowson and Neville [77].

The purpose of this review is to give an up-to-date overview over and analysis of the experimental results for the friction of human skin in vivo. The focus is on untreated skin in dry, moist or wet condition. In Sect. 2, we summarize the available literature data and discuss the various factors that influence the friction behaviour of human skin. Because a variety of experimental techniques and measurement parameters was applied to investigate the friction of human skin in different anatomical regions, we analyse the literature data in detail in Sect. 3. For this purpose, we estimate and analyse the skin contact pressures at which the reported friction coefficients were measured. It is expected that the comparison of measurement results across studies can be significantly improved on this basis. In Sect. 4, we summarise and discuss the friction mechanisms of human skin, draw conclusions about existing friction measurement techniques, and identify important open questions and interesting directions for future research.

2 Friction Behaviour of Human Skin and Influencing Factors

The friction coefficient of human skin is a system property determined by material and surface properties of the skin itself, the contacting material, as well as possible intermediate layers such as temporarily trapped or topically applied substances (e.g. cosmetic products), or sweat and sebum naturally excreted from skin into the tribo-interface. It is generally acknowledged that skin friction depends on the type (solid, soft, and fibrous material) and physical properties of contacting materials, as well as on the physiological skin conditions (e.g. hydration state, sebum level) and mechanical contact parameters, especially on the normal load, i.e. contact pressure (see Sect. 3), all being highlighted in this review. For completeness, the influence of sliding velocity, age, gender, ethnicity, and anatomical region on skin friction is only briefly addressed in this paper; recent articles on these issues are available [64, 72, 73]. Qualitative relationships between the skin friction coefficient and particular influencing factors, as well as interactions of important influencing factors are illustrated at the end of this chapter in Table 2 and Fig. 5.

2.1 Friction Behaviour of Human Skin: Theoretical Background

Human skin is characterised by nonlinear, viscoelastic material properties [51, 69] (see Sect. 2.5). Therefore, Amontons' empirical rules (claiming that friction force is directly proportional to normal force and independent of the apparent contact area under dry contact conditions [78]), do not hold for skin friction, and the theoretical concepts for the friction of elastomers [79] have been applied to human skin to describe its tribological behaviour [70]. The concepts of the friction theory for elastomers [79] imply a two-term (non-interacting) friction model consisting of an adhesion as well as a deformation component. According to Dowson [70], in the dry skin condition, adhesion caused by attractive surface forces at the skin-material interface, as well as deformation (hysteresis, ploughing) of the softer, viscoelastic bulk skin tissue, contribute to the coefficient of friction (COF). Depending on contact conditions, as well as fluid or lubricant amounts (sweat, water, and sebum) and film thicknesses in relation to the surface roughness of the contacting materials, boundary lubrication, mixed lubrication, and elasto-hydrodynamic lubrication (EHL) effects can come into play.

Adhesion is considered as the main contribution to the friction of human skin, whereas deformation mechanisms are assumed to play a minor role [51, 71]. In the literature, several theoretical models (e.g. Hertz, Johnson-Kendall-Roberts, Greenwood-Williamson) were used to describe and discuss the mechanical contact behaviour and friction mechanisms of skin [51, 52, 70, 71, 80, 81]. Different friction mechanisms are characterised by varying load-dependencies of measured friction coefficients [70]. Therefore, in recent articles, friction experiments were analysed with power-law fits to investigate the predominant friction mechanism involved [51, 82].

2.2 Anatomy of Human Skin

The skin is our largest human organ and 'protective envelope', which covers between 1.6 and 2 m^2 surface area of the human body in adults and accounts for approximately 16% of a person's weight [83]. Human skin is composed of three functional layers (Fig. 1). It is a multilayered composite material composed of an upper avascular cellular layer (epidermis), intimately connected to the dermis and an underlying fatty layer, the subcutis [84]. Within the different skin layers, hair and skin appendages, blood vessels as well as sensory receptors can be found. The outermost skin layer, the SC, can be described in terms of a brick-and-mortar model [85], in which the corneocytes (bricks) are embedded in lamellar epidermal lipids (mortar), which function as an efficient barrier against extreme water loss. In the epidermis, keratinocytes differentiate and migrate towards the skin surface, thereby changing their size/shape and composition, and gradually transform to corneocytes [86]. The dermis confers firmness, high elasticity/resilience, tensile strength and tear resistance to the skin [87]. It is made up of a network of closely packed collagen and elastin fibres, embedded in a gel-like ground substance of interstitial fluids (e.g. hyaluronic acid), fibroblasts, proteoglycans and water. This connective tissue meshwork works like a fluid-filled, soaked sponge, expelling the bound water under pressure and incorporating it again upon unloading [88]. The adipose tissue of the subcutis is fully interlaced by loose connective tissue interspersed with firm fibres that anchor the skin to the adjacent and underlying structures of muscles or bone tissues (e.g. fascia and periosteum) [87]. In the subcutis, nutrients are stored in form of liquid fats, ensuring also insulation from cold as well as shock absorption (structural fat and depot fat) [89].

2.3 Surface Properties of Human Skin

2.3.1 Effect of Skin Surface Roughness on Friction

The surface topography of human skin (Fig. 2) is dependent on body region and characterised by either concentric ridges (finger pads), or furrows (e.g. forearm) that delimit polygonal areas of variables size. Typical surface roughness values *Ra* and *Rz* lie in the range (10–30) μm and (30–140) μm (Table 1), respectively, representing the relief of first order furrows (70–200 μm) and that of second order furrows (20–70 μm) [83]. Skin roughness, as well as furrow spacing and anisotropy have been reported to increase with age [90–95]. Table 1 summarises results for the roughness of human skin in different anatomical areas.

Until now, there are only very few studies [10, 96] available that provide an incomplete and unclear picture on the influence of skin topography on friction. Egawa et al. [96] found in single regression analysis that the volar forearm friction coefficient of females (20–51 years) did not significantly correlate with the surface roughness *Ra* of the skin ($r = 0.23$). Contrary, the same authors reported that surface roughness *Ra* significantly improved the predictability of the COF (by 1.5%), using multi-regression analyses with skin moisture and roughness as independent variables [96]. The effect of the skin surface roughness was also studied by Nakajima and Narasaka [10] who showed a correlation between the density of primary lines (>20 μm) and skin friction; the lower the density (higher age), the higher the friction. However, Nakajima and Narasaka found that the density of lines corresponds to the skin elastic modulus. Therefore, the observed correlation between skin roughness and skin friction could have been caused by interaction between roughness and elasticity, or reflect age effects.

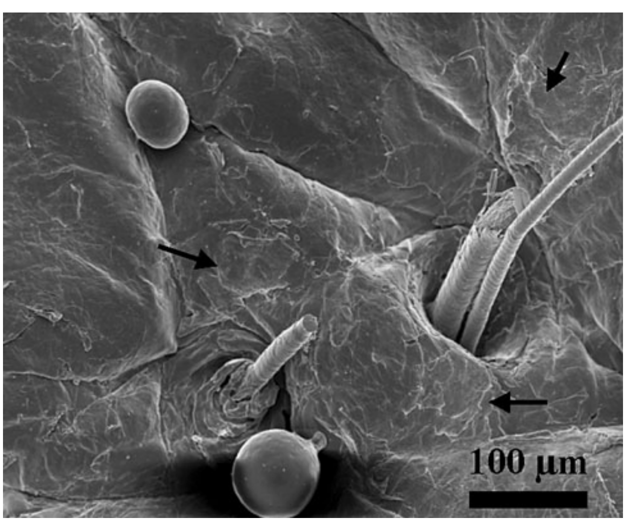


Fig. 2 Surface topography of volar forearm skin (male, 17 years). The scanning electron micrograph of a skin replica shows desquamated corneocytes (arrows), globular shapes corresponding to gland secretion or vapour entrapments, and orifices/pores containing hair follicles. Besides the typical texture of hair shafts, which are covered with a layer of overlapping shingle-type cells (*cuticle*), single fibre bundles of a broken hair are visible

Table 1 Surface roughness values of different skin sites of persons aged between 20 and 45 years, adapted from [36, 196]

Skin region	*Ra* [μm] (range)	*Rz* [μm] (range)
Index finger	26.1 ± 6.1 (19–33)	87.3 ± 17.1 (62–99)
Edge of hand	14.9 ± 6.7 (9–22)	54.1 ± 21.2 (33–73)
Back of hand	(23–28)	(138–144)
Volar forearm	(17–20)	(119–125)
Volar forearm	(12–13)	(82–92)
Forehead (temple)	(12–15)	(84–95)
Cheek	(11–15)	(33–45)

2.3.2 Effect of Superficial Sebum on Friction

The surface of the skin is usually protected by an acidic hydrolipid film (pH 4–6), which controls skin flora, prevents colonisation of the skin by pathogenic species, and acts as defence against invading microorganisms [83]. The hydrolipid film is composed of water from sweat and sebum from sebaceous glands, and covers the SC as a water–oil emulsion.

In connection with skin tribology, the role and importance of sebum lipids and their interactions with water were controversially debated [97–101]. Pailler-Mattei et al. [101] demonstrated that the skin surface lipid film influences the skin adhesion properties due to capillary phenomena. While on normal skin a significant adhesion force could be measured, the adhesion force diminished after removal of the lipid film. Analysing data from Gupta et al. [99], we found a moderate positive linear relationship ($r = 0.64$) between sebum level (5–18 μg/cm^2) and forearm skin friction measured against steel. Cua et al. [97] observed weak correlations between the skin surface lipid content and friction, especially on the forehead ($r = 0.33$) and postauricular skin ($r = 0.41$). The same authors observed no correlation ($r \leq 0.20$) between both parameters for nine other anatomical skin regions and suggested that surface lipids play a limited role for skin friction [97]. The review of existing literature indicates that in the case of sliding friction the properties of the skin surface lipid film should be taken into account. However, it is obvious that more detailed investigations and fundamental studies are required to fully elucidate the influence of sebum lipids on skin frictional properties.

2.4 Influence of Epidermal Skin Hydration on Friction

2.4.1 *Qualitative Relationship Between Skin Moisture and Friction*

Moisture commonly increases the friction at the skin surface, as is experienced in everyday life, e.g. in sports activities if a fabric sticks to the skin due to sweating. The friction coefficients of skin have been reported to vary by factors of 1.5–7 between wet and dry conditions [1, 6, 13, 51, 52, 71, 96, 102–107]. This large spread probably derives from the diversity of test methods, materials and experimental parameters used. One of the most important factors is probably the time delay between a friction measurement and moisturizer application or water exposure of the skin.

In recent studies, in particular the functional and qualitative relationship between skin moisture and friction were investigated. Linear [5, 48], power-law [49], exponential [108] and bell-shaped relationships [109, 110] between skin hydration and friction have been reported. We systematically varied the hydration state of the skin of the volar forearm in 22 subjects and found a highly positive linear correlation between skin moisture and friction coefficients against textiles [48]. A similar increase in friction with rising moisture levels was also observed when the forearm skin, the cheek and other skin sites were brought into contact with metals or polymers [5, 49, 108].

Other authors [109, 110] found an initial increase in finger friction as moisture rises, before a threshold was reached and the COF dropped. This response has been described as a bell-curve behaviour, and indicates a transition from boundary to mixed lubrication if skin is sufficiently wet.

Using corneometry in combination with friction experiments on a force plate [48], we furthermore showed that the COF of volar forearm skin against a hospital textile increased by 33% from very dry to normally moist skin conditions which is in good accordance with earlier experiments [50, 102]. Dinç et al. [15] reported that the friction coefficient between fingertips and polymethylmethacrylate increased by approximately 20–30% if the relative humidity was increased from 35 to 90%. In a very humid climate or under wet conditions, the skin becomes completely hydrated, and the friction has been found to be 2–4 times higher than in dry sliding conditions [48, 49, 82, 103, 110].

2.4.2 *Physical Friction Mechanisms in Moderately Moist Skin Conditions*

Several physical mechanisms have been discussed to explain the increased friction coefficient in humid or wet environments [49, 110]: swelling and softening of the SC [48, 51], capillary adhesion due to meniscus formation [110–112], viscous shearing of liquid bridges formed between the skin and the counter-surface [15], the work of adhesion due to absorbed moisture [81, 101], and finally the formation of a glue-like layer due to the solution of skin lipids and proteins in a thin layer of absorbed water or sweat [71].

Recently, in a pilot study, Tomlinson et al. [110] aimed at quantifying for the first time the relative contributions of water absorption, capillary adhesion and viscous shearing effect on skin friction in moist conditions. They concluded from finger friction measurements on a polyvinylchloride plate that water absorption is the main mechanism responsible for the increase in friction, followed by capillary adhesion, although it was not conclusively proved that the latter contributed significantly. Viscous shearing in the liquid bridges was found to have a negligible effect.

We [48] and others [51] attributed the large increase in skin friction with moisture to the plasticizing effect of water, leading to smoothening of skin roughness asperities and consequently a greater real contact area (RCA). In the case of friction between a cotton-polyester fabric and moist skin [48], we concluded that capillary bridges (fluid menisci) formed by superficial water micro-droplets played an unimportant role for the increase in friction, assuming complete removal of excess water from the skin surface due to the water-absorbing/hygroscopic nature of the studied textile. Further detailed investigations are needed to determine the importance and relative contributions of the above-mentioned mechanisms under different skin and environmental conditions.

2.4.3 *Physical Friction Mechanisms in Wet Skin Conditions*

Johnson and Adams et al. [51, 52] discussed the lubrication of the skin by water in detail. If skin is saturated by water and excess water accumulates in the interface, capillary bridges between the skin and the counter-surface might be relevant to a certain degree, but with still increasing amounts of water lubrication phenomena will become more and more important [57, 82].

Hydrodynamic lubrication is characterised by the complete separation of the sliding surfaces by a liquid film. Under these conditions, the adhesion component of friction is replaced by a contribution due to viscous friction [70]. Depending on contact conditions as well as fluid film thickness in relation to the surface roughness of the skin and the contacting material, mixed lubrication or boundary lubrication can also take place [82]. The former lubrication regime is characterised by the coexistence of dry and wet contact zones, the latter by molecular surface films influencing the friction behaviour.

For finger pads sliding on a wet, smooth glass surface [82], we recently observed considerably lower friction coefficients (0.61 ± 0.37; range: 0.07–2.12) compared to those found on a rough, wet glass surface (1.43 ± 0.57; range: 0.32–4.56); analytical results indicated that hydrodynamic lubrication came into play [82]. However, contributions due to EHL alone were found to be too small to fully explain the friction behaviour of wet skin on smooth glass, which is in accordance with analyses from Adams et al. [51] and Tomlinson et al. [110]. Because the surface roughness of the skin was much greater than the minimum film thickness required for EHL, we assumed that water films between skin and smooth glass were only formed locally, while dry contact zones coexisted in other regions (mixed lubrication) [82].

In practice, efficient aqueous lubrication of the skin can lead to minimum friction coefficients below 0.1 at high contact pressures. This was not only observed for the finger pad sliding on a wet smooth glass surface [82], but also for the foot sole slipping on wet smooth floor surfaces [57]. In experiments, in which barefoot subjects carried out slips with one foot under wet conditions we measured mean friction coefficients between 0.12 and 0.23 on various smooth surfaces [57]. The average foot contact pressures in these slip experiments ranged from 30 to 70 kPa. For comparable contact pressures, the mean friction coefficients of fingers and the edge of the hand against wet smooth glass were 0.14 ± 0.03 [82]. Other studies investigating the friction of foot skin on wet floor surfaces also found critical friction coefficients between 0.1 and 0.2 for a range of smooth materials such as glazed ceramics, steel and polished marbles [56, 113, 114].

2.5 Mechanical Properties of Human Skin

Human skin has a complex structure (Fig. 1) and thus shows also complex material behaviour in mechanical contact with objects and surfaces. Skin can be considered as a multilayer composite with highly non-homogeneous, nonlinear elastic, anisotropic, viscoelastic material properties similar to those of soft elastomers [51, 69]. The viscoelastic properties of human skin derive mainly from the dermis, with some contributions from the epidermis [115, 116]. The viscous part of the skin deformation is attributed to the displacement of the interstitial fluid through the fibrous network; the elastic part is linked to the stretching of elastin and collagen fibres [115, 117]. An important structure for the global mechanical behaviour of the upper skin layers is the epidermal–dermal junction which anchors and interweaves the epidermis with the dermis by finger-like projections (dermal papillae and rete ridges). This subsurface structure plays an important role for the frictional properties because the different mechanical properties of the individual skin layers influence and determine the deformation behaviour and the global mechanical response of skin [116, 118, 119]. Depending on the measurement, anatomical site, skin hydration level, age, individual person, and theoretical model applied, elastic moduli of human skin in vivo varying over 4–5 orders of magnitude (4.4 kPa–57 MPa) have been reported in the literature [120–124] (Fig. 3).

Experimental techniques to determine the mechanical properties of skin in vivo and ex vivo are abundant in the literature; they are based on measurements of torsion, suction, extensibility or (ultrasound) wave propagation. A detailed overview on the different test methods and mechanical properties is beyond the scope of this review. Relevant papers are available in the literature [120, 122, 125, 126]. In brief, there is experimental evidence that the SC exhibits stiffness values and elastic moduli (10 kPa–1 GPa) of at least two orders of magnitude higher than the dermis (0.5 kPa–45 MPa) [127–130] and subcutaneous fat tissue (0.12 kPa–30 kPa) [125, 127, 131] (Fig. 3). In addition, skin hydration reduces the elasticity and stiffness of human skin (SC, epidermis) typically by one order of magnitude [127, 132–135], with elastic moduli of 30 kPa–1,000 MPa for (very) dry skin and 10 kPa–100 MPa for wet skin.

Taken the above-mentioned aspects into consideration, the elastic modulus of biological soft tissues in general and skin in particular is a relatively meaningless measure unless the exact strain level and physiological conditions are specified [125, 136]. Skin hydration level, contributions of the specific skin layers, as well as the anisotropic and

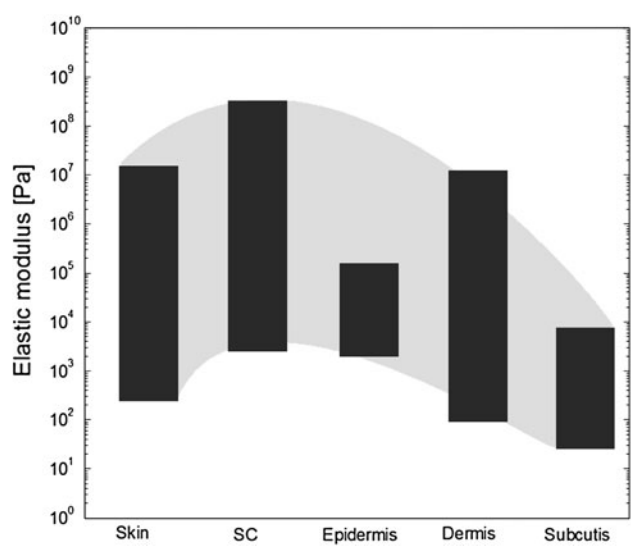


Fig. 3 Mechanical properties of human skin and different skin layers. *SC: stratum corneum*

viscoelastic (time, frequency and temperature dependent) material properties do all determine the global mechanical response of human skin (Fig. 4).

Current research on skin mechanics aims at capturing the above-mentioned properties and integrating them into theoretical/analytical [116, 118, 128] and numerical models (e.g. linear viscoelastic or hyperelastic models) [62, 116, 125, 126, 137–140], previously validated for elastomers and polymers, to develop and implement improved and more realistic mechanical finite element models of human skin.

Apart from the classical physical/mechanical parameters (e.g. storage and loss moduli, Young's moduli), so-called skin bioengineering parameters [83, 141] have been introduced to characterise the viscoelastic properties of human skin. They describe, however, skin structural parameters rather than the pure mechanics and are relatively meaningless in a strict mechanical sense. Nevertheless, skin bioengineering parameters such as Cutometer®-values are commonly used by dermatologists and cosmetic scientists in the clinical, disease-related as well as biological interpretation of skin tissue integrity. For example, with ageing the resilience and viscoelastic recovery (imprecisely defined as 'elasticity') of skin was found to decrease by 15–20% [64, 91, 142].

In the literature, only weak correlations between skin bioengineering parameters and skin friction coefficients have been reported [64, 96]. To our knowledge, there is no paper up-to-date available in which the relationship between the classical mechanical properties (e.g. dynamic shear modulus) and frictional properties of skin has been studied in detail. In particular, the tangential stiffness of human skin and the interfacial shear strength between both tribo-partners are believed to be important factors in determining the friction behaviour of skin [52, 133]. Future research should therefore strive to elucidate these properties, all helping to understand and interpret results obtained from skin friction experiments.

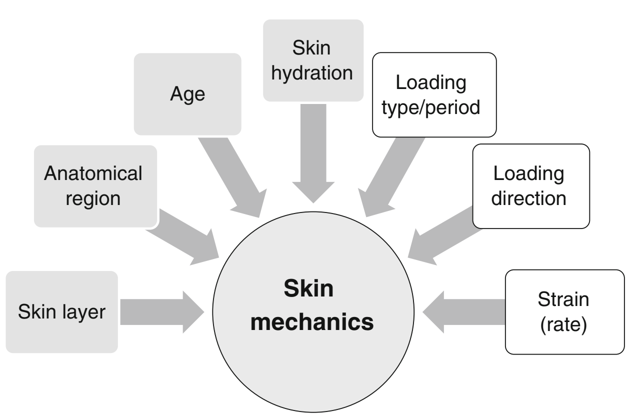


Fig. 4 Intrinsic skin parameters (*grey-filled boxes*) and experimental factors influencing the measured mechanical properties of human skin

2.6 Influence of Physical Properties of Contacting Materials

2.6.1 Effect of Surface Roughness on Friction

Much of today's knowledge about the influence of the surface roughness of a contacting material on skin friction arises from studies on grip properties, or touch and feel aspects of engineering surfaces, as recently reviewed by Tomlinson et al. [17]. The general trend emerging from previous studies is that the COF between a hard surface and naturally dry skin (fingertip or hand) decreases with an increasing material surface roughness [27, 49, 82], when Ra varied in the range (0.03–11.5) μm, $Rz = 0.05$–45 μm [82], or $Rq = 0.004$–2 μm [119]. For example, we recently reported for dry skin (finger, edge of hand) friction coefficients of 2.18 ± 1.09 (range: 0.39–5) against smooth glass ($Rz = 0.05$ μm), whereas on a rough glass surface ($Rz = 45$ μm) friction coefficients dropped to values of 0.53 ± 0.22 (0.03–1.42) [82]. Studies have further shown that the amplitude of the probe surface roughness has a dominant influence on the friction behaviour [49, 119]: the smoother the probe surface, the higher the friction. According to Hendriks and Franklin [49], differences can be as large as a factor 5–10, especially at low Ra roughness values <1 μm.

In the case of very rough surfaces, up to $Rq = 90$ μm, the friction coefficient has been shown to increase with increasing surface roughness [143], an effect that has been attributed to the interaction with the friction ridges and ploughing [57, 143]. Tomlinson et al. [143] observed an increase in skin friction (finger) against brass and steel with surface roughness amplitude ($Rq = 1$–90 μm) showing a constant plateau COF of ≈ 0.8 and ≈ 0.65, respectively, for roughness values $Rq > 25$ μm. Moreover, Gee et al. [31] observed a clear minimum in the friction of finger skin (COF = 0.45, $Ra = 3.2$ μm) when the surface finish of a plane steel counter-surface varied between $Ra = 0.8$ μm (COF $\approx$ 0.75) and $Ra = 25$ μm (COF $\approx$ 0.90).

However, in the case of hydrated skin, Masen [119] has recently reported a bell-shaped relationship between roughness ($Rq = 0.004$–2 μm) and friction coefficients varying between ≈ 0.9 and 1.7, with maximum values at intermediate roughness ($Rq = 0.006$–0.4 μm). He attributed the high friction in the intermediate roughness regime to interacting adhesion and deformation components in the hydrated skin condition.

On the basis of these experimental findings, we propose two friction regimes of dry skin in contact with surfaces with increasing roughness. We suggest that the friction coefficient of skin as a function of probe or counter-surface roughness initially drops with increasing roughness (an adhesion-dominated regime determined through high real contact area), passes through a minimum and then increases up to a certain plateau value (a deformation-dominated regime characterised by hysteresis, ploughing and interlocking).

It has to be pointed out that also the shape (e.g. steepness of the surface asperities or slope of surface peaks) and the surface texture (e.g. spacing parameters, waviness) are important factors in connection with skin tribology [57, 119, 143]. For example, Tomlinson et al. [143] found different skin friction coefficients for brass (COF = 0.8) and steel (COF = 0.65) although both materials had similar surface roughness ($Rq = 90$ µm) and hydrophilicity (see discussion on the importance of hydrophilicity in Sect. 2.6.2). They attributed the higher COF for brass to irregular surface asperity features with ridges inside the single asperities/ridges, and to steeper sides of the ridges. This explanation corroborates results of Derler et al. [57] who found a positive linear correlation ($r^2 = 0.68$) between the slope of surface asperity peaks and friction coefficients of plantar skin sliding on different wet floor coverings. In a recent study on the friction between finger and ridged surfaces, Tomlinson et al. [144] found that at low ridge height and width friction was dominated by adhesion. On surfaces with ridge heights above 42.5 µm, interlocking effects accounted for more than 50% of the total friction, and for a ridge height of 250 µm, hysteresis also started to contribute (<10%).

Skin friction increasing with material or probe roughness is in accordance with the theory of Moore for elastomers [79], which predicts that the friction coefficient of compliant materials on rough surfaces increases with the surface roughness amplitude. According to Hendriks and Franklin [49], the theory of Moore may therefore be applicable to skin in contact with rough surfaces ($Ra > 3$–10 µm), and in cases where interaction between surface asperities and skin ridges (on the fingers, palm or feet) occurs. A thorough study of Moore's theory in relation to skin friction is lacking until now and requires more experimental data, including information on the classical polymer-physical parameters (e.g. tangent modulus) combined with dynamic mechanical analyses (ex vivo skin rheology or in vivo dynamic mechanical analysis), tribological measurements and surface analysis.

Textiles can be considered as soft materials with rough surfaces and complex material behaviour [145]. Skin–fabric friction depends on textile parameters such as fibre materials, yarn design/morphology, surface structure, fabric construction, and finishing. An important role in friction was attributed to the textile microstructure, given by fabric construction and fibre hairiness [64, 67, 102, 146]. The study of Comaish and Bottoms [102] and our own results indicated considerable differences in friction between fabrics made of natural (wool, cotton) and synthetic (polyamide) yarns. Owing to their hairiness [147], natural yarns tend to have greater friction than synthetic fibres. Fine loops or crimps of natural fibres might increase frictional resistance to reciprocating motions, leading to greater COFs and energy dissipation per unit sliding distance [148].

2.6.2 *Effect of Physico-Chemical Properties on Friction*

Several authors have hypothesised that also hydrophilic/hydrophobic interactions between human skin and contacting materials affect skin friction properties [51, 64, 110, 149]. For example, Adams et al. [51] dragged a polypropylene (hydrophobic) and glass probe (hydrophilic) across forearm skin, and observed that the glass probe gave lower friction. This effect was attributed to a more stable lubricating film of water molecules forming on the glass [51]. The same conclusion drew Tomlinson et al. [110], who obtained lower finger friction coefficients for steel (hydrophilic) than for polypropylene despite having all similar surface roughness.

Elkhyat et al. [149], however, reported that volar forearm skin friction increases with hydrophilicity of the tribo-counter face. They found that a hydrophobic polytetrafluoroethylene (PTFE) sphere (COF = 0.18, water contact angle: 114°) sliding against sebum-poor volar forearm skin (sebum content < 10 µg/cm^2, water contact angle: 91°) showed much lower friction than a more hydrophilic steel (COF = 0.42, water contact angle: 54°) and glass sphere (COF = 0.74, water contact angle: 42°). Surface roughness values of the slider materials have not been reported in this study, and therefore the observed physico-chemical effects may be masked by surface roughness effects of the investigated materials.

Friction experiments performed by Cua et al. [5, 97] with a PTFE probe at different anatomical sites (forearm, forehead, abdomen, back, thigh), revealed that friction coefficients at the lower and upper back (sebum-poor and consequently considered hydrophobic skin regions) were considerably lower (COF = 0.19–0.25) than those measured on the sebum-rich, hydrophilic forehead (COF = 0.34) although in both skin areas moisture content was comparable. As sebum-rich skin was shown to be more hydrophilic [98, 100], these findings support the results of Elkhyat et al. [149] who suggested that pairings with hydrophobic surfaces show lower friction than any other pairing. However, the results presented in [5, 97] can simply reflect variations over different body regions rather than systematic physico-chemical (hydrophilicity) effects. The results of the literature discussed in this section indicate that under certain experimental conditions, both hydrophilic/hydrophilic and hydrophobic/hydrophobic tribo-pairs can exhibit low skin friction. Much work remains to be carried out to understand the above reported discrepancies and inconsistencies.

From the hitherto published work [64, 67, 149], it seems that PTFE exhibits lower friction compared to any other dry sliding material. The specific physico-chemical properties of PTFE are probably the main reason for this phenomenon. Non-polar PTFE is known for its low surface free energy and high hydrophobicity, and can be considered as a "fluid" with a finite viscosity [150]. The polymer chains are shielded by the large fluorine atoms so that their interaction is very weak, and the bulk strength of PTFE primarily results from an interlocking of the polymer chains [151]. According to Adams et al. [51], such properties are responsible for PTFE being able to readily orient its molecular chains during sliding, so that the amount of energy dissipation is small [152].

2.7 Other Factors Influencing the Friction of Human Skin

2.7.1 Influence of Sliding Velocity and Rotational Speed on Friction

Few studies investigated the influence of sliding or rotational velocity on skin frictional properties in the natural untreated skin condition [52, 146, 153]. Tang et al. [153] reported that when the sliding speed of a spherical probe on the forearm was increased from 0.5 to 4 mm/s, the friction coefficients increased from 0.39 to 0.52 and "stick–slip" phenomena became more pronounced, indicating that hysteresis contributed to the friction. For different rotating disc materials Zhang and Mak [146] observed slightly increasing friction coefficients as rotation speed increased from 25 rpm (maximum linear circumferential speed $\approx$ 17 mm/s) to 62.5 rpm ($\approx$42 mm/s). On the other hand, Adams et al. [51] did not find any change in the COF with increasing speed (1–8 mm/s) of a steel sphere. Johnson et al. [52] described friction coefficients increasing with sliding velocity (0.25–33 mm/s) using power-law expressions. The exact physical mechanisms (e.g. suggested velocity dependent interactions of the contact times of both tribo-partners at micro-scale surface asperities with internal viscoelastic skin relaxation times) leading to an increase of skin friction with velocity are unknown and need to be explored. The presence or absence of freely available fluid in the contact can be expected to greatly influence the effect of the sliding speed by determining whether it is physically possible for EHL effects to occur.

2.7.2 Influence of Ethnicity, Gender and Age on Friction

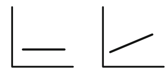
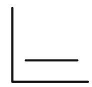
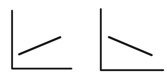
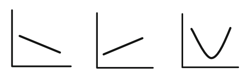
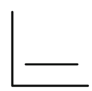
Previous studies found no significant differences in skin friction with regard to ethnicity [1]. With respect to gender and age, the majority of studies, investigating skin friction on different anatomical sites [1, 5, 64, 97, 154], found no significant differences. Sivamani et al. [1] and Egawa et al. [96] found that volar forearm friction against a PTFE wheel or a metallic wire did not change with age. Cua et al. [5, 97] found no significant age- and gender-related differences in skin friction for eleven parts of the body. Some other authors found, however, higher friction coefficients for the forearm skin [106, 155] or the canthus of younger (i.e. pre-menopausal, 20–50 years) women [13]. Zhu et al. [13] reported for a large Chinese population that the skin friction coefficient is associated with both age and gender. They attributed the discrepancy with the above-mentioned reports [1, 5, 64, 96, 97, 103] to different ethnicities studied, and associated gender and age differences with higher sex hormone levels (oestrogen) particularly in pre-menopausal females [13].

In our own research, the friction of textiles against natural, untreated volar forearm skin was found to be independent of age and gender [64]. However, we observed that the friction of female skin in contact with textiles was more sensitive/susceptible to moisture changes [48]; this effect was attributed to enhanced skin softening and formation of a greater real contact area for women.

2.7.3 Influence of Anatomical Region on Friction

Previous studies revealed considerable differences in skin frictional properties at different anatomical regions [5, 13, 49, 75, 82, 97, 146, 156]. There is a tendency to greater friction at areas with higher skin hydration. In brief, the friction on the finger pad, palm of the hand, forehead and vulva was found to be higher compared to that on edge of hand, abdomen, thighs, legs and lower back [5, 13, 75, 82, 97, 146, 156] (Table 2). Hendriks and Franklin [49] reported that friction coefficients on the cheek were typically lower than on the forearm (in particular at higher environmental humidity), probably due to the presence of beard stubbles. Hairs at the dorsal forearm in men were probably the reason for the lower COF measured at this side compared with the volar forearm [5, 97]. The exact physical (reduction of RCA) and/or chemical (lubricants covering the hair cuticle) reasons why hairs lower skin friction are unclear. The influence of hairs on the friction behaviour of human skin remains an interesting future research topic.

Table 2 Factors influencing the friction of human skin and qualitative behaviour of friction coefficients as a function of the influencing factor

Parameter	Qualitative tendency of friction	
Skin hydration		Increase or bell-shape
Sebum		Constant or increase
Surface roughness of skin		Constant
Hydrophilicity of contacting material		Increase or decrease
Surface roughness of contacting material		Decrease, increase or inverse bell-shape
Age		Constant
Body region	(FH, PA) > (VF, UB) > DF > (A, P) > LB > TH > ABD F > EH; VF > CH; VU > VF	

FH forehead, *PA* postauricular, *VF* volar forearm, *UB* upper back, *DF* dorsal forearm, *A* ankle, *P* palm, *LB* lower back, *TH* thigh, *ABD* abdomen, *F* finger, *EH* edge of hand, *CH* cheek, *VU* vulva

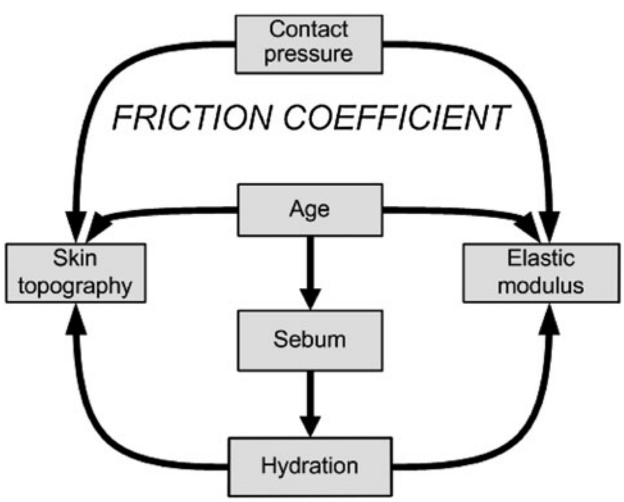


Fig. 5 Interactions of important factors influencing the friction of human skin

3 Detailed Analysis of Friction Coefficients of Human Skin Measured In Vivo

Friction coefficients of human skin in vivo were measured using various experimental setups and test conditions. The applied measurement principles can be divided into two main categories, namely tribological measurements in which probe materials are rubbed against the skin (Sect. 3.1) and experiments in which human subjects rub their skin against materials and surfaces (Sect. 3.2).

Owing to the diversity of measurement techniques and test conditions, it is difficult to compare experimental results across studies. This might be one reason why previous review articles on skin tribology (see Sect. 1) primarily compared the applied experimental methods and focused on a rather general discussion concerning the range of measured friction coefficients and factors influencing the friction of human skin.

We assume that the comparison and discussion of literature data on skin tribology can considerably be improved if the apparent contact pressure between the human skin and probe materials or surfaces is analysed as an additional parameter. In the majority of previous studies reviewed here, the skin contact pressure was not measured or specified. Nevertheless, quantitative information on this parameter can often be estimated on the basis of a suitable mechanical contact model if the normal contact force is known.

As described in the following, in the case of friction measurements with spherical probes on plane skin surfaces, the Hertz contact model [157] can provide a reasonable basis for determining contact pressures [51, 52]. The Hertz model is valid for linear elastic behaviour and is limited to small deformations [158, 159]. However, skin and the underlying soft tissue are characterised by nonlinear mechanical behaviour [84, 136] (Sect. 2.5), and it is common to observe significant skin and tissue deformations in tribological experiments [64, 108]. In order to study the contact behaviour of finger pads pressed against a flat substrate, Xydas and Kao [160] applied the Ramberg–Osgood model [161] which was developed for the description of elastic–plastic material behaviour. In the case of convex anatomical areas contacting a flat rigid counter-surface, this approach seems appropriate to estimate realistic skin contact pressures up to large tissue deformations.

Table 3 gives an overview over the 53 studies analysed in detail below. The table summarizes general characteristics as well as ranges of friction coefficients found for dry and wet skin. For the further analyses, however, all available specific results for individual anatomical areas, probe materials and normal loads were used. In many studies, such results are explicitly given, but in other cases, they had to be determined as mean values ± standard deviation (SD) or as representative and typical ranges from tables, data fits or graphical results.

3.1 Friction Between Skin and Various Probe Materials

To rub probe materials against human skin for measuring friction, linear sliding movements (Sect. 3.1.1) as well as rotations (Sect. 3.1.2) were used as basic principles in numerous experimental setups and measurement devices developed over the past decades (Table 3). Portable devices are generally based on the rotating probe principle and allow friction measurements on small skin areas at any anatomical region. The main disadvantage of such devices is that friction contacts between the skin and small rotating discs or rings are little representative in practice. On the other hand, measurement devices based on linear movements of probe materials are stationary and only suitable for anatomical areas that have a relatively even surface and can be placed on a sample stage [73].

3.1.1 *Sliding Friction Coefficients of Skin Measured with Spherical Probes*

Spherical probes were mainly used for the measurement of sliding friction coefficients of skin (unidirectional or reciprocating), and the inner forearm was the anatomical area investigated most frequently (Table 3). A few studies used alternative probes such as cylinders [1, 10, 162], a steel weight [99], or a quadratic contact probe covered with wires [96] for the unidirectional or reciprocating measurement of dynamic friction coefficients on skin.

Figure 6 illustrates results of friction measurements with spherical probes. Mean friction coefficients of skin are plotted against apparent skin contact pressures, estimated on the basis of the Hertz model for elastic contact between a sphere (probe) and a plane (skin). The Hertz model relates the geometrical contact parameters (R = radius of the sphere, a = radius of the circular contact zone, and d = vertical deformation), the normal force N and the composite elastic modulus E_c according to the following equations [157, 163]:

$$a = \left(\frac{3RN}{4E_c}\right)^{1/3}; d = \frac{a^2}{R} = \left(\frac{9N^2}{16RE_c^2}\right)^{1/3};$$
$$E_c = \left(\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}\right)^{-1} \cong \frac{E_{skin}}{1-\nu_{skin}^2} \quad (1)$$

The composite elastic modulus E_c is given by the elastic moduli $E_{1,2}$ and the Poisson ratios $\nu_{1,2}$ of the two contacting materials. If one material is considerably softer (skin) than the other (spherical probe), E_c can be approximated by the elastic properties of the soft material.

To calculate contact pressures between forearm skin and spherical probes, Adams and Johnson et al. [51, 52] used an elastic modulus of 40 kPa determined from loading data in combination with an assumed Poisson ratio of 0.49 (skin is considered as a nearly incompressible material). In other studies, similar results for the elastic modulus were reported for forearm skin [108] and the skin of fingertips [164]. Therefore, we adopted these values to determine mean apparent contact pressures $p = N/(\pi a^2)$ for analysing the literature data measured with spherical probes.

Even though the results in Fig. 6 are strongly scattered, they convey a consistent and plausible general picture despite all differences in the measurement conditions and skin areas investigated. The typical range of friction coefficients for dry skin is around 0.5 (mean value ± SD: 0.57 ± 0.32, median: 0.47) and above 1 for wet skin (mean ± SD: 1.5 ± 0.6, median: 1.4). The fits in Fig. 6 indicate that the average friction coefficients of wet or moist skin are a factor of about 2 (at high contact pressures) to more than 3 (at low contact pressures) higher than those of dry skin. Studies that compared dry and wet skin conditions reported factors between 2 (calf [165]) and 7 (inner forearm [51]).

The important influence of moisture on skin friction is evident from the literature data, although no details on the skin hydration level were reported in the studies analysed in Fig. 6. For measurements in the dry condition, the skin was either untreated or cleaned. To produce wet skin conditions, on the other hand, the skin was immersed in water [52], wetted with water [51] or caused to sweat

Table 3 Overview over the analysed studies and experimental results

Type	Study	Subjects	Probe/material	Skin area	Skin condition	COF (–) (mean ± SD or range)	Normal force (*N*) (mean ± SD or range)
A	Naylor [165]	1	PE sphere	Calf	Dry (untreated)	0.5 ± 0.02	5.1 ± 1.5
					Wet (sweating)	1.0 ± 0.1	6.4
A	Koudine [80]	1	Glass sphere	Forearm (inner), Forearm dorsal	Dry (untreated)	0.24–0.75	0.05–0.5
A	Johnson [52]	1	Glass sphere	Forearm (inner)	Dry (cleaned)	0.26–0.4	0.2–0.5
					Wet (immersed)	1.2–1.55	
A	Asserin [155]	1	Ruby sphere	Forearm (inner)	Dry (normal)	0.7 ± 0.07	0.2 ± 0.1
A	Elkhyat [149]	2	Glass sphere, steel sphere, Teflon sphere	Forearm (inner)	Dry (normal)	0.18–0.74	0.105
A	Sivamani [166]	4	Steel sphere	Finger dorsal	Dry (normal)	0.52–0.95	0.075–0.4
A	Tang [153]	4	PP sphere	Forearm (inner)	Dry (normal)	0.46	0.2–0.5
A	Adams [51]	1	Glass sphere, PP sphere	Forearm (inner)	Dry (cleaned)	0.23–0.36	2
					Wet (water)	1.05–2.62	
A	Kwiatkowska [108]	1	Steel sphere	Forearm (inner)	Dry (cleaned)	0.7–1.2	0.19–0.5
A	Fotoh [197]	75	Steel sphere	Forehead	Dry (normal)	0.8 ± 0.5	0.1
A	Li [11]	8	PE sphere	Calf (side)	Dry (cleaned)	0.18–0.72	0.1–8.0
A	Elleuch [198]	3	Steel sphere	Forearm (inner)	Dry (normal)	1.63 ± 0.07	0.05 ± 0.03
B	Sivamani [1]	59	Copper cylinder	Forearm (inner)	Dry (untreated)	0.45–0.65	0.2
					Wet (occluded)	1.0 ± 0.4	
B	Li [162]	1	Copper cylinder	Forearm (inner)	Dry (cleaned)	0.37–0.8	0.1–2.0
B	Nakajima [10]	–	Gold cylinder	Forearm (inner)	Dry (normal)	0.9 ± 0.5	0.08
B	Egawa [96]	53	Steel wires	Forearm (inner)	Dry (cleaned)	0.24 ± 0.05	0.244
B	Gupta [99]	41	Steel slider	Forearm (inner)	Dry (normal)	0.41 ± 0.08	0.49
					Wet (hydrated)	0.71 ± 0.11	
B	Sanders [12]	10	Interface materials (6), Wool sock	Tibia	Dry (washed)	0.48–0.825	1.445–6.11
C	Prall [199]	8	Glass disc	Forearm (inner)	Dry (cleaned)	0.42 ± 0.11	1.96 ± 0
C	Highley [104]	12	PA disc	Forearm (inner)	Dry (cleaned)	0.235 ± 0.045	0.28 ± 0.1
					Wet (water)	1.4 ± 0.3	
C	Gerrard [168]	5	Steel washer	Forearm (inner)	Dry (untreated)	0.19 ± 0.02	0.075 ± 0.005
					Wet (immersed)	0.7 ± 0.15	
C	Batt [200]	6	Steel washer	Forearm (inner)	Dry (untreated)	0.2 ± 0.01	0.075 ± 0.005
					Wet (water)	0.75 ± 0.09	
C	Cua [5]	29	Teflon wheel	11 Anatomical areas	Dry (untreated)	0.22 ± 0.07	1.96
C	Elsner [106]	44	Teflon wheel	Forearm (inner), Vulva	Dry (untreated)	0.48–0.66	1.96
C	Christensen [201]	8	Teflon wheel	Cheek, Forehead, Nose	Dry (normal)	0.12–0.22	1.96
C	Zhang [146]	10	Aluminium ring, cotton sock, PA ring	6 Anatomical areas	Dry (untreated)	0.37–0.51	0.98
C	Tanimoto [2]	9	Metal disc	Forearm	Dry (untreated)	0.6–1.65	2.16–4.32
C	Hendriks [49]	10	Aluminium ring, PTFE ring	Forearm (inner), Cheek	Dry (washed)	0.3–0.85	0.625
					Wet (humid climate)	0.925–2.1	
D	El-Shimi [105]	11	Steel sphere	Forearm (inner)	Dry (untreated)	0.53 ± 0.21	1 ± 0.5
F	Dinç [15]	1	Nylon 66, phenolic, plexiglas, polycarbonate, Teflon	Index finger	Dry (untreated)	0.09–0.61	1.25–15
F	Seo [181]	10	Aluminium, rubber hose	Middle finger	Dry (washed)	0.4–1.3	1.3–19.6
F	Warman [54]	1	Acrylic glass	Index finger, Middle finger, Ring finger, Little finger, Thumb	Dry (untreated)	0.95–1.6	1
F	Savescu [184]	12	Cotton, polyester, rayon, sandpaper P320, silk	Index finger	Dry (washed)	0.33–0.96	4.02–11.93
F	Derler [35]	12	Wool fabric	Index finger	Dry (untreated)	0.415 ± 0.124	1.5 ± 0.7
F	Ramalho [191]	17	Glass	Index finger	Dry (untreated)	0.49 ± 0.12	25 ± 8

Table 3 continued

Type	Study	Subjects	Probe/material	Skin area	Skin condition	COF (–) (mean ± SD or range)	Normal force (*N*) (mean ± SD or range)
F	Gee [31]	1	Glass, paper, steel	Index finger	Dry (cleaned)	0.6–1.75	11
F	Skedung [27]	1	Papers (21)	Index finger	Dry (washed)	0.38 ± 0.1	1.2 ± 0.08
F	Childs [164]	1	Polyester sheets (15)	Index fingerpad, Index fingertip	Dry (washed)	0.63–1.1	1.5
F	Roberts [202]	1	Rubber glove	Index finger	Dry (untreated)	0.7 ± 0.08	0.32
					Wet (water)	1.2 ± 0.05	
F	Lewis [26]	1	Glossy paper, plastic (2) aluminium lacquered (2)	Index finger	Dry (washed)	0.16–0.31	20
					Wet (water)	0.36–0.44	
F	Skedung [16]	14	Papers (8)	Index finger	Dry (washed)	0.475 ± 0.125	1.3 ± 0.3
F	Masen [119]	1	Steel polished and rough	Index finger	Dry (washed)	0.45–0.9	1
					Wet (immersed)	1.25	
F	Tomlinson [110]	1	Aluminium, brass, HDPE, PP, PVC, steel	Middle finger	Wet (water)	1.2–2.5	0.75–14
F	Bobjer [203]	14	Polycarbonate smooth and textured	Index finger	Dry (washed)	0.64–2.22	1–20
					Wet (saltwater)	0.61–1.23	
G	Kinoshita [171]	6	Rayon, sandpaper P220, Suede	Index finger, Thumb	Dry (washed)	0.42–1.67	1.4–5.5
G	Uygur [185]	16	Acetate, rubber	Index finger, Thumb	Dry (washed)	0.676–1.53	3.7–8.8
G	Cole [204]	66	Acetate, sandpaper P320	Index finger-Thumb	Dry (washed)	0.31–1.4	1.5–7
G	Burstedt [186]	7	Rayon, sandpaper P320	Index-Thumb-Middle	Dry (washed)	0.66–1.01	1.33–2.07
G	André [109]	10	Moisture sensor	Index finger-Thumb	Dry to wet	0.415–1.18	0.2–25
G	Buchholz [205]	7	7 Materials	Index finger-Thumb	Dry (washed)	0.45 ± 0.14	31.3 ± 13.8
					Wet (moistened)	0.53 ± 0.1	
G	Westling [206]	16	Sandpaper P320, silk, Suede	Index finger-Thumb	Dry (washed)	0.35–1.21	5
G	Seo [187]	12	Cardboard, aluminium, rubber	All Fingers	Dry (washed)	0.44–1.43	2–3.6
G	Smith [207]	8	Polyamide smooth and textured	Index finger-Thumb	Dry (washed)	1.5–1.7	1.5–1.7

Types of studies: *A* spherical probe sliding on skin; *B* non-spherical probe sliding on skin; *C* cylindrical, disc- or ring-shaped probe rotating on skin; *D* spherical probe rotating on skin; *F* finger sliding on flat material surface; *G* grip experiment (incipient slip). The two last columns indicate the range of measured friction coefficients and applied normal forces (results for dry and wet skin conditions separated)

[165]. Figure 6 shows several data points for dry skin lying in the same range as those of wet skin. Such results probably indicate enhanced levels of skin hydration during the friction measurements (e.g. due to sweating).

While variations in skin hydration seem to be an essential factor for the data scatter in Fig. 6, the contribution of other factors remains unclear. Most of the literature data were measured on the inner forearm. The results for the other anatomical areas investigated with spherical probes (calf, forehead, dorsal finger and dorsal forearm) are distributed over the same data range. The effective elastic properties of the skin and the subcutaneous tissue vary with the tissue thicknesses and due to anatomical differences. However, estimations based on the Hertz model show that changes of the elastic moduli within a realistic range (see Fig. 3) cannot alone explain the variations in the skin friction measurement data in Fig. 6.

According to Hendriks and Franklin [49] the material of the probe brought into contact with the skin is less important than its surface roughness (see Sects. 2.6.1 and 3.1.2). However, in none of the studies using spherical probes the surface roughness was specified. In most cases the probe materials were steel and glass, but probes made of ruby, PE, PP and PTFE were also used. Measurements with steel spheres yielded the highest friction coefficients.

The results of in vivo measurements are generally expected to vary among individuals as well as for repeated experiments on the same subject. Only six of the twelve studies that used spherical probes investigated more than one subject. Many of the data points shown in Fig. 6 are therefore based on a small number of friction measurements, and the representativeness of such results is unclear.

Data fits using a power-law of the form $\mu(p) = a{\cdot}p^b$ indicate a pressure-dependence of the friction coefficients of wet skin ($b = -0.53$, standard error: 0.37). The slight pressure-dependence observed for dry skin is uncertain ($b = -0.10$, standard error: 0.21). Johnson and Adams et al. [51, 52] who investigated the friction coefficient of skin at the inner forearm as a function of the normal load found exponents b between -0.07 and $+0.07$ for dry skin and values between -0.17 and -0.12 for wet skin. For dry skin, Koudine et al. [80] and Sivamani et al. [166] found corresponding values of -0.28 and -0.32, respectively. Assuming an elastic contact behaviour of skin according to the Hertz model and assuming the friction force to be determined by adhesion forces proportional to the skin contact area ($F_{adh} \sim A$), the friction coefficient is expected to decrease with increasing normal force to the power of $-1/3$ [71]. Under these assumptions it also follows that the friction coefficient due to adhesion is inversely proportional to the contact pressure: $\mu_{adh} \sim F_{adh}/N \sim A/N = p^{-1}$. The pressure-dependence of the friction coefficient will be further discussed in connection with the friction mechanisms of human skin in Sect. 4.2.

An important limitation of the analysis of contact pressures between skin and spherical probes is that the Hertz model is only valid for small deformations $d/R < 0.10$ [158, 159, 167]. Assuming an E-modulus of 40 kPa for skin as described above, this is approximately fulfilled for 15 out of the 40 data points for spherical probes in Fig. 6. For the majority of the data the deformations are still below 0.3, but in 13 cases—especially those characterised by small probe diameters or relatively high normal forces—the deformations are greater than 0.5, i.e. the applicability of the assumptions made is questionable. A higher elastic modulus of skin would reduce the calculated deformations according to $d/R \sim E_c^{-2/3}$, while the calculated skin contact pressures in Fig. 6 would be scaled according to $p \sim E_c^{2/3}$.

In most of the friction experiments in which alternative probes were used in combination with linear sliding movements [1, 10, 99, 162] the estimated contact pressures were relatively low (Fig. 6, black data points). All these measurements were carried out on the inner forearm, and the mean friction coefficients ranged from 0.24 to 1 (mean ± SD: 0.61 ± 0.25). The mean values of wet skin were found to be a factor of 1.7–1.8 higher than those of dry skin [1, 162]. Sanders et al. [12] used a small rectangular plate covered with different sample materials to measure static friction coefficients on dry skin (tibia). Within the range of investigated contact pressures the mean friction coefficients of six interface materials for prosthetics lay between 0.70 and 0.83, the mean values of a wool sock between 0.48 and 0.66 (Fig. 6, grey data points).

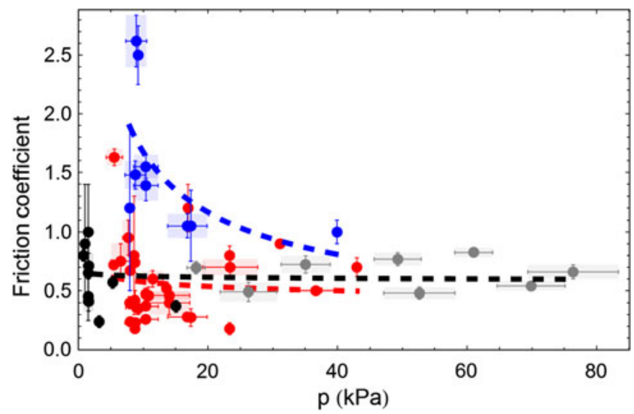


Fig. 6 Friction coefficients of skin measured with linearly moved spherical probes (*red* dry skin, *blue* wet skin; data from the studies of type A in Table 3) and alternative probes (*black* and *grey* [12]; data from the studies of type B in Table 3) as a function of the apparent contact pressure (mean values ± SD or range). Fits to the data of spherical probes using the model $\mu(p) = a{\cdot}p^b$ indicate that the friction coefficients of wet skin depend on the contact pressure, whereas for dry skin no pressure-dependence can be seen

3.1.2 *Friction Coefficients of Skin Measured with Rotating Probes*

Figure 7 illustrates the results of studies in which the friction of skin was measured by means of rotating probes. The applied principle is to measure the torque that is needed to maintain a constant angular velocity of the probe. In most cases, disc- or ring-shaped probes with outer diameters of typically 12 mm were used, and the most frequent probe materials were PTFE, PA and aluminium. The contact pressures against the skin were either specified or could be estimated from the probe geometry and the normal loads applied. For one study [105], in which a steel sphere was rotated on the skin, the contact pressure was estimated on the basis of the Hertz model analogous to Sect. 3.1.1.

There are available small, hand-held devices that use rotating probes to measure skin friction. Because the method is flexible and can be applied on relatively small skin areas, numerous different skin areas were investigated beside the inner forearm (Table 3). For example, six and eleven different anatomical regions were studied by Zhang and Mak [146] and Cua et al. [5], respectively. For these two studies, mean friction coefficients over all anatomical areas were calculated and analysed in Fig. 7.

The range of skin friction coefficients measured with rotating probes is similar to that found in linear friction measurements (Sect. 3.1.1). For dry skin, the literature values vary around 0.5 (mean value ± SD: 0.53 ± 0.39, median: 0.42). The friction coefficients of wet skin are significantly higher, but wet skin was investigated only in a few studies. From measurement data on the cheek [49], a factor of 1.6 can roughly be estimated for the difference between wet and dry conditions, while results on the inner forearm indicate factors between about 3 and 6 [49, 104, 168].

In contrast to the results of sliding friction measurements, the data of rotating probes on dry skin show an increasing trend with contact pressure (Fig. 7). Such a behaviour cannot be explained by a simple adhesion mechanism alone. It implies that deformation mechanisms are involved or that friction at high contact pressures is increased by skin moisture. Even thermal effects in the contact zone due to local heating of the skin cannot be excluded. Friction coefficients increasing with pressure would be qualitatively compatible with expectations for elastomers, for which viscoelastic hysteresis is considered to be an essential friction mechanism [79] (see Sect. 4.2). With increasing contact pressure, deeper skin layers are accessed and sinking-in of the probe and bulging of the adjacent skin provide higher effective contact and working surface, leading to more pronounced skin twisting and wrinkling during probe rotations and thus increased frictional resistance. On the other hand, a linear increase in measured friction coefficients could also be associated with the effects of skin hydration [48, 110]. Elevated skin moisture might be caused by occlusion, provoking sweating or the accumulation of water from impaired trans-epidermal water loss.

From the literature data based on rotating probes as a whole (Fig. 7), no marked effects of the applied probe materials are evident. Hendriks and Franklin [49] found the

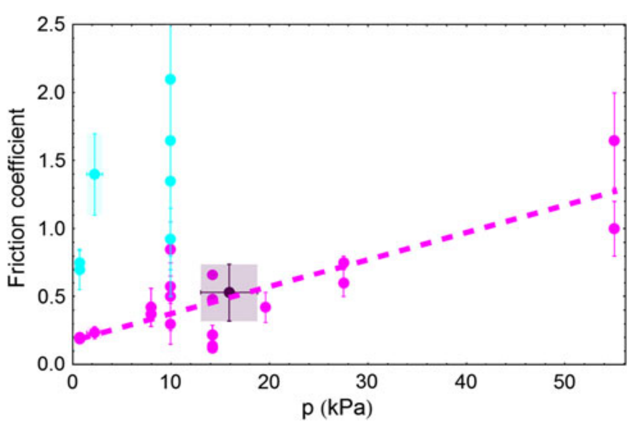


Fig. 7 Friction coefficients of dry (*pink*) and wet (*cyan*) skin measured with rotating discs and rings as a function of the apparent contact pressure (mean values ± SD or range; data from the studies of type C in Table 3). An additional single data point (study of type D) is based on measurements with a rotating sphere (*purple*). Linear regression $\mu(p) = \mu_0 + a \cdot p$ of the results for dry skin yields $\mu_0 = 0.17$ (standard error: 0.05) and $a = 0.020$ (standard error: 0.002) with a correlation coefficient of 0.85. The correlation is considerably improved by two data points at pressures above 50 kPa [2], however, linear regression without these two data points leads to fit parameters in the neighbourhood of those for all data

friction of skin (forearm and cheek) to be reduced about 25% when PTFE was used as a probe material compared to other materials such as aluminium. In their study, a change from dry to humid climate conditions in the laboratory increased the friction of skin by a factor of 2 due to skin hydration.

3.2 Friction of Fingers When Touching Surfaces and Gripping Objects

Experimental results on the friction and contact behaviour of human fingers are available from studies concerning the tactile properties of surfaces as well as from research on the gripping of objects. The exploration of the human sense of touch and the mechanisms of gripping is also important in robotics, aiming at a realistic simulation of sensory tasks and object manipulation by means of artificial systems.

Force plates are a widely used method to measure dynamic friction coefficients of the finger rubbing against flat material samples (Sect. 3.2.1), because friction is thought to be closely related to the tactile properties of surfaces. In grip experiments, on the other hand, small measuring bodies with integrated force sensors are used, to which surface samples to be tested are attached on two sides. The measuring body is held between two fingers and loaded by defined external forces while the grip forces are measured (Sect. 3.2.2).

The glabrous skin of the human finger pad is characterised by the fingerprint ridges and a high density of sweat glands [15], both having important implications for the friction behaviour. A recent study suggests that the main role of the epidermal surface ridges is not to influence friction, but to improve tactile perception by amplifying mechanical stimuli for the excitation of mechanoreceptors located in the subsurface skin tissue [54]. On the other hand, results of André et al. [53] indicated that sweat excretion changes the moisture of the fingertip during object manipulation such that the grip forces are minimised.

3.2.1 Dynamic Friction of Fingers on Flat Surfaces (Force Plate Measurements)

Since the review article of Tomlinson et al. [17] about the friction between finger and objects, a series of new experimental studies were published on this topic. Table 3 summarises currently available literature data on the dynamic friction coefficient between the human finger and materials with flat surfaces, measured by means of force plates or analogous measurement systems. In the majority of the studies, finger friction was measured at normal forces below 5 N, covering the typical range which is used for the tactile assessment of surfaces.

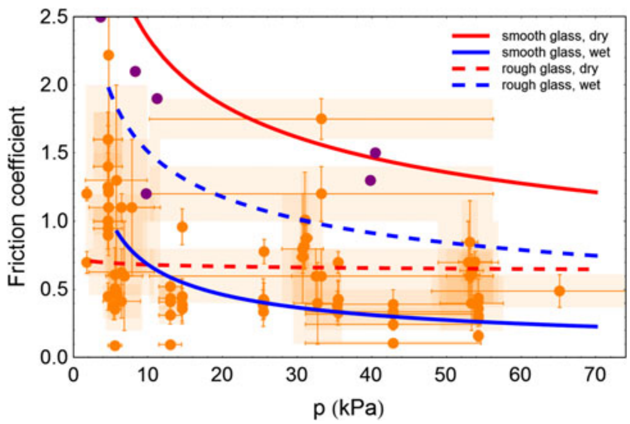


Fig. 8 Friction coefficients of finger pads against flat surfaces as a function of the apparent contact pressure (mean values ± SD or range; data from the studies of type F in Table 3) in comparison with average friction coefficients between the index fingers of four subjects and smooth and rough glass as a function of the apparent contact pressure (*solid* and *dashed lines*) [82]. Results of Tomlinson et al. [110] for moist skin are shown in *purple*

Information on the skin contact pressure is not generally available, as this requires the additional measurement of the skin contact area. The contact area (A) between fingers and flat surfaces as a function of the normal force (N) has been investigated using optical techniques [169, 170], finger pad prints [54, 164, 171] and pressure sensitive films [82]. Measurement results for $A(N)$ show nonlinear curves which are characterised by a steep initial increase for normal forces up to 2–5 N and moderately increasing, stabilizing values at higher forces. For contact forces around 10 N, the apparent contact area of the index finger pad is typically between 2 and 3.5 cm^2 [82, 169–171]. The finger contact areas vary due to individual differences and measurement parameters such as the angle between finger and the contacted surface. When investigating one subject, Warman and Ennos [54] found that the contact area of the index finger was slightly greater than that of the other fingers.

In order to estimate skin contact areas and to calculate contact pressures for all literature data on fingers (Fig. 8), we used experimental results for the apparent contact area of the index fingers of four subjects for normal forces up to 40 N [82]. The average data show a typical curve within the range of other studies and can be approximated (least squares fit) by the function $A(N) = 2.15{\cdot}N^{0.18}$ (contact area in cm^2 as a function of the normal force in N).

Han et al. [172] and Xydas and Kao [160] also used functions of the form $A(N) = a{\cdot}N^b$ to analyse the apparent contact area of finger pads and soft elastomer spheres when pressed against a flat substrate. Their approach was based on the description of nonlinear mechanical behaviour using a power-law stress–strain relation according to the Ramberg–Osgood model [161, 173] which was initially developed to analyse uniaxial stress–strain curves of elastic–plastic materials (metals) using only three parameters. The Ramberg–Osgood model was applied to describe the mechanical behaviour of textiles and fibres [174, 175] as well as biomaterials such as bones [69] and prosthetic heart valves [176]. It provides a phenomenological description of nonlinear elastic materials showing strain-stiffening/hardening. For skin and other soft biological tissues, nonlinear stress–strain behaviour is typical [136, 177], and stiffening at high strains serves to prevent large deformations threatening tissue integrity [178]. The nonlinear elastic stress–strain behaviour of skin can be associated with the properties of the collagen-elastin fibre network and interactions with the viscous ground substance [84, 177] (Sect. 2.5). When compressed, the human finger pad as a whole shows an analogous force–deformation behaviour, characterised by forces that increase roughly linearly for deformations below 1 mm and evolve nonlinearly into a steep increase for deformations above 1.5 mm [179, 180]. Along with its nonlinear stress–strain behaviour, the relaxation time of the finger pad under normal load and tangential traction is 8–11 s [123], allowing one to consider finger skin pseudo-plastically (visco-plastically) deformed and to apply the Ramberg–Osgood model in connection with friction contacts of the finger.

Figure 8 shows measurement results for the friction between fingers and flat material samples. For dry finger pads, the friction coefficients typically range from 0.2 to 1 (mean value ± SD: 0.60 ± 0.38, median: 0.45). A few studies investigated wet or moist fingers and typically found friction coefficients above 1 (mean value ± SD: 1.28 ± 0.67, median: 1.25). In experiments in which the friction of the finger pad was systematically investigated against various materials under different air humidities, Dinç et al. [15] found on average 24% higher friction coefficients at a relative humidity of 90% compared to 35–38% relative humidity.

In general, the index finger was used for measuring tactile friction. The results of studies investigating the middle finger [110, 181] were in agreement with the results of index fingers. Warman and Ennos [54] observed broadly similar friction behaviour for all fingers of the hand. The various materials investigated (comprising glass, metals, plastics, elastomers, papers and textiles with a wide range of surface characteristics) are certainly contributing to the considerable variations of the friction coefficients seen in Fig. 8. While PTFE surfaces and textiles were characterised by low friction coefficients, the values of smooth surfaces and elastomers tended to higher values.

Apparently, the skin moisture condition is of crucial importance for the friction of the finger pad. Fingers tend towards abundant sweating. Tomlinson et al. [110] varied the moisture condition of the middle finger pad using different methods of water application and measured its friction against six different materials with surface roughness values *Ra* between 0.2 and 1.7 μm. The friction coefficients of the dry finger pad were below 0.5 for all materials. In the moist condition, the values rose to maxima between 1.3 and 2.5 (results shown in purple in Fig. 8). In a second study, Tomlinson et al. [143] investigated the friction behaviour of the finger pad of one subject under controlled dry conditions. They found average friction coefficients that varied within a relatively limited range (0.14–0.83) for twelve materials (metals, plastics and elastomers). In addition, the measured friction coefficients did not show a pronounced load-dependence for normal forces up to 40 N.

Adhesion forces (see also Sect. 4.2.1), i.e. short-range molecular attractive forces, normally provide the main component of the friction of human skin under both dry and moist conditions [51]. In this case, the friction force is proportional to the real contact area between the contacting surfaces. Because for solids with rough surfaces the real contact area is proportional to the normal load [182], the corresponding friction coefficient is load-independent. According to Adams et al. [51], dry human skin behaves like a rough surface due to its visible and microscopic topographical features.

The dashed lines in Fig. 8 indicate average friction coefficients between the index fingers of four subjects and rough glass as a function of the apparent contact pressure [57]. For dry conditions (red dashed line) the friction coefficients were practically load-independent within the investigated pressure range. Under wet conditions, on the other hand, the coefficients of friction increased with decreasing contact pressures (blue dashed line). This was mainly attributed to the hydration and softening of the skin, leading to an increased effective contact area with rough glass. The differences between wet and dry finger friction were especially pronounced for contact pressures below 20 kPa. Interestingly, a similar divergence between wet and dry friction can also be seen in the results of other anatomical skin areas investigated by means of sliding probes (Fig. 6).

The solid lines in Fig. 8 show average friction coefficients of index fingers on smooth glass [57]. Under wet conditions (blue line), the friction coefficients were found to be low due to hydrodynamic lubrication. The friction coefficients on dry smooth glass were much higher (red line) because the skin of the finger pad is relatively moist, leading to a large microscopic contact area and high adhesion. Recently, Pasumarty et al. [107] likewise reported that the human finger pad typically shows large coefficients of friction on dry smooth surfaces.

The comparison of the plots in Figs. 6, 7 and 8 shows that the friction behaviour of fingers is in general accordance with that of other skin areas. This was also noticed by Warman and Ennos [54] who discussed the function of fingerprint patterns from the biological point of view. Nevertheless, they assumed that fingerprint ridges could increase the contact area against rough surfaces by intruding into depressions (interlocking) or facilitate a certain drainage of small liquid amounts in order to increase friction under wet conditions.

In a number of studies in which dry finger pads were investigated without specifying the applied normal forces, mean friction coefficients of the same order of magnitude as in Fig. 8 were measured against metal cooking foil (0.42–0.54) [183], packaging materials (0.2–0.9) [44] and textiles (0.28–0.62) [25], respectively. A particular observation made in friction experiments with fingers is that liquid substances (sweat and sebum) are transferred to the counter-surface, leading to slightly decreasing trends in repeatedly measured friction coefficients [15, 27, 183].

3.2.2 *Static Friction of Fingers and the Hand Determined from Grip Experiments*

In a typical grip experiment, a measuring body bearing material samples is held by a subject between two fingers or other parts of the hand. Normal grip forces and tangential force components are measured through integrated force sensors. If either an increasing tangential force is applied or the grip forces are released until slippage between the fingers and the measuring body occurs, the ratio of the tangential and normal force components corresponds to the static friction coefficient. Savescu et al. [184] found that the results of grip experiments (incipient slip method) are comparable to those of dynamic friction measurements (imposed displacement method). Results of other studies [26, 102, 153, 155] indicated that the static friction coefficient of human skin is between 10 and 40% higher than the dynamic coefficient of friction.

The static friction coefficients determined from grip experiments (Fig. 9) lie in the same range as dynamic friction coefficients measured for fingers (Fig. 8) and show a similar systematic decrease with contact pressure. The majority of the grip experiments analysed in Fig. 9 was related to dry skin conditions. However, André et al. [109] reported higher static friction coefficients for wet skin compared to dry, normal and very wet skin.

In order to determine the contact pressures of finger pads in grip experiments it was assumed that the grip forces were evenly distributed over all fingers and that all the fingers show the same characteristics of the contact area as a function of the normal load (according to Sect. 3.2.1). Most of the studies analysed in Fig. 9 investigated the case

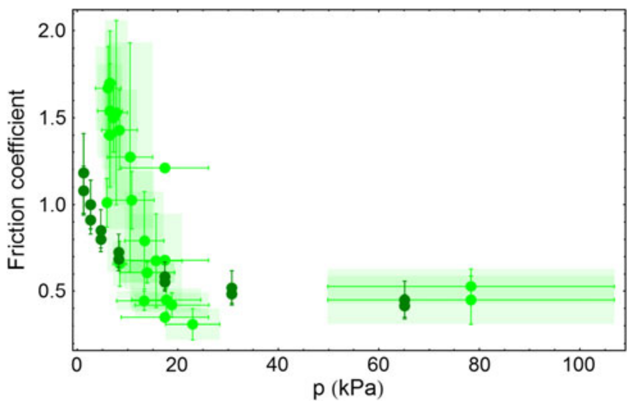


Fig. 9 Static friction coefficients of fingers determined from grip experiments as a function of the apparent contact pressure (mean values ± SD or range; data from the studies of type G in Table 3). Results of André et al. [109] indicating load-dependence are highlighted (*dark* data points)

of the precision grip, in which an object is held between the index finger and the thumb. However, some studies used alternative grip configurations such as the grip between the same fingers of two hands [185], grip between three fingers [186], grip of five fingers [187] or grip of the whole hand [188].

A number of studies reported static and dynamic friction coefficients of the palm or the entire hand in a similar range as those of fingers. In different experiments, O'Meara and Smith [21, 154] found mean static friction coefficients from 0.98 to 1.72 between hand and five handle materials under dry and wet conditions. In a comparison of two experimental methods to measure the static friction of five fingers and the flat palm against different surfaces, Seo et al. [187] found average friction coefficients of 0.46 ± 0.17 (cardboard), 1.11 ± 0.48 (aluminium) and 1.60 ± 0.44 (rubber) for dry skin conditions. The friction coefficients of the palm were higher than those of the fingers, indicating an influence of the skin area and the skin contact pressure. Also Uygur et al. [185] measured higher static friction coefficients for the palm than for fingers (against rubber and acetate, respectively). When investigating the sliding friction of the human palm on smooth glass, Ramalho et al. [189] found mean friction coefficients of 1.07 ± 0.08 for untreated skin and values of 0.87 ± 0.06 for washed skin. For the edge of the hand we observed dynamic friction coefficients of 1.21 ± 0.34 against smooth glass and of 0.38 ± 0.03 against rough glass under dry conditions and for an apparent skin contact pressure of 20 ± 2 kPa [82]. Corresponding friction coefficients of the index finger pad were greater, and we assumed increased skin hydration levels to be the main reason for this observation.

4 Discussion

In this review, we summarized the current knowledge on skin tribology and analysed the available experimental data for friction coefficients of human skin. By additionally estimating and analysing the skin contact pressures during the friction measurements, it was possible to compare the results from a relatively large number of studies using different measurement techniques and investigating various skin areas and materials in contact with skin.

Substantial variations are a characteristic feature of the experimental data for the friction coefficient of human skin (Figs. 6, 7, 8, 9). In vivo friction measurements on skin are generally scattered, and studies investigating more than one subject normally report considerable variations among individuals. The two most important factors for the observed variations are differences in skin hydration as well as the varying surface properties of the materials brought into contact with the skin. Because many studies did not provide detailed information on the skin hydration levels and surface characteristics, both these factors were discussed in the Sects. 2 and 3 without further statistical analysis.

The estimation of skin contact pressures for the analyses carried out in Sect. 3 is afflicted with some uncertainties. An important limitation is the application of the Hertz contact model for all literature data available for spherical probes, leading to errors for small probe diameters and high normal contact forces. In the analysis of contact pressures of finger pads, we assumed a common empirical relationship for the apparent contact area as a function of the normal load for all data. This simplification neglects differences in individual finger sizes and finger orientations in specific friction or grip experiments.

Despite the described variations in the friction measurement data and uncertainties of the data analysis, the performed analyses of literature data allow general conclusions regarding measurement techniques, friction mechanisms of human skin and interesting future research questions. These three topics are further discussed in the following.

4.1 Friction Measurement Techniques and Parameters

By analysing friction coefficients of human skin as a function of the skin contact pressure, it was possible to compare the results of different measurement techniques and differing experimental conditions for a range of anatomical areas. Figures 6 and 8 show that friction coefficients obtained with spherical probes on various skin areas are in good overall agreement with the results of finger pads rubbed against planar surfaces. Also the static friction coefficients determined from grip experiments (Fig. 9) lie in a comparable range and show systematics in accordance with the results of dynamic measurements.

Nevertheless, friction coefficients of skin are influenced by the measurement technique, as is evident from the data measured with rotating probes (Fig. 7). The corresponding results are in the same range as those found in the other experiments, but seem to be influenced by systematic effects, indicated by a linear increase of the friction coefficients with increasing skin contact pressure. A possible explanation is that high contact pressures of the probe promote sweating at the occluded skin area, leading to enhanced friction. The rotating probe principle therefore seems less suitable to measure reliable friction coefficients of human skin. Rotating probe devices are portable and thus convenient for comparisons among different skin areas, but it is unclear to which extent friction contact conditions occurring in practice can be realistically simulated.

Because the friction behaviour of human skin strongly depends on the hydration state of the skin (see Sect. 2.4), it is advisable to combine friction measurements with skin hydration measurements. It is also important to specify the ambient conditions, as air humidity can noticeably influence the results of skin friction measurements, especially at low contact pressures.

Studies from recent years related to skin tribology have consistently specified the surface roughness of the materials brought into contact with the skin. This is a very important aspect, and additionally, it would even be useful to determine surface roughness parameters of the skin areas investigated in friction experiments in order to provide further information about the contact between skin and counter-surfaces on the microscopic level.

A limitation of many studies published in the literature is that only the skin of one subject was investigated (see Table 3). Beside the question of representativeness, the investigation of more than one subject is useful to quantitatively assess variations among individuals.

In addition to the specification of the normal loads applied in friction measurements, the estimation of apparent skin contact pressures would contribute to improve the comparability among different studies. The simultaneous measurement of friction and skin contact areas was accomplished by special experimental setups using optical techniques and investigating smooth glass surfaces [169, 170]. However, the relationship between the apparent skin contact area and the normal contact force can also be studied in separate measurements using optical methods, ink prints or pressure sensitive films (see Sect. 3.2.1).

The measurement of the elastic and viscoelastic properties of skin would provide interesting further information to improve the interpretation of friction measurement data. Because the results of tribological measurements on skin depend on a variety of parameters (see Fig. 5), it is generally important to reproduce the actual contact conditions as realistic as possible if specific cases or applications are investigated.

4.2 Friction Mechanisms of Human Skin

4.2.1 Adhesion Friction

The common view that adhesion is the main friction mechanism of human skin is also confirmed by the analyses carried out in this review. According to the adhesion model of friction [151], the friction force is given by $F = \tau \cdot A_r$, where τ is the interfacial shear strength and A_r the real area of contact. For the interfacial shear strength of skin, Adams et al. [51] adopted the model $\tau = \tau_0 + \alpha \cdot p_r$ for shear properties of thin organic films [190], where τ_0 denotes the intrinsic shear strength, α a pressure coefficient and $p_r = N/A_r$ the real contact pressure (N = normal force). The friction coefficient can then be written as

$$\mu(p_r) = \frac{\tau \cdot A_r}{N} = \frac{\tau_0}{p_r} + \alpha \qquad (2)$$

Since the apparent and real contact areas and contact pressures are related by $A \cdot p = A_r \cdot p_r$, the friction coefficient as a function of the apparent contact pressure $p = N/A$ is given by:

$$\mu(p) = \frac{A_r}{A} \cdot \frac{\tau_0}{p} + \alpha \qquad (3)$$

Figure 10 shows a plot containing all data (mean values) from Figs. 6, 7, 8, 9. The majority of the friction

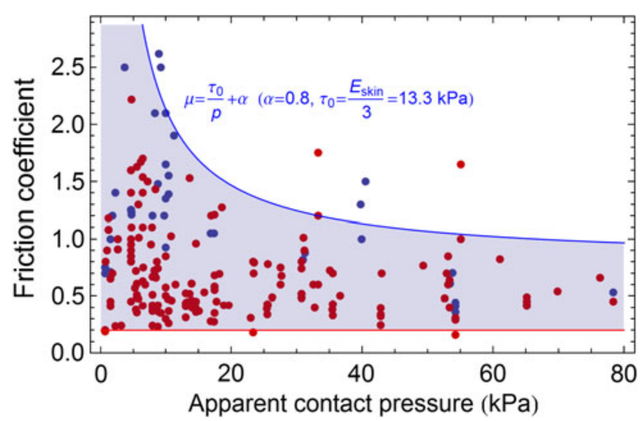


Fig. 10 Overview over the experimental results for the friction of human skin (data from Figs. 6, 7, 8, 9), without taking into account measurements against PTFE. Mean friction coefficients of dry (*red*) and wet skin (*blue*) are shown as a function of the apparent contact pressure. The typical range of friction coefficient is characterised by values above 0.2 (*red line*) and limited by a rational function (*blue*) given by the adhesion friction model for human skin. See text in Sect. 4.2.1 for details

coefficients measured for skin are higher than 0.2; only results measured against PTFE fall below this minimum value. On the other hand, friction coefficients of skin rarely exceed values above a rational function according to Eq. 3. If the real and the apparent contact area coincide, the difference between apparent and real contact pressure vanishes. This is assumed to be the case for a soft material in a completely conforming contact with the counter-surface. This situation seems realistic for skin which is softened through hydration and adheres to the counter-surface—with the possible aid of small quantities of interfacial water acting as adhesive liquid bridges.

The blue curve in Fig. 10 was calculated using a pressure coefficient $\alpha = 0.8$ reported for skin [49, 51]. The intrinsic shear strength τ_0 was assumed to be equal to the shear modulus G of 13.3 kPa, calculated via $E = 3 \cdot G$ from the elastic modulus $E = 40$ kPa of skin [52] (see also Sect. 3.1.1), which is a realistic value representing the mechanical shear properties of the upper skin layers [116]. With these values the curve represents a limiting case close to static friction, in which the skin sticks to the contacted surface and is sheared, so that the ratio between the tangential and normal force is solely determined by the shear properties of the skin.

The friction of dry skin strongly contrasts to that of moist and wet skin and is characterised by relatively low friction coefficients. In several studies investigating the volar forearm [51, 52] or fingers [143, 191], it was observed that the friction coefficients of dry skin were practically independent of the normal load. This result was explained by the model of Greenwood and Williamson [182] according to which the real contact area of rough solid surfaces linearly increases with the normal load. For a friction coefficient that is independent of the apparent contact pressure, also Eq. 3 implies $\frac{A_r}{A} \cdot \frac{1}{p} = \frac{A_r}{N} = \text{const.}$

Numerous studies reported for dry skin friction coefficients around 0.5, regardless of the anatomical area, measurement technique, type of probe, investigated material and normal load applied (Sect. 3 and Figs. 6, 7, 8, 9, 10). This fact can be interpreted as general evidence supporting the view that the friction behaviour of dry skin is similar to that of rough solids. In specific cases, however, the microscopic contact geometry between skin and the contacted material remains unclear. There is also no detailed understanding of the transition from dry to wet skin friction. In principle, Fig. 10 can be used to roughly estimate the real contact area for certain friction coefficients and apparent skin contact pressures. By comparing with the limiting case for full contact (blue curve), it can be estimated for example, that at a contact pressure of 5 kPa which is typical in tactile assessments with the finger pad [35], the real area of contact is about 15% of the apparent contact area if the friction coefficient between the skin and the touched surface is 0.5.

4.2.2 *Deformation Friction*

According to Dowson [70], deformation of the skin and the subsurface soft tissue during friction contacts can contribute to the friction coefficient in form of viscoelastic hysteresis or ploughing. A contribution due to hysteresis is expected to increase with normal load and contact pressure, while ploughing would lead to a load-independent contribution to the friction coefficient [70, 79]. Only a few of the studies listed in Table 3 reported results on the deformation component of skin friction:

Johnson et al. [52] and Adams et al. [51] analysed the friction of skin at the volar forearm in contact with spherical probes, thereby applying the approach of Greenwood and Tabor [192]. They found that the contribution of hysteresis to the friction coefficient is of the order of magnitude of 0.05. Results in the same range (0.04–0.06) were also reported by Kwiatkowska et al. [108]. In connection with measurements on the forearm and the cheek using rotating probes [49], on the other hand, friction mechanisms related to the deformation of the skin were not considered relevant.

In a recent study, Masen [119] concluded that forces related to micro-scale deformations of the skin can significantly contribute to the total friction of the human finger pad. When we investigated the friction of human skin (finger and edge of hand) against glass, we found that contributions to the friction coefficient due to viscoelastic skin deformations were below 0.2 [82]. For foot skin sliding on wet floor coverings, the contributions due to skin deformations were found to be up to 0.4 [57] on very rough surfaces. It was concluded that such high deformation components are probably caused by the combination of hysteresis effects and ploughing of the skin by the asperities of rough surfaces. For the friction between finger and small, triangular ridged surfaces, Tomlinson et al. [144] reported considerable contributions of interlocking effects (>50%) and noticeable contributions of hysteresis (<10%) to the total friction as the ridge heights exceeded values of 42.5 and 250 μm, respectively.

Deformation was also assumed to play a role in the friction between human skin and textiles [35]. Sanders et al. [12] investigated the friction of soft prosthetic interface materials as well as a sock fabric against the skin at the tibia. For both types of materials they measured friction coefficients that increased with the applied normal load, indicating that deformation was involved in friction. In a study in which we compared the skin of the volar forearm of young and elderly subjects [64], we found further evidence that skin deformation mechanisms are relevant for the friction of skin against textiles. In particular, aged skin was characterised by reduced viscoelastic recovery and skin turgor, associated with more pronounced skin tissue displacements and greater shear forces during frictional contact.

In summary, the literature data suggests that in general the deformation component of friction is small compared to adhesion friction, but that there are specific cases in which deformation mechanisms become important.

4.2.3 Friction of Wet Skin

Aqueous lubrication of the skin was discussed in detail by Johnson and Adams et al. [51, 52]. In contrast to hydrated skin or the case of small amounts of interfacial water, closed water films can cause hydrodynamic lubrication, resulting in low friction coefficients. For full hydrodynamic lubrication, calculations predict much lower friction coefficients than normally observed for wet skin [51, 82, 110]. The main reason is that water films are locally penetrated by the surface asperities of the skin and the surface in contact, leading to mixed or boundary lubrication [70]. Under such conditions, sliding friction coefficients of wet skin on smooth surfaces can reach minimum values below 0.1 at high contact pressures, as was observed in practical cases such as touching a smooth wet glass surface by the finger pad [82] or slipping barefoot on wet, smooth floor surfaces [57].

4.3 Open Research Questions

We think that studies investigating the contact behaviour of human skin on the microscopic scale will be the key to an improved understanding of the macroscopic friction behaviour of skin. High-priority research questions are related to (1) the accurate measurement of the adhesion component of friction, (2) the applicability of the two-term model of friction in the case of skin, (3) the influence of skin hydration on the microscopic contact geometry and (4) appropriate theoretical contact models for human skin:

1. The accurate determination of the adhesion component of friction on the one hand requires the measurement of the real area of contact (microscopic scale) and/or on the other hand the precise measurement of the shear strength of the skin. However, the application of modern tools such as micro-tribometers and atomic force microscopy so far seems to be limited in connection with in vivo measurements on skin. Furthermore, optical methods which were used to measure the microscopic contact area between finger pads and smooth glass are not suitable for rough surfaces and nontransparent materials.
2. Adhesion is generally considered as the predominant friction mechanism of human skin. Knowledge of the adhesion component allows a detailed investigation of the two-term model of friction as well as the determination of deformation friction for skin. So far it is unclear under which conditions deformation mechanisms (viscoelastic hysteresis, ploughing, interlocking) become important. Another question is whether the adhesion and deformation components of friction are two non-interacting terms as assumed in the two-term model [79].
3. It is evident from the literature data that skin hydration and interfacial water have an enormous influence on the friction coefficient of skin, but the transition from dry to moist skin conditions was so far not systematically investigated. The influence of skin hydration and softening on the surface and micromechanical properties of skin as well as the associated changes in the microscopic contact geometry are widely unknown. Also unclear are the role of small amounts of water in the interface between skin and the counter-surface (formation of capillary bridges, filling of gaps and influence of hydrophilicity/hydrophobicity) and the contribution of other substances such as skin lipids (sebum).
4. Theoretical concepts for solids such as the models of Greenwood and Williamson [182] and Archard [193] were used to qualitatively describe certain aspects of the contact and friction behaviour of dry skin [49, 51, 170]. The limitations of such models in connection with the complex surface topography of human skin are still unclear. Another interesting open question is, to what extent theoretical concepts for the contact behaviour of soft materials [112, 194, 195] are applicable to the case of hydrated skin.

Also on the macroscopic and phenomenological level, there are numerous open questions related to skin tribology. In particular, the influence of different skin layers on friction (5), tactile friction and haptics (6), skin injuries and ageing (7) as well as the influence of hairs, skin abrasion and desquamation (8) seem to be relevant and interesting topics for future research studies:

5. The anisotropic mechanical properties of the upper skin layers (under normal and tangential loads) and their influence on skin friction need to be studied under case-specific contact conditions. More experimental data on the mechanical properties (strain- and scale-dependent shear moduli/strength, compressive moduli/strength) and dynamic mechanical skin parameters (tangent modulus, skin relaxation times) in the large strain regime is required to understand velocity-dependent skin friction properties and fully validate

the applicability of theoretical concepts used for elastomers [79] in skin tribology.

6. Tactile perception and haptics in relation to skin tribology is largely unstudied and poorly understood. This research topic is not only interesting for the design of surfaces with pre-defined tactile feel (smooth, soft) that increase the customer satisfaction, but also for developments and applications in robotics.
7. It is expected that advanced case/problem-specific mathematical and computational skin models (e.g. finite element models including the geometry of the relevant body parts and taking into account the influence of subsurface soft tissues and bones) can significantly improve the knowledge of skin tribology and understanding of skin deformation, damage mechanisms, wound and blister formation, mechanisms of wrinkling and skin ageing.
8. So far, tribological studies on human skin focused on glabrous (hairless) and shaved skin. However, the effect of hairs on skin friction is often overlooked and important in connection with applications such as sport textiles or the comfort of clothing in general. Skin abrasion and the influence of abraded corneocytes and desquamation on friction are further interesting questions for future research in the field of skin tribology.

5 Conclusion

We reviewed the currently available literature on skin tribology and discussed the published experimental results for the friction coefficient of human skin as well as the factors influencing the friction behaviour of skin. Friction coefficients measured for skin are generally characterised by considerable variations, for which differences in skin hydration as well as the varying surface properties of the materials brought into contact with the skin play the most important role. In order to compare the results of studies using different measurement techniques and investigating various skin areas and materials in contact with the skin, we analysed the friction coefficients of skin as a function of the contact pressure. We found that the literature data are scattered over a wide range that can be understood based on the adhesion friction model. While the friction of dry skin is characterised by relatively low and pressure-independent friction coefficients similar to the case of dry friction of rough solids, moist or wet skin shows high friction coefficients that strongly increase with decreasing contact pressure and are essentially determined by the shear properties of wet skin. Further research on the microscopic contact area of skin during friction and on the mechanical properties of the upper skin layers would improve our understanding of the complex tribological behaviour of human skin.

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