Tribology and Materials
Vol. 2, No. 3, 2023, pp. 128-153

ISSN 2812-9717
https://doi.org/10.46793/tribomat.2023.013

Skin as an interface: Understanding the synergy of dermatology, biomimetics and tribology

Hakan GÖÇERLER [1,*], Carsten GACHOT [1], Philipp G. GRÜTZMACHER [1], Stefan J. EDER [1,2]

[1] Institute of Engineering Design and Product Development, Vienna University of Technology, Vienna, Austria
[2] AC2T research GmbH, Wiener Neustadt, Austria
*Corresponding author: hakan.gocerler@tuwien.ac.at

Keywords
tribology
biotribology
dermatology
skin
dermatribology
biomimetic

History
Received: 21-07-2023
Revised: 07-08-2023
Accepted: 17-08-2023

Abstract

This review explores the intersection of tribology and dermatology, explicitly focusing on studying the human skin and drawing inspiration from natural systems. It investigates animal adaptations and their implications for biotribological applications, with examples such as the friction anisotropy and wear tolerance of snakeskin, the healing properties of fish skin and the lotus effect for reducing adhesion in biomedical devices. Understanding human skin presents challenges due to its complex structure and variability influenced by age, gender, race and environment. The paper discusses *in vivo* and *ex vivo* measurements, substitute models replicating human skin properties and contact mechanics considerations. It explores contact models, measurement methods and factors impacting skin friction, emphasising the interplay between adhesion and deformation components. Techniques such as atomic force microscopy and the colloidal probe technique provide insights into mechanical properties and molecular interactions. By comprehending the complexities of human skin and its tribological behaviour, researchers can develop innovative solutions in areas ranging from soft robotics to medical research and aerospace technology.

1. Introduction

Tribology is the science of friction, wear and lubrication. While many may think directly of things like machine elements and cars, all of us encounter tribological phenomena everyday even much more closely, namely in or on our bodies. The field that deals with these phenomena is a sub-category of tribology, called biotribology, which can have a significant impact on human well-being. Within biotribology, dermatology, ophthalmology, orthopaedics, dentistry, hematology/cardiology, gastroenterology and neurology are prominent fields of study. This review article aims to delve into the realm of dermatology, which involves comprehensive investigation, diagnosis and management of skin-related health conditions. By examining relevant studies, we shed light on the fundamental theorems employed to comprehend contact conditions, which have also played a pivotal role in shaping the broader field of tribology. Exploring captivating animal kingdom instances before delving into human skin's intricate properties can provide valuable insights for many industrial applications.

At the crossroads of tribology and dermatology, an intriguing avenue of exploration lies in uncovering the design principles that govern the remarkable adaptability and performance of natural systems in response to their environments. Natural systems, while functionally complex, are usually optimised in terms of shape and performance. It is believed that the functional complexity of natural systems is what allows natural species to morph continuously to adapt to their respective operating environments [1]. Often, these adaptations concern surface design features. These may include superior functionality, the ability to harness functional complexity to achieve optimal performance and harmony between shape, form and function. To deduce design rules, there exists a need for quantification of the relationship governing microstructure and mechanical properties of the bio-surface, exploring the influence of macro- and microstructures and finally devising working formulae that describe (and potentially predict) the load-carrying capacity of macro- and micro-scale features during relative motion.

The skin's appearance, health and well-being are inextricably bound to an individual's physiological and psychological well-being since its look, colour and features influence societal perception and personal interactions. The skin has many functions, but the most important is to be a blockade against the entrance of chemical, physical and microbiological agents, thus protecting all other body tissues. It is where hair, nails and certain glands, such as sweat glands and mammary tissue, form. The hair coat, cutaneous (skin) blood circulation and sweat glands are essential in temperature regulation. Electrolytes, water, vitamins, fat, carbohydrates, proteins and other materials are stored in the skin. The skin allows radiation from the sun to convert the inactive form of vitamin D to the active form. It then transfers active vitamin D to the rest of the body through the skin's capillary system, as the roughness dimension is smaller than the blood platelets [2]. Additionally, the skin changes colour to darker with the help of melanin and it helps prevent damage from ultraviolet light. We can also monitor a person's health as internal diseases, external diseases, and the effects of topical substances can change the visual look of the skin [3]. Skin is a primary sense organ for touch, heat, pain, itch, cold and pressure. It can also be identified as an extraction organ as it has a part in eliminating waste from the body.

2. Observations in nature

One of the most studied topics concerning the functionality of natural surfaces is their wetting behaviour, which has direct implications on tribological properties. Here the most famous effect is the lotus effect, which results in superhydrophobicity (i.e. contact angles > 150°). Plants have a skin called a cuticle that covers the above-ground surfaces. It is composed of waxes and a polymer network consisting of fatty acid building blocks called cutin. Barthlott and Neinhuis noticed that some plants seemed to have a self-cleaning effect, and this effect was most obvious for the lotus [4]. It is caused by combining two features of the leaf surface: its waxiness and the microscopic bumps covering it. When the pre-requisite of water-repelling surface chemistry is met, the surface structure becomes dominant [5]. The resulting high water contact angles and the small roll-off angles lead to water droplets rolling easily off the leaves and dragging dirt particles with them. The most exciting application of the lotus effect related to this review is that it reduces the adhesion of blood cells to surfaces. Micro- or nanostructured surfaces mimicking the lotus effect therefore can be used for biomedical devices such as catheters, stents and artificial or prosthetic cardiovascular components [6]. Inspired by the natural blood vessel micro- or nanostructure, Fan et al. devised a strategy for mimicking the topography of the blood vessel tissue's inner cell layer. Using a self-assembly technique together with soft lithography, they fabricated an artificial blood vessel of polydimethylsiloxane (PDMS) with dimensions close to that of natural blood vessels, consisting of submicron ridges (500 nm wide and 100 nm high) and nanoscale protuberances (100 nm wide and 40 nm high) [7]. The results indicated that blood platelet adhesion was reduced only with multiscale-structured PDMS when the roughness matched the platelet size [8]. Liu et al. designed an *in vivo* experiment on the vascular graft of rats that connects to the abdominal aorta to evaluate its effect on the patency rate. They fabricated a longitudinally aligned graft topography on medically graded polyurethane with a surface mimicking the arterial vessel's inner coat. Thrombosis formation was significantly reduced for the aligned topography, and its patency rate was increased from 28.6 to 100 % for the smooth surface. They concluded that the blood compatibility of the aligned topography was observed because of the reduced contact area between the surface and the platelet, as the roughness dimension is smaller than that of the platelets [9].

Furthermore, specific microstructures on natural surfaces also induce anisotropic wetting behaviour. Thorny devils (*Moloch horridus*) and the Texas horned lizard (*Phrynosoma cornutum*) are two fascinating lizard species that can collect and transport water [10] with channel-like structures on their skin (Fig. 1). Specialised skin structures, comprising a microstructured surface with capillary channels between imbricate overlapping scales, enable the lizard to collect water by capillarity and transport it to the mouth for ingestion [11]. It has been suggested that these structures can also be used in tribological settings to guide lubricants across surfaces to designated positions where lubrication is needed to reduce friction and wear [12].

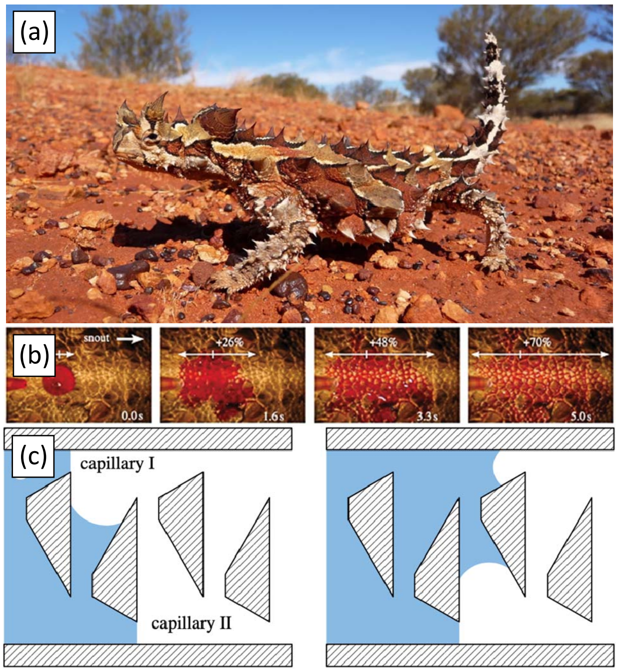

Figure 1. Capillary fluid transport mechanisms in *Moloch horridus*: (a) *Moloch horridus* can drink water from sand through its feet and back, reprinted from Wikimedia Commons, licensed under CC BY-SA 3.0, (b) the fluid transport properties through the channels on the surface of the Texas horned lizard (*Phrynosoma cornutum*) are demonstrated with the help of a coloured water droplet, adapted from Comanns et al. [13], licensed under CC BY 4.0 and (c) schematic illustrating the mechanism of fluid transport by capillary forces; the liquid stops at the sharp edge of capillary I and is picked up by the liquid going through the interconnection, forming a new liquid front, adapted from Comanns et al. [13], licensed under CC BY 4.0

An exciting example of animal skin, which has demonstrated fascinating tribological behaviour and has been investigated as a substitute for human skin, is the skin of a snake [14]. One advantage concerning its tribological evaluation is that snakeskin can be obtained without injury to the animal and does not have to be subjected to chemical or thermal stress prior to use. Shed snakeskin, a non-living tissue, can be stored for extended periods at room temperature and transported conveniently. Stored and fresh snakeskin does not appear to exhibit any differences in permeability. Moreover, snakeskin, lacking hair follicles, does not suffer from issues associated with transfollicular penetration encountered in mammalian skins. The shed skin of ball pythons is of particular interest in tribology due to their locomotion within a non-breakable boundary lubrication regime [15]. The skin's ornamentation facilitates this performance feature, making it relevant for the design of sliding assemblies (e.g. cylinder piston) and prostheses.

Artificial snakeskin can be used in soft robotics [16]. Snakes can grasp objects with their body and move around using various gaits, including slithering and creeping. They need a surface structure that provides friction anisotropy, enabling them to navigate more quickly and efficiently through their environment. The critical part is not only in the actuation system but also in the design of the artificial skin. The skin should possess flexibility and stretchability, while the scales need to be positioned on a pliable base body at a specific angle of attack. In experimental investigations of artificial snakeskin, researchers observed friction anisotropy when using two different stiffness base materials and three angles of attack [17]. Interestingly, they discovered that employing a flexible base material reduces friction in the forward direction and increases it in the reverse direction, resulting in enhanced friction anisotropy. In a separate study by Sánchez-López et al., long-term low friction maintenance and wear reduction on snakes' ventral scales were explored [18]. The main issue is that even though the softness of the material in robotics is essential for friction anisotropy, how would such a material endure permanent friction and wear during sliding? The wear resistance is attributed to the fibrous layered composite material of the skin, comprising a gradient of material properties, surface microstructure and ordered layers of lipid molecules on the skin surface [19].

Shed snakeskin has also been considered as a substitute for human skin in tribological research. The frictional response of shed skin obtained from *Python regius* and human skin from different anatomical sites, gender and age, was compared. It was observed that the mechanisms governing the friction response of human skin are common to snakeskin despite differences in chemical composition and apparent surface structure. Both skin types display sensitivity to hysteresis and adhesive dissipation. This observation also means researchers can use shed snakeskin under certain circumstances as an *ex vivo* substitute for tribological evaluation [20]. However, the frictional performance of human skin is not solely determined by surface topography but is also influenced by water content within the skin cells. A study that focused on the skin's permeation parameters and physiological characteristics, e.g. the water and lipid content and the thickness of shed snakeskin and human skin, demonstrated that the permeability coefficients of lipophilic drugs in shed snakeskin, were in the same range as those in human skin (0.9 to 1.8 times), whereas those of hydrophilic drugs were remarkably lower (3.3 to 6.1 times).

Frictional anisotropy like that of snakeskin can also be observed on many biological surfaces such as butterfly wings [21], animal attachment pads [22], insect unguitractor plates [23], spider tarsi [24], gecko toe [25], peristome of pitcher plants [26], wheat awns [27], plant fruits and leaves and fish skin [28]. On the other hand, some non-biological examples, such as single crystal surfaces [29], monolayer graphene [30] and engineered surfaces with texture patterns [31] also demonstrate this friction anisotropy, thus proving an association between these two worlds. If we understand the mechanical response depending on differently oriented micro- or nanostructures and the relationships between the topographic orientation and biological functions, such as locomotion [32], predation [33], cleaning [34] and transporting fluids and items [35], there is always a possibility to learn from nature and to apply this knowledge in other industrial applications. Therefore, frictional anisotropy increasingly attracts the interest of scientists and engineers [36].

There is another example of skin found in nature that has garnered significant attention across a wide range of industrial applications, i.e. shark skin [37]. The skin of fast-swimming sharks protects against the drag that sharks experience when swimming. The tiny scales covering the skin called dermal denticles (generally 0.2 – 0.5 mm small, with fine regularly spaced denticles of 30 – 100 µm), are shaped like small ribs and are oriented in the direction of fluid flow [38]. Riblets inspired by shark skin have been shown to reduce drag by up to 9.9 % [39]. In addition, the spacing between these skin ridges is enough to impede the attachment of microscopic aquatic organisms to the surface. Slower-swimming sharks also have skin protrusions, although they lack the riblet-shaped features that provide drag-reducing benefits [40].

Dean et al. highlighted the fact that different species of shark have different riblet formations, but also the same shark species have different formations on different parts of their bodies (Fig. 2). While certain riblet formations exhibit superior drag reduction properties, there is room for optimising material durability. The manufacturing of riblets, both for research purposes and large-scale applications, has been a major challenge in the field. Due to the associated costs, typical microscale manufacturing techniques would fit better for large-scale applications. Various milling, grinding and rolling techniques, micro-moulding, micro-embossing and 3D printing were used to produce the riblets. These applications fail to mimic nanodetails on the riblets and focus on the form of the surface. To explore the potential of nanoroughness enhancing the overall hydrophobicity of shark skin, it is necessary to conduct atomic force microscope studies on the nanoscale surface characteristics of shark skin [40].

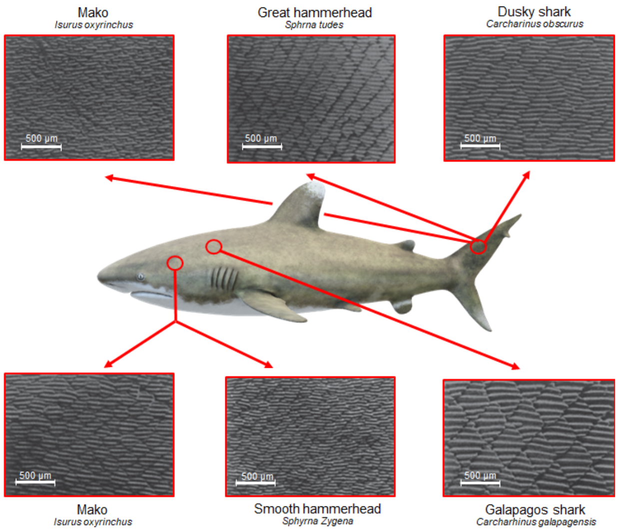

Figure 2. Different species of shark have different riblet formations, but also same shark species have different formations on different parts of their bodies; adapted from Dean and Bhushan [40], used with permission of The Royal Society (U.K.), from Shark-skin surfaces for fluid-drag reduction in turbulent flow: A review, B. Dean, B. Bhushan, 368, 1929, 2010; permission conveyed through Copyright Clearance Center, Inc.

One of the industrial applications of shark skin is swimsuits. The 83 % of the swimmers who won a medal at the Olympic Games in Sydney wore a shark skin suit. Due to the exceptional speed achievable with them, they were subsequently banned. This decision spurred scientific investigations to demonstrate the scientific advantages of the swimsuit. George Lauder, an ichthyologist, led a study that found shark skin does increase speed – in sharks [41]. However, the functionality of the swimsuit relies on many other factors such as non-textile parameters, how the suit ensures a particular posture during swimming, and how tight the swimsuit fits on the swimmer's body, but not on the biomimetic aspect, as the suit does not feature shark skin riblets [41].

Through parametric modelling to query a wide range of different designs, Domel et al. discovered a set of denticle-inspired surface structures that achieve simultaneous drag reduction and lift generation on an aerofoil, resulting in improvements of up to 323 % [42]. Lufthansa Group and BASF embraced this technology, and in 2022 Lufthansa Cargo equipped all Boeing 777 freighters with these structures to improve fuel efficiency and help airlines reach sustainability targets. The presence of the 50 µm riblets reduces aircraft drag by 10 % and fuel consumption by around 1 %. For the entire fleet of ten aircraft, this translates to annual savings of around 11,700 tons of CO_2 emissions, equivalent to worldwide commercial airliner savings of approx. $16.13 billion per year [43].

The skins of other types of fish are also noteworthy subjects due to their tribological properties and their relevance to medical applications for both humans and other species. Researchers in dermatology can gain valuable insights from the biology of fish skin, as it addresses several fundamental questions of great significance to mammalian skin. Fish, being constantly exposed to aqueous environments that harbour a higher concentration of pathogens compared to the aerial environment of mammals, have evolved a complex antimicrobial defence system [44]. The materials in fish skin have a natural anti-inflammatory effect that speeds healing, which can be used in human wound recovery [45].

Pape and Poll observed a correlation between the tribological properties and the occurrence and appearance of the fish flakes. While the mudskipper has soft skin adapted to the periods outside of the water, the fish scales protect the skin but provide higher friction in the case of rubbing contacts. Still, the coefficient of friction (COF) values were between 0.2 – 0.5 [46]. Wu et al. investigated biomimicking lubrication using responsive hydrogels [47]. The slippery mucus produced by fish skin is the cause for its ultra-low COF with many counter-surfaces, which is vital to protect fish against predator attack and allow them to swim faster and remain elusive. The researchers developed responsive hydrogels that mimic this slick skin by responding to external stimuli such as pH and temperature. These hydrogels outperformed fish skin, achieving not only a low COF (in the range of 5×10^{-3}) but also demonstrating tuneable COFs from low to relatively high (higher than 0.1) through sequential regulation of pH and temperature.

While comparing the dermatological properties provides valuable insights into the skin properties of various animal species, it also forms the basis for our understanding of human skin. As part of the animal kingdom, we share fundamental biological processes and evolutionary history with other species. However, the unique characteristics of human skin, including its structure, composition and the diverse range of diseases it can develop, warrant a focused examination. By delving into the intricacies of human dermatology, we can uncover specific factors that contribute to skin health and diseases in our own species. This allows us to explore the interplay between genetics, environmental influences, and the intricate mechanisms underlying skin health and disease in the context of human dermatology.

3. Observations on human skin

Unlike other animals, humankind's evolution has influenced the body to have to withstand more extreme conditions. Social constructs made unnecessary applications to daily routines. Electric and non-electric razors, with shaving and after-shave creams, hair-removal creams and even lasers are frequently used. Humans go to places with temperatures between – 50 to 70 °C, 80 m deep under water, and even in space. No other animals touch electronic devices the entire day and use their fingertips as probes. So, very different test systems, using different materials, are needed to understand human skin's interaction with different environments.

3.1 Mechanical properties of human skin

One of the main challenges in the investigation of the skin is the complex structure of the skin (Fig. 3). The skin has a multi-layered structure, and its mechanical properties vary with the depth of the layers. The thickness of the various skin layers varies significantly, with the epidermis being the thinnest, ranging from 0.05 to 1.5 mm, the dermis ranging from 0.3 to 3 mm, and the subcutaneous tissue being the thickest, ranging from 1 to 2 cm. The *stratum corneum*, the top layer of the epidermis, thickness varies between 10 to 20 µm. Given its complex multi-layered structure, the skin exhibits a wide range of viscoelastic phenomena like most soft tissues, including creep, relaxation, hysteresis [48] and strain rate dependency [49]. In addition to multiple layers, the skin has a dermal matrix with embedded fibres, leading to viscoelastic and anisotropic mechanical behaviour [50]. The dermis, due to its significant thickness compared to that of the *stratum corneum* and viable epidermis, is the main contributor to the tensile mechanical properties of the skin [51]. Other structures in the skin are sebaceous and eccrine glands and blood and lymph vessels. Sebaceous glands produce sebum, which keeps the skin and hair supple and protects the skin against bacteria and fungi. Eccrine glands produce sweat, which regulates body temperature but also significantly affects the skin's tribological behaviour, as we will discuss later in this chapter. The *stratum corneum* is often described as having a brick-and-mortar structure: the dense structure of corneocyte bricks and keratin mortar makes it very difficult for external hazards to attack the body through the skin and for body fluids to leave the body through the skin. A combination of substances like amino acids, salts and lactate, referred to as natural moisturising factors, play an essential role in the hydration of the *stratum corneum* [52]. A healthy *stratum corneum* is essential for the skin's defence mechanism and dehydration function as a whole [53].

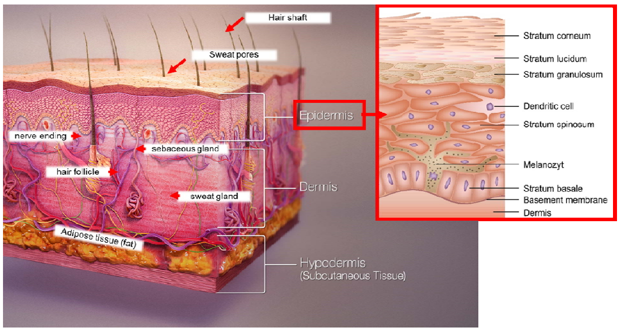

Figure 3. Schematic illustration of skin layers and main functioning parts (adapted from Wikimedia Commons, licensed under CC BY-SA 4.0) with a detailed image of layers of the epidermis (obtained from Alamy Limited, credited as MedicalStocks/Alamy Stock Vector)

The mechanical properties of the *stratum corneum* are fundamental in conditioning the transmission of loads and subsequent deformations of the other underlying skin layers across several length scales [54]. These mechanical aspects are vital for the stimulation of mechanoreceptors that convert mechanical energy into neural signalling (e.g. tactile perception [55]) or are involved in metabolic processes. Any variation in the mechanical properties of the *stratum corneum* is likely to affect the material's mechanical response; also, the subsequent altered external surface topography will eventually have evident and significant consequences for the tribological response of the skin [56].

The skin's characteristics (thickness, strength, elasticity and colour) also depend on various subject-related variables, such as age, gender, body composition, race, stress, season, nutrition and mechanical load, therefore rendering these properties very dynamic, particularly over the life course [57]. Moreover, there is substantial variability according to specific environmental conditions such as temperature and relative humidity, and the skin's properties are dependent on the locations on the body [58]. The skin on the palms and soles contains more eccrine glands per square centimetre than hairy skin. When people are nervous or anxious, the production of sweat is increased, which results in an increase in the coefficient of friction and finally increased grip of the palms and soles [59].

There remains an unresolved question concerning the consistency of skin stiffness measurements across various length scales, which have yielded values ranging from kPa [60], to several MPa [61]. The elastic modulus of human skin *in vivo* has been reported to vary over 4 – 5 orders of magnitude (ranging from 4.4 kPa to 57 MPa) in the literature, depending on factors such as the measurement method, anatomical site, skin hydration level, age, person and theoretical model used [62-65]. Moreover, skin hydration also influences these values, leading to a reduction in the elasticity and stiffness of human skin, typically by one order of magnitude. For dry skin, elastic modulus ranges from 30 kPa to 1,000 MPa, while for wet skin, it ranges from 10 kPa to 100 MPa [66-69]. It should be noted that the elastic modulus of biological soft tissues, particularly skin, lacks significance unless the exact strain level and physiological conditions are specified. In summary, experimental evidence suggests that the *stratum corneum* exhibits stiffness values and elastic moduli (ranging from 10 kPa to 1 GPa) at least two orders of magnitude higher than those of the dermis (ranging from 0.5 kPa to 45 MPa) [57,70-72] and subcutaneous fat tissue (0.12 – 30 kPa) [70,73,74].

3.2 Measuring techniques for the mechanical properties of human skin

Skin testing involves various *in vivo* and *ex vivo* measurement methods, with suction, indentation and extension tests being the most common ones. Suction measurements play a vital role in determining both *in vivo* and *in situ* skin properties [75]. By applying negative pressure, tissue is drawn into the probe opening, and an optical system measures the resulting bulge height. The relationship between pressure and bulge height is directly linked to the probe opening size and loading protocol. These suction measurements are essential for characterising the nonlinear, viscoelastic, and time- and location-dependent behaviour of the skin. Through suction tests, important skin properties such as compliance, elastic recovery, creep and permanent deformation can be quantified. These measurements help assess the influence of factors like fatigue, ageing, sex and body location on the skin's behaviour [76].

The *ex vivo* mechanical properties of the skin can be characterised with extension tests. They allow the investigation of the skin's anisotropic response related to the Langer lines (skin tension lines) distributed across the body [77]. Using a uniaxial or multiaxial loading rig, we can observe skin's time and history-dependent behaviour through monotonic and cyclic creep and relaxation experiments [78]. The mechanical properties of the samples vary based on their derivation and are significantly influenced by storage duration, conditions and temperature. Therefore, it becomes crucial to analyse the relevant application and control these parameters to ensure the validity of the research data. Sample preparation typically involves removing the epidermis and fat to isolate the dermal layer. However, this technique alters the skin tissue's physiological state and results in the loss of the *in vivo* multiaxial pre-tension, causing changes in the unique tensioned configuration of collagen and elastin networks. When studying skin extension, many research studies interpret experimental data using linear elasticity theory. They extract the slope of the linear regime from uniaxial or multiaxial measurements to determine the ultimate tensile strength and elastic modulus of the dermis [61].

The dynamic response of superficial skin can be measured by indentation. In a range of 10 – 60 Hz and at a low indentation depth of 200 ± 3 µm skin stiffness and viscosity are frequency-independent [79]. For determining the skin's mechanical properties at higher resolution atomic force microscopy (AFM) can be used. In earlier studies, the influence of hydration on the mechanical response of the *stratum corneum* and epidermis was quantified using AFM [80]. The measurements involve indentation depths of up to 200 nm, which are three orders of magnitude smaller than the previously described indentation tests. As a result, they capture the mechanical response at a much finer length scale.

Previously, shear tests on individual skin layers were conducted, but due to experimental constraints, they were restricted to the linear regime. However, more recent developments have addressed this limitation. Gerhardt et al. [81] and Lamers et al. [82] introduced an innovative experimental approach to examine the shear response of full-thickness human skin. In their method, they combined large amplitude oscillatory shear tests, applying strains up to 0.1 on a rheometer, with digital image correlation techniques to analyse the cross-sectional area of the skin. This new method allows for a more comprehensive investigation of the skin's shear behaviour. The novel imaging-based method introduced in this study allows them to perform shear tests and to study layer-dependent skin properties using full-thickness skin; hence no need to separate skin layers which is a time-consuming procedure and possibly disrupts skin layers. Using this method, they investigated skin heterogeneity, namely the non-linear viscoelastic response, by determining local displacements. The visualisation of the shear experiment provides real-time optical feedback improving quality assurance and reliability of the results. Moreover, their method can be used to directly measure large strains, i.e. skin mechanics in the non-linear viscoelastic strain regime in which modulus is strain-dependent and the analysis and interpretation of conventional rheometer measurements is complicated [83]. With this modification, one short shear experiment provides raw datasets that can be used to fully characterise the viscoelastic, and local strain and layer-dependent shear properties of full-thickness skin.

Precise prediction of mechanical responses holds significant relevance in a wide range of applications. Examples include plastic surgery, where it aids in modelling artificial skin grafts; skin tissue engineering, enabling better design and development; cosmetics, for improved product formulations; shaving, to enhance razor performance; and research involving trans-epidermal drug delivery, which benefits from a better understanding of skin mechanics [84,85]. However, no constitutive model in literature can describe the complex mechanical response of full-thickness human skin, specifically to shear deformation. The decision to select a certain level of mechanical complexity with a constitutive model is application-dependent. A simplified constitutive skin model often simplifies the contact situation by neglecting parameters such as nonlinearity, viscosity and heterogeneity. On the other hand, for accurate predictions more complex approaches are necessary. Experiments now employ the fusion of full-field deformation analysis, which tracks complex 3D tissue deformations, with local force measurement during *ex vivo* tests of global force-displacement curves under different loading conditions.

Besides the classical physical/mechanical parameters, skin bioengineering parameters have been introduced to characterise the viscoelastic properties of human skin. These parameters describe skin structural aspects rather than pure mechanics, making them somewhat limited in a strictly mechanical context. However, despite this limitation, dermatologists and cosmetic scientists frequently rely on skin bioengineering parameters, such as Cutometer values, in clinical, disease-related and biological interpretations of skin tissue integrity. In the existing literature, weak correlations between skin bioengineering parameters and skin friction coefficients have been reported. Specifically, the tangential stiffness of human skin and the interfacial shear strength in tribo-pair are believed to be crucial factors in determining the friction behaviour of the skin [86,87].

Concerning testing cosmetics on skin samples, animal skin substitutes became less eligible, as from 11 July 2013 trade-in cosmetics tested on animals is prohibited in EU member states under the EU cosmetics regulation. Every year almost 10 million mice, rats, rabbits and dogs are used in laboratories for research and testing. According to the global *in vitro* diagnostics (IVD) market, approximately $76 billion will be spent on product testing by 2023 in the skincare, cosmetics and pharmaceutical companies [88]. A series of standard tests require up to 12,000 animals and can take years to complete, so there is a need for replicated skin models, if possible, consisting of human skin cells, that feature the same properties and functions as normal human skin.

Various chemical and physical considerations must be considered when designing a skin model to produce a biomimetic design, which should mimic the skin's structural characteristics and mechanical strength. Various commercial products have made significant progress toward achieving a native skin alternative. One successful model, the ThinCert® cell culture insert, offers an ideal artificial environment for *in vitro* reconstruction and is thus perfect for cultivating skin cells [89]. The base of the cell culture inserts features a capillary pore membrane which consists of USP (United States Pharmacopeia) Class VI certified polyethylene terephthalate (PET). The membrane enables oxygen to reach the cells from above while they are simultaneously supplied with nutrients from the multi-well plate below. This is important because skin cells need specific nutrients and contact with oxygen to develop the *stratum corneum*. The membrane surface is treated in a way that ensures optimum adhesion and growth for the cultivated cells. The hanging geometry of the ThinCert® cell culture inserts ensures the distance to the well base and the side walls, so it prevents capillary suction between the internal and external well walls. ThinCert® inserts are thus ideal for primary cell cultures, transport, secretion, diffusion studies, migration experiments, cytotoxicity tests, co-cultures and transepithelial electrical resistance (TEER) measurements. A biotech company, Genoskin, developed a method to keep human skin alive for up to a week, long enough to conduct a wide range of pharmaceutical and cosmetic tests [90]. Skin samples are collected from plastic surgery patients and classified as *in vivo*.

Further research perspectives involve the development of a functional bi-layered model that mimics the constituent properties such as viscoelasticity and organisation of the native epidermis and dermis, as well as incorporating dynamic elements to mimic skin's interactions with other organs. The models, therefore, react even more authentically than animal skin to cosmetics in testing.

3.3 Contact mechanics and friction behaviour of human skin

To gain a deeper understanding of the friction behaviour of human skin, researchers have turned their attention to the contact mechanics involved in the interaction between skin and various surfaces. From a contact mechanics point of view, most models trace back to the Hertz theory [91], assuming a pure elastic contact situation without adhesion between the surfaces. However, this can only be used for a first assumption and its accuracy is limited. A friction model for skin that also accounts for adhesion is summarised in Equation (1) [92,93].

$$F_{\mathrm{friction}} \sim C\,(F_{\mathrm{normal}})^{n}. \tag{1}$$

If we combine it with Equation (2)

$$\mu = F_{\mathrm{friction}} / F_{\mathrm{normal}}, \tag{2}$$

we can express the coefficient of friction as:

$$\mu \sim C\,(F_{\mathrm{normal}})^{n-1}. \tag{3}$$

In Equation (3), the properties of the tribological system determine the constant n. The constant in the equations includes an estimation of the real area of contact, which can be calculated based on the roughness of the skin and the topography of the contact material. The estimation is based on parameters such as the elastic modulus and an indicator for the viscoelastic behaviour of the skin. Based on these models, in friction situations primarily influenced by adhesion n has a value of 2/3 [94], and in friction situations with skin deformations primarily right under the surface n is 4/3 [95]. According to Comaish and Bottoms [93], n should be smaller than 1, although El-Shimi [96] is more specific for the n value (between 0.66 and 1). Other values for n reported in the literature range from 0.73 to 1.07 [97-99].

Estimating the actual contact area can be calculated based on the skin's and the contact material's roughness, the elastic modulus and the indicator for the viscoelastic behaviour of the skin. Determining these parameters is complex and time-consuming. For example, the elastic modulus of the skin has been obtained through *in vitro* techniques or measuring techniques that are uncomfortable for the subjects. Furthermore, some studies conclude that "the" elastic modulus for the skin does not exist. This modulus depends on the position of the limb, the muscle tension and many more variables [100].

In terms of measuring skin friction, several methods are available. Initially, it was measured with a reciprocating linear movement [101]. Later, a handheld tribometer was designed [102] as a rotating indenter to measure skin friction. The axis of rotation of the annular contact material was perpendicular to the skin's surface. The vital part of this application was that the rotation allows for continuous movement with larger displacements without being affected by the anisotropic properties of the skin. Another application used a rotating contact material with the rotation axis parallel to the skin's surface [103], allowing for continuous movements. Dinc et al. employed a force transducer to measure the friction between the tip of a finger sliding over a flat sample of material. The force transducer measures both the applied load and the resulting shear load. The input conditions, such as the applied load and the sliding velocity in these setups, depend strongly on the subject and are therefore typically not very accurately controlled or constant during the test, but how close this system is to real-world application makes it very useful and used even in psychophysics investigations [104].

The results in the literature for skin friction measurements were obtained under vast variations of test parameters. The relative motion of the counterparts was changed, as well as the normal load (0.01 – 70 N) and velocity (0.13 mm/s – 3.5 m/s) over a wide range. It is not surprising that the reported values for the kinematic coefficient of friction fluctuate between 0.071 [67] to 5.0 [96], and the values for the static coefficient of friction fluctuate between 0.11 [105] to 3.4 [97]. The results have significant differences according to loading conditions, lubrication and material couples. Bobjer et al. tested using fingers against polycarbonate (PC) (e.g. typical for bottles or mobile phone housings) under different loads and observed a strong load dependence when measuring skin friction. They observed a COF value of 2.22 for the test under 1 N load and 0.85 under 20 N loading [106]. Cua et al. used polytetrafluorethylene (PTFE) against the abdomen and forehead skin and observed 0.12 and 0.34, respectively showing how the location also strongly affects the tribological properties [107]. El-Shimi et al. used forearm skin against polished steel lubricated with silicone oil and without lubrication. COF value dropped from 0.31 to 0.07 due to the application of silicone oil [96]. They also applied the same test parameters on polished and rough stainless steel without lubrication. The rough sample represented a COF of 0.16, whereas the polished surface represented a COF of 0.63. This test hints at the role of surface roughness in skin contact. Gee et al. used different counter-bodies against the finger under the normal load of 2 – 20 N. PC against the finger had a COF value of 2.7, glass had 1.2 and paper 0.6 [108]. This shows how the COF is not only a material property but the property of the entire tribological system, and specifically how that material pairing influences friction. Koudine et al. showed that the loading condition is the dominant parameter for the forearm skin and glass tribo-pair, where the results varied between 0.6 – 3.6 [97].

Additionally, several substances present on the skin can substantially affect skin friction. Such substances reported in the literature include oil, petrolatum, glycerine, isopropyl alcohol, ether, talcum powder and lard [67,95,96,98,99,109-113]. Another example of variation in test methods affecting the friction results is the preparation of the skin. Pre-testing treatments include removing hair [99,101,114], cleaning the skin with water, detergents or alcohol [92,93,95,99,108,110,114-120] and finally, no pre-testing treatment [86,107, 109,113,121-123]. Cleaning the skin before measurements would enhance the repeatability, but it influences the skin's state of hydration; also, the skin may host some contaminants that influence the measured skin friction.

Depending on the intricate interplay of contact conditions, the presence of fluids or lubricants (such as sweat, water and sebum), and film thicknesses relative to the surface roughness of the contacting materials, diverse lubrication effects come into play, encompassing boundary lubrication, mixed lubrication and elastohydrodynamic lubrication (EHL). When a product interfaces with the skin through sliding motion, the lateral friction force governing the skin-product interaction is governed by the intricate interplay of adhesion and deformation phenomena, influenced by a multitude of intricate factors. The adhesion component emerges from the interfacial shear resistance arising due to the formation and subsequent breaking of interatomic junctions, primarily driven by short-range forces such as Van der Waals interactions within the contact zone. The existence of a naturally produced continuous thin lipid film on the outer skin surface assumes paramount importance in modulating adhesion forces while concurrently altering the area of contact and stress distribution [124]. Conversely, the deformation friction component arises from viscoelastic hysteresis. Depending on the sliding speed of the product, the strain energy might only exhibit partial recovery, leading to an additional loss in friction.

3.4 The main components of friction: Adhesion and deformation

Adhesion stands prominently as the principal contributor to the frictional characteristics of human skin, with deformation mechanisms deemed to play a secondary role [94,95]. Extensive scholarly literature has employed various theoretical models to elucidate the mechanical contact behaviour and friction mechanisms inherent to the skin [67,94,97]. Consideration of skin surface roughness's impact on friction reveals typical values of *Ra* and *Rz* falling within the range of 10 – 30 μm and 30 – 140 μm, respectively [125], with such values reportedly increasing with age [62,126-129]. Although a handful of studies have offered insights into the influence of skin topography on friction [87,130], the results remain somewhat contradictory. For instance, a study on female patients' volar forearm friction coefficient did not exhibit a significant correlation with the surface roughness *Ra* of the skin. Nevertheless, the same study observed that surface roughness *Ra* significantly improved the predictability of the COF [87]. Additionally, Nakajima and Narasaka reported a correlation between the density of primary lines and skin friction, indicating that the lower the density of primary lines, the higher the friction. However, an additional parameter potentially assumes vital significance here, as the density of lines corresponds to the skin's elastic modulus, which itself changes with age [130].

Studies have provided additional evidence that the amplitude of the probe surface roughness assumes a commanding role in determining friction behaviour [131]. Particularly, in the context of highly rough surfaces, reaching up to *Rq* = 90 μm, a direct correlation has been observed, with the COF escalating alongside the increasing surface roughness [131,132]. Tomlinson et al. observed a constant plateau COF of ≈ 0.8 and ≈ 0.65 for roughness values *Rq* > 25 μm against steel and brass. On the other hand, in the case of hydrated skin, a Gaussian-like relationship between roughness (*Rq* = 0.004 – 2 μm) and friction coefficients varying between 0.9 – 1.7, with maximum values at intermediate roughness (*Rq* = 0.006 – 0.4 μm) was reported [133]. The elevated friction observed within the intermediate roughness regime may be attributed to the intricate interplay of interacting adhesion and deformation components, especially in the context of the hydrated skin condition. It must be pointed out that in skin tribology the skewness and kurtosis parameters of the roughness, together with the surface texture, are essential factors [132,133]. This corroborates the findings of Derler et al. [131], whose investigations revealed a positive linear correlation between the slope of surface asperity peaks and friction coefficients during the sliding of plantar skin on various wet floor coverings. Furthermore, in a recent study focusing on friction between the finger and ridged surfaces, Tomlinson et al. [134] discovered that at low ridge height and width, adhesion played a dominant role in governing friction behaviour. However, as the ridge heights surpassed 42.5 μm, interlocking effects emerged, accounting for over 50 % of the total friction. Additionally, at a ridge height of 250 μm, hysteresis also became a contributing factor, albeit at a level below 10 %.

The observed phenomenon of skin friction rising in response to increasing material or probe roughness aligns with Moore's theory for elastomers [135]. This theory posits that the friction coefficient of compliant materials on rough surfaces escalates proportionally with the amplitude of surface roughness. Notably, the insightful work by Hendriks and Franklin [115] suggests that Moore's theory can indeed be extrapolated to the context of the skin interacting with rough surfaces (Ra > 3 – 10 µm) particularly in scenarios where interactions between surface asperities and skin ridges are prevalent, such as on the fingers, palm or feet.

The skin's surface is typically safeguarded by an acidic hydrolipid film, maintaining a pH range of 4 to 6. This protective film plays pivotal roles, such as governing the skin flora, forestalling colonisation by pathogenic organisms and serving as a potent defence mechanism against invading microorganisms [125]. Comprising a blend of water from sweat and sebum secreted by sebaceous glands, the hydrolipid film envelops the *stratum corneum*. In the domain of skin tribology, the role and significance of sebum lipids and their interactions with water have sparked debates and controversies [107,136-139]. A study conducted by Pailler-Mattei et al. [139] illuminated how the skin surface lipid film influences skin adhesion properties through capillary phenomena. Likewise, Gupta et al. [137] presented noteworthy findings, illustrating a moderate positive linear correlation between sebum levels and the forearm skin's friction when measured against steel.

Conversely, when exploring the forehead, a discovery of weak correlations between the skin surface lipid content and friction emerged [107]. This finding further emphasises the location-specific nature of the skin's tribological behaviour. Interestingly, in the same study, no significant correlation was evident between the parameters in nine other anatomical skin regions, indicating that surface lipids hold a restricted role in governing skin friction. Consequently, a deeper investigation and more fundamental studies are imperative to comprehensively elucidate the intricate influence of sebum lipids on the frictional properties of the skin.

Skin friction coefficients exhibit variations by factors ranging from 1.5 to 7 between wet and dry conditions, as documented in numerous studies [87,93-96,103,140-145]. In regions characterised by high humidity or under wet conditions, the skin becomes thoroughly hydrated, and friction values surge to be 2 – 4 times higher than those observed during dry sliding conditions [115,116,143,146,147]. This substantial escalation in skin friction in moist environments may be ascribed to the plasticizing influence of water, which results in the smoothing of skin roughness asperities, consequently leading to a more substantial real contact area. Depending on the contact conditions and the relative fluid film thickness concerning the skin's surface roughness and the material it interacts with, a combination of mixed lubrication or boundary lubrication phenomena might also come into play [148]. Nonetheless, investigations revealed that the contribution solely due to elastohydrodynamic lubrication (EHL) is inadequate in fully explaining the friction behaviour of wet skin sliding against smooth glass. This discrepancy is attributed to the skin's surface roughness significantly surpassing the minimum film thickness required for EHL, leading to the supposition that water films between the skin and smooth glass are locally formed, while dry contact zones coexist in other regions [147].

As mentioned before, adhesion is the dominating friction mechanism on human skin. According to the adhesion model of friction [149], the friction force is given by $F = \tau A_r$, where τ is the interfacial shear strength and A_r is the real area of contact. For the interfacial shear strength of skin, Adams et al. [95] adopted the model $\tau = \tau_0 + \alpha p_r$ for shear properties of thin organic films [150], where τ_0 denotes the intrinsic shear strength, α a pressure coefficient and $p_r = N/A_r$ the real contact pressure with N the normal load. The friction coefficient can then be written as:

$$\mu(p_r) = \frac{\tau A_r}{N} = \frac{\tau_0}{p_r} + \alpha. \quad (4)$$

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

$$\mu(p) = \frac{A_r}{A}\frac{\tau_0}{p} + \alpha. \quad (5)$$

When the real contact area aligns perfectly with the apparent contact area, the disparity between the apparent and actual contact pressure becomes negligible. Such a circumstance is postulated to occur when a soft material is in a state of complete conformational contact with the counter-surface. This particular scenario appears to be realistic in the context of hydrated skin, which softens and adheres closely to the counter-surface, facilitated by the potential presence of minute quantities of interfacial water that function as adhesive liquid bridges [151].

The frictional response of dry skin stands in stark contrast to that of moist and wet skin, demonstrating relatively low friction coefficients. Multiple studies have shown that the friction coefficients of dry skin remain largely unaffected by variations in the applied normal load. This observation finds its rationale in the Greenwood and Williamson model [152], wherein the real contact area of rough solid surfaces is hypothesised to exhibit a linear increase with changes in the normal load. For a friction coefficient independent of the apparent contact pressure, $(A\mathrm{r}/A)\,(1/p) = A\mathrm{r}/\mathrm{N}$ = constant.

The frictional interactions involving the skin and underlying soft tissue during contact entail contributions to the friction coefficient through viscoelastic hysteresis or ploughing mechanisms [153]. It is anticipated that the contribution arising from hysteresis would increase proportionally with the applied normal load and contact pressure, whereas ploughing would lead to a load-independent effect on the friction coefficient [138,153]. Johnson et al. [154] and Adams et al. [95] investigated skin friction at the volar forearm, interacting with spherical probes, employing the approach proposed by Greenwood and Tabor [155]. They discerned that the contribution of hysteresis to the friction coefficient ranged at approximately 0.05. Notably, similar findings in the range of 0.04 to 0.06 were reported by Kwiatkowska et al. [124]. However, measurements on the forearm and cheek, using rotating probes, did not regard friction mechanisms associated with skin deformation as particularly relevant [115]. On the contrary, a recent study indicated that forces stemming from microscale deformations of the skin could significantly contribute to the overall friction experienced by the human finger pad [133]. Investigations concerning the friction of human skin against glass revealed contributions to the friction coefficient due to viscoelastic skin deformations, hovering below 0.2 [147]. Moreover, when studying foot skin sliding on wet floor coverings, contributions due to skin deformations were found to reach up to 0.4 [131], particularly on notably rough surfaces.

The confluence of hysteresis effects and the ploughing action of the skin by the asperities present on rough surfaces is likely responsible for the emergence of pronounced deformation components. Notably, in the context of friction between the finger and small, triangular ridged surfaces, Tomlinson et al. [134] documented substantial interlocking effects and prominent contributions of hysteresis to the overall friction, particularly when the ridge heights exceeded 42.5 and 250 µm, respectively. Moreover, it was posited that deformation also plays a pivotal role in the friction between human skin and textiles [156]. Sanders et al. [157] embarked on an investigation of the frictional interactions involving soft prosthetic interface materials and a sock fabric against the skin at the tibia (shin). The resulting measurements of friction coefficients for both material types exhibited an increasing trend with the applied normal load, hinting at the involvement of deformation in the observed friction. Likewise, in a study examining the skin of the volar forearm in both young and elderly subjects [86] it was observed that skin deformation mechanisms bear relevance to the frictional behaviour exhibited when the skin interacts with textiles.

Thoroughly determining the adhesion component of friction necessitates the measurement of the real contact area. However, the application of modern tools such as microtribometers and atomic force microscopy is presently constrained in connection with *in vivo* measurements of skin. Furthermore, optical methods used to assess the microscopic contact area between finger pads and smooth glass are unsuitable for rough surfaces and non-transparent materials.

Another aspect of inquiry revolves around whether friction's adhesion and deformation components remain as two non-interacting terms, as postulated in the two-term model [138]. The literature also underscores the substantial impact of skin hydration and interfacial water on the skin friction coefficient. Nevertheless, a more comprehensive and systematic investigation is warranted to discern the intricate transition from dry to moist skin. The influence of skin hydration and softening on the skin's surface and its micromechanical properties, as well as the accompanying alterations in the microscopic contact geometry, remain widely unknown. Additionally, the role of small quantities of water at the interface between the skin and the counter-surface, as well as the contribution of other substances like skin lipids, remains unclear.

Theoretical frameworks devised for solids, exemplified by the models of Greenwood and

Williamson [152] and Archard [158], have been harnessed to qualitatively elucidate specific facets of the contact and friction behaviour of dry skin [95,115,159]. However, the applicability of such models to the intricate surface topography of human skin remains a subject that requires further elucidation. Furthermore, an intriguing open question arises concerning the extent to which theoretical concepts governing the contact behaviour of soft materials [160-162] are applicable to hydrated 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 reduced modulus E^* according to the following equations [163,164]:

$$a=\left(\frac{3RN}{4E^*}\right)^{1/3},\ d=\frac{a^2}{R}=\left(\frac{9N^2}{16RE^{*2}}\right)^{1/3},$$

$$E^*=\left(\frac{1-v_1^2}{E_1}+\frac{1-v_2^2}{E_2}\right)^{-1}. \tag{6}$$

The reduced modulus E^* is given by the elastic moduli $E_{1,2}$ and the Poisson's ratios $v_{1,2}$ of the two contacting materials. If one material is considerably softer (skin) than the other (spherical probe), E^* can be approximated by the elastic properties of the soft material.

$$E^*\approx\frac{E_{\text{skin}}}{1-v_{\text{skin}}^2}. \tag{7}$$

Adams et al. [95] employed an elastic modulus of 40 kPa, as deduced from loading data, combined with an assumed Poisson's ratio of 0.49. Similar outcomes regarding the elastic modulus were also reported in other investigations concerning forearm skin [124] and the skin of fingertips [165]. As posited by Hendriks and Franklin [115], the material constituting the probe brought into contact with the skin holds less significance compared to its surface roughness. Nonetheless, intriguingly, none of the studies employing spherical probes explicitly specified the surface roughness. While the most frequently used probe materials were steel and glass, other materials like ruby, PE, PP and PTFE probes were also utilised. Notably, measurements involving steel spheres yielded the highest friction coefficients. Moreover, in various friction experiments, wherein alternative probes were employed alongside linear sliding movements [114,130,137,140], the estimated contact pressures were consistently maintained at relatively low levels.

The friction coefficient remains unaffected by the apparent contact area [165] and the sliding velocity [166]. However, it is essential to acknowledge that these laws are of a phenomenological nature, primarily applied at the macroscopic scale. When adhesion forces within the system fall within the range of the applied load, their influence effectively assumes that of an additional loading force. Because of this additional force, friction forces extend to negative applied loads according to Equation (8) proposed by Derjaguin [167,168]:

$$F_{\text{friction}}(F_{\text{load}})=\mu F_{\text{load}}+F_{\text{friction}}(0), \tag{8}$$

where $F_{\text{friction}}(0)$ corresponds to the friction force at zero applied load. This formulation is a useful simplification and allows the friction coefficient and adhesion to be obtained independently of each other, where the adhesion or "contact adhesion" [169] is obtained from the intercept of the friction-load relationship with the load axis (Fig. 4).

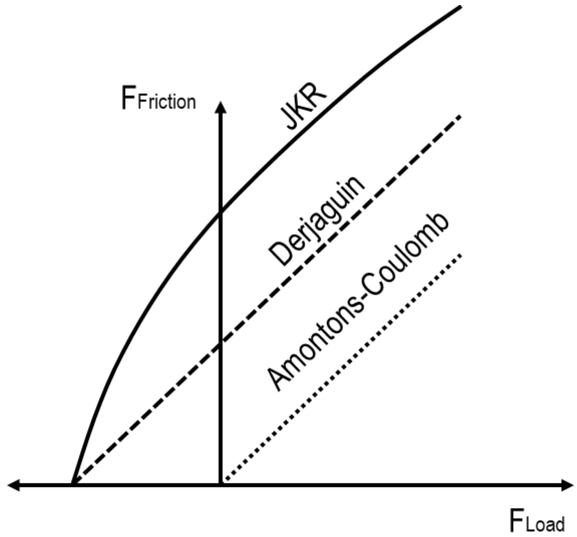

Figure 4. Effect of the applied load on the friction force according to three different approximations: the Amontons-Coulomb and Derjaguin friction laws, as well as the Johnson-Kendall-Roberts (JKR) theory

This simple model claims that the friction force is not proportional to the load but to the real area of contact A_r [170] according to:

$$F_{\text{friction}}(F_{\text{load}})=S_c A, \tag{9}$$

where S_c is the critical shear contact stress at the contacting. This friction-force relationship can be generally used and has been proven in many experimental systems [171-174]. Therefore, a good understanding is required of how surface interactions, such as Van der Waals and capillary forces, affect friction and adhesion at the molecular and atomic scale [169,175,176].

3.5 The tribology is in the details: Atomic force microscopy on skin

The scientific community assumes that the secret to a deeper understanding of skin's macroscopic friction behaviour may reveal itself through studies examining the behaviour of human skin on a microscopic scale [177]. Around 1942, Bowden and Tabor [178], brought considerable insights to this subject, revealing that the actual contact area between two solids constitutes only a fraction of the apparent contact area, primarily owing to surface roughness. Consequently, as the normal load is applied, the real contact area augments due to the deformation of asperities. On the nanometre and micrometre scales, all surfaces are inherently rough, making contact only at discrete microscopic points referred to as asperities. Therefore, delving into the interactions between these asperities at the molecular and atomic levels holds the potential to offer a refined comprehension of contacts on the macroscopic scale. Considering the aforementioned observation, it would seem logical to focus on one of the most sophisticated techniques available for micron- and submicron-level force analysis. Atomic force microscopy (AFM) is a powerful tool to investigate molecular interactions at biointerfaces, as well as their mechanical properties, with nanometric spatial resolution and 1 to 10 pN force resolution [179,180]. AFM, originally designed to investigate topography by discerning height variations on the sample surface, has yielded pertinent insights from various studies. Notably, these investigations indicate that scar tissue tends to exhibit greater stiffness than healthy skin [110]. Moreover, it has been observed that the elastic modulus of the *stratum corneum* roughly doubles when compared to that of the epidermis [114]. Specifically, the latter study reported stiffness values ranging from 1 to 2 MPa, while values reported for "skin" range between 5 to 10 kPa [181-183]. These indentation experiments thus compellingly showcase the influence of length scale on the mechanical properties of skin.

The colloidal probe technique developed by Ducker et al. [184,185] and Butt [186] is based on the exchange of the AFM cantilever tip by a colloidal particle (1 – 20 μm in diameter), as shown in Figure 5.

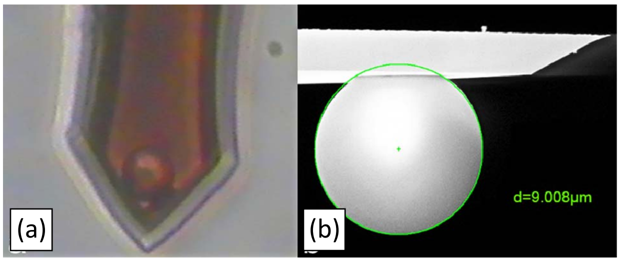

Figure 5. Figure 5 Colloidal probe produced without glue for stable adhesion forces: (a) image of the probe on cantilever with the microscope attached to the AFM and (b) scanning electron microscopy (SEM) image of the probe with geometrical detail; reprinted from Tomala et al. [187], copyrighted by Springer Nature and reproduced with permission from SNCSC

One of its advantageous aspects lies in its flexibility to enable force measurements with a probe crafted from virtually any material, provided the probe possesses a well-defined shape and is nearly incompressible. In these measurements, the magnitude of the acquired force is proportionate to the size of the probe. Nevertheless, when comparing forces obtained with distinct probes, straightforward comparisons prove elusive, necessitating the application of the Derjaguin approximation to normalise the results [167]. This approximation relates the normal force to the energy per unit area (W) between two flat surfaces, according to:

$$\frac{F(D)}{2\pi R_{\mathrm{eff}}} = W(D), \tag{10}$$

where R_{eff} is the effective radius that depends on the interacting surfaces and D is the surface-surface distance. When a rigid sphere is sliding on a deformable surface, it should be noted that the energy dissipation is like that of a rolling sphere. The frictional force in such contact can be expressed by derivation from Greenwood and Tabor [155] as:

$$F_{\mathrm{def}} = \beta \left(\frac{9}{128 R_{\mathrm{eff}}} \right)^{2/3} \left(\frac{1-\nu^2}{E} \right)^{1/3} W^{4/3}. \tag{11}$$

In Equation (11), F_{def} is the frictional force due to the deformation component and β is the viscoelastic loss fraction. In the context of a colloidal probe interacting with a flat surface, the probe's spherical shape streamlines the computation of the effective radius, which can be reasonably approximated as the radius of the colloidal probe. In the realm of force and friction measurements, the precise determination of the normal and torsional spring constants is of utmost importance, as these constants translate the cantilever's bending and twisting motions into corresponding forces. Over the past two decades, numerous solutions have been proposed, spanning theoretical, experimental or hybrid approaches. Among these, one technique has garnered widespread acceptance due to its combination of accuracy and simplicity. This method, pioneered by Sader et al. [188], derives from observing the effects of the surrounding fluid on the cantilever's vibration frequency response. Specifically, the cantilever is allowed to vibrate in response to thermal motion while submerged in a fluid, typically air. The normal resonance frequency (f_z) and the normal quality factor (Q_z) are obtained by fitting a simple harmonic oscillator function to the normal resonance peak obtained from the thermal power spectra of the cantilever, and afterwards, they are combined with the measured length (L) and width (w) of the cantilever, as well as, the density (ρ) of the fluid, to determine the normal spring constant k_z, where $\Gamma_i^z(Re_z)$ is the imaginary component of the hydrodynamic function for normal vibrations and Re is the Reynolds number [189,190].

$$k_z = 0.1906 \rho w^4 L Q_z (2\pi f_z)^2 \Gamma_i^z(Re_z), \quad Re_z = \frac{\rho b^2 2\pi f_z}{4\eta}. \tag{12}$$

The determination of the torsional spring constant k_Φ is analogous to the calculation of k_z in Equation (12), but in this case, the torsional resonance frequency (f_Φ) and the torsional quality factor (Q_Φ) are obtained from the torsional resonance peak. Therefore, k_Φ is calculated using:

$$k_\Phi = 0.1592 \rho w^4 L Q_\Phi (2\pi f_\Phi)^2 \Gamma_i^\Phi(Re_\Phi), \quad Re_\Phi = \frac{\rho b^2 2\pi f_\Phi}{4\eta}, \tag{13}$$

where $\Gamma_i\Phi(Re_\Phi)$ is the imaginary component of the hydrodynamic function for torsional vibrations [190]. There is a limitation in the determination of the torsional resonance frequency from the torsional thermal power spectra because of its lower resolution, and for stiffer cantilevers this resonance is difficult to measure.

The mechanical attributes of the *stratum corneum* assume paramount importance in facilitating its distinctive functions as the outer protective layer, encompassing roles such as skin barrier and photoprotection. An intriguing area of inquiry centres around biointeractions, examining factors like the extent of deflection occurring when human hair meets the skin. Nonetheless, data pertinent to this remain limited [191-193]. In an endeavour to deepen our comprehension of the *stratum corneum's* mechanical properties, surface indentation and PeakForce® QNM measurements were conducted [194].

The reduced modulus [195] was derived by fitting the contact mechanical theory of Derjaguin, Muller and Toporov (DMT) to the force curve obtained at each pixel. The resultant mean reduced modulus amounted to 0.51 GPa. Moreover, for purposes of comparison, the values of the reduced modulus were converted into elastic modulus (E_{SC}) by applying the equation below, duly omitting the contribution of silicon due to its substantially higher relative stiffness.

$$\frac{1}{E^*} = \frac{1-v_{SC}^2}{E_{SC}} + \frac{1-v_S^2}{E_S}, \quad \frac{1}{E^*} = \frac{1-v_{SC}^2}{E_{SC}}, \tag{14}$$

where the subscript S corresponds to silicone, SC to the *stratum corneum*, and v to Poisson's ratio (v_{SC} = 0.48). Therefore, the reduced modulus of 0.51 GPa was transformed into a value of 0.39 GPa, which is consistent with the relatively high stiffness of the SC reported in the literature [193,196,197].

For example, in the design of shaving applications, it is crucial to describe in detail the behaviour of the top layers of the skin as well as the sebum distribution. Therefore, Indrieri et al. used AFM [198] and a spherical probe that was produced specifically for the AFM measurements. A novel approach for the production and characterisation of epoxy- and adhesive-free colloidal probes was introduced, which was important to avoid contamination of the skin samples. Borosilicate glass microspheres were attached to commercial AFM cantilevers, exploiting the capillary adhesion force due to the formation of a water meniscus. Then, thermal annealing of the sphere-cantilever system at a temperature slightly below the softening point of borosilicate glass was carried out. Moreover, Indrieri et al. presented a statistical characterisation protocol of the probe dimensions and roughness based on AFM inverse imaging of colloidal probes on spiked gratings [199]. In a "point-and-shoot" capture mode of the AFM, significant differences were observed between the lipid-covered and uncovered areas (see Fig. 6) [187]. In the area that was assumed to be covered with lipids, the force curve captured by the AFM reaches a plateau that looks as if the force exerted by the probe was damped by a viscous material.

This is assumed to be the first sign of phospholipids on the *stratum corneum* epidermis.

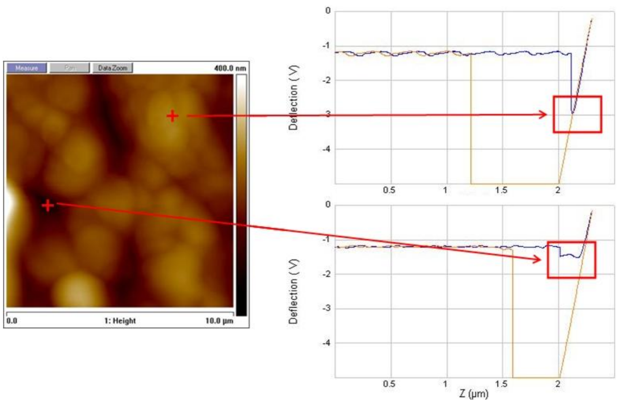

Figure 6. Observation of the plateau on the images acquired by the AFM using a colloidal probe in the darker zone of the image, assuming the presence of the sebum; reprinted from Tomala et al. [187], copyrighted by Springer Nature and reproduced with permission from SNCSC

Podestà et al. [200] delved into the intricacies of topographic correction and pondered the prospect of employing a model-independent approach, thereby obtaining friction versus load characteristics of the investigated system without resorting to postulating any contact-friction model. They adeptly addressed the topographic correction conundrum pertaining to adhesive multiasperity contact, a frequent occurrence in numerous experimental setups. Their calculations revealed a coefficient of friction values, hovering around 0.025 ± 0.002, wherein the relatively modest coefficient is attributed to the lubricative properties of the sebum. Subsequent investigations focusing on a specific area designated for friction measurements, aided by a comprehensive topography and adhesion map, illuminated that even on the micrometre scale, human skin showcases significantly diverse phases [187].

4. Conclusion

In conclusion, the study of dermatology and tribology in nature offers valuable insights and inspiration for various scientific and engineering fields. Observations from nature, including examples from snakes, fish, plants and sharks, have provided valuable knowledge about optimised shape, performance and friction characteristics. These insights have been applied in soft robotics, medical research, tribology and aerospace technology, leading to innovative solutions and improved functionality.

Human skin, as a complex and versatile organ, presents its own set of challenges in understanding its tribological properties. Factors such as skin structure, hydration, age and environmental conditions influence its behaviour. To overcome limitations in studying human skin directly, biomimetic skin models and *ex vivo* tests have been developed. These approaches have contributed to understanding skin compliance, stiffness and shear response.

Contact mechanics considerations are crucial for studying skin friction. The coefficient of friction is influenced by factors such as adhesion, deformation, lubrication and surface roughness. Skin roughness and material topography make the estimation of the real contact area complex. Adhesion is a significant contributor to skin friction, while deformation mechanisms play a minor role. The interplay between adhesion and deformation components and the transition from dry to moist skin require further investigation.

Various measurement techniques, including reciprocating linear movement, rotating contact materials, force transducers, atomic force microscopy and colloidal probe technique, have been employed to study skin friction at various scales. These techniques have provided valuable insights into the mechanical properties and molecular interactions involved in skin tribology.

Overall, the synergy between dermatology and tribology in nature has the potential to drive advancements in various scientific and engineering disciplines. By understanding and harnessing the unique properties of natural systems, researchers can develop innovative solutions for improved performance, efficiency and functionality in areas such as soft robotics, medical devices and biomaterials. Further research and exploration in this interdisciplinary field will continue to deepen our understanding and lead to exciting advancements in the future. The emergence of artificial intelligence (AI) is one of the examples of these advancements. The use of AI is becoming common in the diagnosis of skin cancer, psoriasis and dermatitis. Sensors and algorithms used in these applications could also be beneficial for tribological research. Enhancements in skin tissue equivalents for accuracy will play a vital role in the future, which will allow testing methods for consumer products and skin models, and also aid in several research efforts to provide treatments for different diseases. The confluence of shared applications observed between tribology and dermatology in this scholarly work invites contemplation regarding the appropriateness of the neologism "dermatribology", suggesting that the prospect of its usage is not premature.

Acknowledgements

The authors gratefully acknowledge funds for parts of this work from the Austrian COMET-Program (project XTribology, no. 849109 and project K2 InTribology1, no. 872176) via the Austrian Research Promotion Agency (FFG) and the Province of Lower Austria, and European Commission for supporting part of this work through their WEMESURF Marie Curie Research Training Network.

References

[1] H.A. Abdel-Aal, M. El Mansori, S. Mezghani, Multi-scale investigation of surface topography of ball python (*Python regius*) shed skin in comparison to human skin, Tribology Letters, Vol. 37, No. 3, 2010, pp. 517-527, DOI: 10.1007/s11249-009-9547-y

[2] D. Bikle, S. Christakos, New aspects of vitamin D metabolism and action – addressing the skin as source and target, Nature Reviews Endocrinology, Vol. 16, No. 4, 2020, pp. 234-252, DOI: 10.1038/s41574-019-0312-5

[3] L.M. Biga, S. Dawson, A. Harwell, R. Hopkins, J. Kaufmann, M. LeMaster, P. Matern, K. Morrison-Graham, D. Quick, J. Runyeon, The integumentary system, in Anatomy & Physiology, Oregon State University, Corvallis, 2019, pp. 213-264.

[4] W. Barthlott, C. Neinhuis, Purity of the sacred lotus, or escape from contamination in biological surfaces, Planta, Vol. 202, No. 1, 1997, pp. 1-8, DOI: 10.1007/s004250050096

[5] S.M. Lößlein, F. Mücklich, P.G. Grützmacher, Topography versus chemistry – How can we control surface wetting?, Journal of Colloid and Interface Science, Vol. 609, 2022, pp. 645-656, DOI: 10.1016/j.jcis.2021.11.071

[6] B. Bhushan, Y.C. Jung, M. Nosonovsky, Lotus effect: Surfaces with roughness-induced superhydrophobicity, self-cleaning, and low adhesion, in B. Bhushan (Ed.), Springer Handbook of Nanotechnology, Springer, Berlin, 2010, pp. 1437-1524, DOI: 10.1007/978-3-642-02525-9_42

[7] H. Fan, P. Chen, R. Qi, J. Zhai, J. Wang, L. Chen, L. Chen, Q. Sun, Y. Song, D. Han, L. Jiang, Greatly improved blood compatibility by microscopic multiscale design of surface architectures, Vol. 5, No. 19, 2009, pp. 2144-2148, DOI: 10.1002/smll.200900345

[8] L. Chen, D. Han, L. Jiang, On improving blood compatibility: From bioinspired to synthetic design and fabrication of biointerfacial topography at micro/nano scales, Colloids and Surfaces B: Biointerfaces, Vol. 85, No. 1, 2011, pp. 2-7, DOI: 10.1016/j.colsurfb.2010.10.034

[9] R. Liu, Y. Qin, H. Wang, Y. Zhao, Z. Hu, S. Wang, The *in vivo* blood compatibility of bio-inspired small diameter vascular graft: Effect of submicron longitudinally aligned topography, BMC Cardiovascular Disorders, Vol. 13, 2013, Paper 79, DOI: 10.1186/1471-2261-13-79

[10] A. Bouchard, This lizard can drink water from sand through its feet & back, available at: https://www.labroots.com/trending/plants-and-animals/4626/lizard-drink-water-sand-feet, accessed: 01.08.2023.

[11] P. Comanns, P.C. Withers, F.J. Esser, W. Baumgartner, Cutaneous water collection by a moisture-harvesting lizard, the thorny devil (*Moloch horridus*), Journal of Experimental Biology, Vol. 219, No. 21, 2016, pp. 3473-3479, DOI: 10.1242/jeb.148791

[12] P.G. Grützmacher, A. Rosenkranz, A. Szurdak, C. Gachot, G. Hirt, F. Mücklich, Lubricant migration on stainless steel induced by bio-inspired multi-scale surface patterns, Materials & Design, Vol. 150, 2018, pp. 55-63, DOI: 10.1016/j.matdes.2018.04.035

[13] P. Comanns, G. Buchberger, A. Buchsbaum, R. Baumgartner, A. Kogler, S. Bauer, W. Baumgartner, Directional, passive liquid transport: The Texas horned lizard as a model for a biomimetic 'liquid diode', Journal of The Royal Society Interface, Vol. 12, No. 109, 2015, Paper 20150415, DOI: 10.1098/rsif.2015.0415

[14] C.G. Scanes, Animal attributes exploited by humans (nonfood uses of animals), in C.G. Scanes, S.R. Toukhsati (Eds.), Animals and Human Society, Elsevier, Amsterdam, 2018, pp. 13-40, DOI: 10.1016/B978-0-12-805247-1.00002-2

[15] H.A. Abdel-Aal, M. El Mansori, Characterization of the frictional response of squamata shed skin in comparison to human skin, available at: https://arxiv.org/ftp/arxiv/papers/1008/1008.1367.pdf, accessed: 01.08.2023.

[16] F. Lamping, S.N. Gorb, K.M. de Payrebrune, Frictional properties of a novel artificial snakeskin for soft robotics, Biotribology, Vol. 30, 2022, Paper 100210, DOI: 10.1016/j.biotri.2022.100210

[17] H. Marvi, J.P. Cook, J.L. Streator, D.L. Hu, Snakes move their scales to increase friction, Biotribology, Vol. 5, 2016, pp. 52-60, DOI: 10.1016/j.biotri.2015.11.001

[18] J.C. Sánchez-López, C.F. Schaber, S.N. Gorb, Long-term low friction maintenance and wear

reduction on the ventral scales in snakes, Materials Letters, Vol. 285, 2021, Paper 129011, DOI: 10.1016/j.matlet.2020.129011

[19] J.E. Baio, M. Spinner, C. Jaye, D.A. Fischer, S.N. Gorb, T. Weidner, Evidence of a molecular boundary lubricant at snakeskin surfaces, Journal of The Royal Society Interface, Vol. 12, No. 113, 2015, Paper 20150817, DOI: 10.1098/rsif.2015.0817

[20] H.A. Abdel-Aal, M. El Mansori, H. Zahouani, A comparative study of frictional response of shed snakeskin and human skin, Wear, Vol. 376-377, No. A, 2017, pp. 281-294, DOI: 10.1016/j.wear.2016.12.055

[21] C. Liu, J. Ju, Y. Zheng, L. Jiang, Asymmetric ratchet effect for directional transport of fog drops on static and dynamic butterfly wings, ACS Nano, Vol. 8, No. 2, 2014, pp. 1321-1329, DOI: 10.1021/nn404761q

[22] D. Voigt, A. Schweikart, A. Fery, S. Gorb, Leaf beetle attachment on wrinkles: Isotropic friction on anisotropic surfaces, Journal of Experimental Biology, Vol. 215, No. 11, 2012, pp. 1975-1982, DOI: 10.1242/jeb.068320

[23] C.H. Nelson, Surface ultrastructure and evolution of tarsal attachment structures in Plecoptera (*Arthropoda*: *Hexapoda*), Aquatic Insects, Vol. 31, Supplement 1, 2009, pp. 523-545, DOI: 10.1080/01650420802598210

[24] S. Niederegger, S.N. Gorb, Friction and adhesion in the tarsal and metatarsal scopulae of spiders, Journal of Comparative Physiology A, Vol. 192, No. 11, 2006, pp. 1223-1232, DOI: 10.1007/s00359-006-0157-y

[25] M.P. Murphy, S. Kim, M. Sitti, Enhanced adhesion by gecko-inspired hierarchical fibrillar adhesives, ACS Applied Materials & Interfaces, Vol. 1, No. 4, 2009, pp. 849-855, DOI: 10.1021/am8002439

[26] E.V. Gorb, S.N. Gorb, The effect of surface anisotropy in the slippery zone of *Nepenthes alata* pitchers on beetle attachment, Beilstein Journal of Nanotechnology, Vol. 2, 2011, pp. 302-310, DOI: 10.3762/bjnano.2.35

[27] R. Elbaum, L. Zaltzman, I. Burgert P. Fratzl, The role of wheat awns in the seed dispersal unit, Science, Vol. 316, No. 5826, 2007, pp. 884-886, DOI: 10.1126/science.1140097

[28] M. Spinner, M. Kortmann, C. Traini, S.N. Gorb, Key role of scale morphology in flatfishes (*Pleuronectiformes*) in the ability to keep sand, Scientific Reports, Vol. 6, No. 1, 2016, Paper 26308, DOI: 10.1038/srep26308

[29] F.P. Bowden, C.A. Brookes, A.E. Hanwell, Anisotropy of friction in crystals, Nature, Vol. 203, No. 4940, 1964, pp. 27-30, DOI: 10.1038/203027b0

[30] J.S. Choi, J.-S. Kim, I.-S. Byun, D.H. Lee, M.J. Lee, B.H. Park, C. Lee, D. Yoon, H. Cheong, K.H. Lee, Y.-W. Son, J.Y. Park, M. Salmeron, Friction anisotropy-driven domain imaging on exfoliated monolayer graphene, Science, Vol. 333, No. 6042, 2011, pp. 607-610, DOI: 10.1126/science.1207110

[31] S. Aoki, D. Fukada, Y. Yamada, A. Suzuki, M. Masuko, Synergistic friction-reducing effects between the transverse direction of anisotropic surface roughness and the high-density adsorbed films under a boundary lubrication regime, Tribology International, Vol. 58, 2013, pp. 98-106, DOI: 10.1016/j.triboint.2012.10.003

[32] J. Hazel, M. Stone, M.S. Grace, V.V. Tsukruk, Nanoscale design of snake skin for reptation locomotions via friction anisotropy, Journal of Biomechanics, Vol. 32, No. 5, 1999, pp. 477-484, DOI: 10.1016/S0021-9290(99)00013-5

[33] H.F. Bohn, W. Federle, Insect aquaplaning: *Nepenthes* pitcher plants capture prey with the peristome, a fully wettable water-lubricated anisotropic surface, Proceedings of the National Academy of Sciences of the United States of America, Vol. 101, No. 39, 2004, pp. 14138-14143, DOI: 10.1073/pnas.0405885101

[34] G.J. Amador, D.L. Hu, Cleanliness is next to godliness: Mechanisms for staying clean, Journal of Experimental Biology, Vol. 218, No. 20, 2015, pp. 3164-3174, DOI: 10.1242/jeb.103937

[35] J. Li, Q.H. Qin, A. Shah, R.H.A. Ras, X. Tian, V. Jokinen, Oil droplet self-transportation on oleophobic surfaces, Science Advances, Vol. 2, No. 6, 2016, Paper e160014, DOI: 10.1126/sciadv.1600148

[36] Z. Ji, C. Yan, S. Ma, S. Gorb, X. Jia, B. Yu, X. Wang, F. Zhou, 3D printing of bioinspired topographically oriented surfaces with frictional anisotropy for directional driving, Tribology International, Vol. 132, 2019, pp. 99-107, DOI: 10.1016/j.triboint.2018.12.010

[37] J.A. Musick, G. Burgess, G. Cailliet, M. Camhi, S. Fordham, Management of sharks and their relatives (*Elasmobranchii*), Fisheries, Vol. 25, No. 3, 2000, pp. 9-13, DOI: 10.1577/1548-8446(2000)025<0009:MOSATR>2.0.CO;2

[38] B. Bhushan, Shark skin effect, in B. Bhushan (Ed.), Encyclopedia of Nanotechnology, Springer, Dordrecht, 2012, pp. 2401-2412, DOI: 10.1007/978-90-481-9751-4_159

[39] Y.F. Fu, C.Q. Yuan, X.Q. Bai, Marine drag reduction of shark skin inspired riblet surfaces, Biosurface and Biotribology, Vol. 3, No. 1, 2017, pp. 11-24, DOI: 10.1016/j.bsbt.2017.02.001

[40] B. Dean, B. Bhushan, Shark-skin surfaces for fluid-drag reduction in turbulent flow: A review, Philosophical Transactions of the Royal Society

A: Mathematical, Physical and Engineering Sciences, Vol. 368, No. 1929, 2010, pp. 4775-4806, DOI: 10.1098/rsta.2010.0201

[41] L. Wen, J.C. Weaver, G.V. Lauder, Biomimetic shark skin: Design, fabrication and hydrodynamic function, Journal of Experimental Biology, Vol. 217, No. 10, 2014, pp. 1656-1666, DOI: 10.1242/jeb.097097

[42] A.G. Domel, M. Saadat, J.C. Weaver, H. Haj-Hariri, K. Bertoldi, G.V. Lauder, Shark skin-inspired designs that improve aerodynamic performance, Journal of The Royal Society Interface, Vol. 15, No. 139, 2018, Paper 20170828, DOI: 10.1098/rsif.2017.0828

[43] Nature as a role model: Lufthansa group and BASF roll out sharkskin technology, available at: https://www.basf.com/global/en/media/news-releases/2021/05/p-21-204.html, accessed: 01.08.2023.

[44] S. Dash, S.K. Das, J. Samal, H.N. Thatoi, Epidermal mucus, a major determinant in fish health: A review, Iranian Journal of Veterinary Research, Vol. 19, No. 2, 2018, pp. 72-81, DOI: 10.22099/ijvr.2018.4849

[45] E. Biazar, S.H. Keshel, M.R. Tavirani, M. Kamalvand, Healing effect of acellular fish skin with plasma rich in growth factor on full-thickness skin defects, International Wound Journal, Vol. 19, No. 8, 2022, pp. 2154-2162, DOI: 10.1111/iwj.13821

[46] F. Pape, G. Poll, Frictional properties of freshwater fish skin, in Proceedings of the 3rd African Congress in Tribology, 26-29.04.2020, Dakar, Senegal, p. 1.

[47] Y. Wu, X. Pei, X. Wang, Y. Liang, W. Liu, F. Zhou, Biomimicking lubrication superior to fish skin using responsive hydrogels, NPG Asia Materials, Vol. 6, No. 10, 2014, Paper e136, DOI: 10.1038/am.2014.82

[48] W.L.E. Wong, T.J. Joyce, K.L. Goh, Resolving the viscoelasticity and anisotropy dependence of the mechanical properties of skin from a porcine model, Biomechanics and Modeling in Mechanobiology, Vol. 15, No. 2, 2016, pp. 433-446, DOI: 10.1007/s10237-015-0700-2

[49] M. Ottenio, D. Tran, A. Ní Annaidh, M.D. Gilchrist, K. Bruyère, Strain rate and anisotropy effects on the tensile failure characteristics of human skin, Journal of the Mechanical Behavior of Biomedical Materials, Vol. 41, 2015, pp. 241-250, DOI: 10.1016/j.jmbbm.2014.10.006

[50] J. van Smeden, J.A. Bouwstra, *Stratum corneum* lipids: Their role for the skin barrier function in healthy subjects and atopic dermatitis patients, in T. Agner (Ed.), Skin Barrier Function, Karger, Basel, 2016, pp. 8-26, DOI: 10.1159/000441540

[51] J.C.J. Wei, G.A. Edwards, D.J. Martin, H. Huang, M.L. Crichton, M.A.F. Kendall, Allometric scaling of skin thickness, elasticity, viscoelasticity to mass for micro-medical device translation: From mice, rats, rabbits, pigs to humans, Scientific Reports, Vol. 7, 2017, Paper 15885, DOI: 10.1038/s41598-017-15830-7

[52] J. Fowler, Understanding the role of natural moisturizing factor in skin hydration, Practical Dermatology, No. 7, 2012, pp. 36-40.

[53] M.B. Murphrey, J.H. Miao, P.M. Zito, Histology, *Stratum Corneum*, StatPearls Publishing, St. Petersburg, 2023.

[54] M.F. Leyva-Mendivil, A. Page, N.W. Bressloff, G. Limbert, A mechanistic insight into the mechanical role of the *stratum corneum* during stretching and compression of the skin, Journal of the Mechanical Behavior of Biomedical Materials, Vol. 49, 2015, pp. 197-219, DOI: 10.1016/j.jmbbm.2015.05.010

[55] C.R. Dunkley, C.D. Henshaw, S.K. Henshaw, L.A. Brotto, Physical pain as pleasure: A theoretical perspective, The Journal of Sex Research, Vol. 57, No. 4, 2020, pp. 421-437, DOI: 10.1080/00224499.2019.160532

[56] M.F. Leyva-Mendivil, J. Lengiewicz, A. Page, N.W. Bressloff, G. Limbert, Skin microstructure is a key contributor to its friction behaviour, Tribology Letters, Vol. 65, No. 1, 2016, Paper 12, DOI: 10.1007/s11249-016-0794-4

[57] F.H. Silver, J.W. Freeman, D. DeVore, Viscoelastic properties of human skin and processed dermis, Skin Research and Technology, Vol. 7, No. 1, 2001, pp. 18-23, DOI: 10.1034/j.1600-0846.2001.007001018.x

[58] R.E. Burgeson, A.M. Christiano, The dermal-epidermal junction, Current Opinion in Cell Biology, Vol. 9, No. 5, 1997, pp. 651-658, DOI: 10.1016/S0955-0674(97)80118-4

[59] M. Asahina, A. Poudel, S. Hirano, Sweating on the palm and sole: Physiological and clinical relevance, Clinical Autonomic Research, Vol. 25, No. 3, 2015, pp. 153-159, DOI: 10.1007/s10286-015-0282-1

[60] V.F. Achterberg, L. Buscemi, H. Diekmann, J. Smith-Clerc, H. Schwengler, J.-J. Meister, H. Wenck, S. Gallinat, B. Hinz, The nano-scale mechanical properties of the extracellular matrix regulate dermal fibroblast function, Journal of Investigative Dermatology, Vol. 134, No. 7, 2014, pp. 1862-1872, DOI: 10.1038/jid.2014.90

[61] A. Ní Annaidh, K. Bruyère, M. Destrade, M.D. Gilchrist, M. Otténio, Characterization of the anisotropic mechanical properties of excised human skin, Journal of the Mechanical Behavior of Biomedical Materials, Vol. 5, No. 1, 2012, pp. 139-148, DOI: 10.1016/j.jmbbm.2011.08.016

[62] S. Diridollou, V. Vabre, M. Berson, L. Vaillant, D. Black, J.M. Lagarde, J.M. Grégoire, Y. Gall, F. Patat, Skin ageing: Changes of physical properties of human skin *in vivo*, International Journal of Cosmetic Science, Vol. 23, No. 6, 2001, pp. 353-362, DOI: 10.1046/j.0412-5463.2001.00105.x

[63] C. Pailler-Mattei, S. Bec, H. Zahouani, *In vivo* measurements of the elastic mechanical properties of human skin by indentation tests, Medical Engineering & Physics, Vol. 30, No. 5, 2008, pp. 599-606, DOI: 10.1016/j.medengphy.2007.06.011

[64] L. Pan, L. Zan, F.S. Foster, *In vivo* high frequency ultrasound assessment of skin elasticity, in Proceedings of the 1997 IEEE Ultrasonics Symposium, 05-08.10.1997, Toronto, Canada, pp. 1087-1091, DOI: 10.1109/ULTSYM.1997.661769

[65] Q. Wang, V. Hayward, *In vivo* biomechanics of the fingerpad skin under local tangential traction, Journal of Biomechanics, Vol. 40, No. 4, 2007, pp. 851-860, DOI: 10.1016/j.jbiomech.2006.03.004

[66] X. Liang, S.A. Boppart, Biomechanical properties of *in vivo* human skin from dynamic optical coherence elastography, IEEE Transactions on Biomedical Engineering, Vol. 57, No. 4, 2010, pp. 953-959, DOI: 10.1109/TBME.2009.2033464

[67] C. Pailler-Mattei, S. Pavan, R. Vargiolu, F. Pirot, F. Falson, H. Zahouani, Contribution of *stratum corneum* in determining bio-tribological properties of the human skin, Wear, Vol. 263, No. 7-12, 2007, pp. 1038-1043, DOI: 10.1016/j.wear.2007.01.128

[68] B.F. Van Duzee, The influence of water content, chemical treatment and temperature on the rheological properties of *stratum corneum*, Journal of Investigative Dermatology, Vol. 71, No. 2, 1978, pp. 140-144, DOI: 10.1111/1523-1747.ep12546836

[69] G.L. Wilkes, A.-L. Nguyen, R. Wildnauer, Structure-property relations of human and neonatal rat *stratum corneum* I. Thermal stability of the crystalline lipid structure as studied by X-ray diffraction and differential thermal analysis, Biochimica et Biophysica Acta: General Subjects, Vol. 304, No. 2, 1973, pp. 267-275, DOI: 10.1016/0304-4165(73)90244-4

[70] M. Geerligs, L. van Breemen, G. Peters, P. Ackermans, F. Baaijens, C. Oomens, *In vitro* indentation to determine the mechanical properties of epidermis, Journal of Biomechanics, Vol. 44, No. 6, 2011, pp. 1176-1181, DOI: 10.1016/j.jbiomech.2011.01.015

[71] F.H. Silver, G.P. Seehra, J.W. Freeman, D. DeVore, Viscoelastic properties of young and old human dermis: A proposed molecular mechanism for elastic energy storage in collagen and elastin, Journal of Applied Polymer Science, Vol. 86, No. 8, 2002, pp. 1978-1985, DOI: 10.1002/app.11119

[72] B. Holt, A. Tripathi, J. Morgan, Viscoelastic response of human skin to low magnitude physiologically relevant shear, Journal of Biomechanics, Vol. 41, No. 12, 2008, pp. 2689-2695, DOI: 10.1016/j.jbiomech.2008.06.008

[73] F.M. Hendriks, D. Brokken, J.T.W.M. Van Eemeren, C.W.J. Oomens, F.P.T. Baaijens, J.B.A.M. Horsten, A numerical-experimental method to characterize the non-linear mechanical behaviour of human skin, Skin Research and Technology, Vol. 9, No. 3, 2003, pp. 274-283, DOI: 10.1034/j.1600-0846.2003.00019.x

[74] J. Su, H. Zou, T. Guo, The study of mechanical properties on soft tissue of human forearm *in vivo*, in Proceedings of the 3rd International Conference on Bioinformatics and Biomedical Engineering, 11-16.06.2009, Beijing, China, Paper: 10778606, DOI: 10.1109/ICBBE.2009.5163671

[75] J.W.Y. Jor, M.D. Parker, A.J. Taberner, M.P. Nash, P.M.F. Nielsen, Computational and experimental characterization of skin mechanics: identifying current challenges and future directions, Wiley Interdisciplinary Reviews: Systems Biology and Medicine, Vol. 5, No. 5, 2013, pp. 539-556, DOI: 10.1002/wsbm.1228

[76] J. Weickenmeier, E. Mazza, Inverse methods, in G. Limbert (Ed.), Skin Biophysics, Springer, Cham, 2019, pp. 193-213, DOI: 10.1007/978-3-030-13279-8_6

[77] K. Langer, On the anatomy and physiology of the skin I. The cleavability of the cutis, British Journal of Plastic Surgery, Vol. 31, No. 1, 1978, pp. 3-8, DOI: 10.1016/0007-1226(78)90003-6

[78] M.B. Rubin, S.R. Bodner, A three-dimensional nonlinear model for dissipative response of soft tissue, International Journal of Solids and Structures, Vol. 39, No. 19, 2002, pp. 5081-5099, DOI: 10.1016/S0020-7683(02)00237-8

[79] S. Park, J. Tao, L. Sun, C.-M. Fan, Y. Chen, An economic, modular, and portable skin viscoelasticity measurement device for *in situ* longitudinal studies, Molecules, Vol. 24, No. 5, 2019, Paper 907, DOI: 10.3390/molecules24050907

[80] H. Zahouani, R. Vargiolu, G. Boyer, C. Pailler-Mattei, L. Laquièze, A. Mavon, Friction noise of human skin *in vivo*, Wear, Vol. 267, No. 5-8, 2009, pp. 1274-1280, DOI: 10.1016/j.wear.2009.03.007

[81] L.-C. Gerhardt, J. Schmidt, J.A. Sanz-Herrera, F.P.T. Baaijens, T. Ansari, G.W.M. Peters, C.W.J Oomens, A novel method for visualising and quantifying through-plane skin layer deformations, Journal of the Mechanical Behavior of Biomedical Materials, Vol. 14, 2012, pp. 199-207, DOI: 10.1016/j.jmbbm.2012.05.014

[82] E. Lamers, T.H.S. van Kempen, F.P.T. Baaijens, G.W.M. Peters, C.W.J. Oomens, Large amplitude oscillatory shear properties of human skin, Journal of the Mechanical Behavior of Biomedical Materials, Vol. 28, 2013, pp. 462-470, DOI: 10.1016/j.jmbbm.2013.01.024

[83] K. Hyun, M. Wilhelm, C.O. Klein, K.S. Cho, J.G. Nam, K.H. Ahn, S.J. Lee, R.H. Ewoldt, G.H. McKinley, A review of nonlinear oscillatory shear tests: Analysis and application of large amplitude oscillatory shear (LAOS), Progress in Polymer Science, Vol. 36, No. 12, 2011, pp. 1697-1753, DOI: 10.1016/j.progpolymsci.2011.02.002

[84] R.E. Horch, J. Kopp, U. Kneser, J. Beier, A.D. Bach, Tissue engineering of cultured skin substitutes, Journal of Cellular and Molecular Medicine, Vol. 9, No. 3, 2005, pp. 592-608, DOI: 10.1111/j.1582-4934.2005.tb00491.x

[85] L.-P. Kamolz, P. Kotzbeck, M. Schintler, S. Spendel, Skin regeneration, repair, and reconstruction: present and future, European Surgery, Vol. 54, No. 3, 2022, pp. 163-169, DOI: 10.1007/s10353-022-00757-9

[86] L.-C. Gerhardt, A. Lenz, N.D. Spencer, T. Münzer, S. Derler, Skin-textile friction and skin elasticity in young and aged persons, Skin Research and Technology, Vol. 15, No. 3, 2009, pp. 288-298, DOI: 10.1111/j.1600-0846.2009.00363.x

[87] M. Egawa, M. Oguri, T. Hirao, M. Takahashi, M. Miyakawa, The evaluation of skin friction using a frictional feel analyzer, Skin Research and Technology, Vol. 8, No. 1, 2002, pp. 41-51, DOI: 10.1034/j.1600-0846.2002.080107.x

[88] *In vitro* diagnostics market size, share & trends analysis report by product (reagents, services), by test location (PoC, homecare), by end-use (hospitals, laboratory), by application, by technology, and segment forecasts, 2023-2030, available at: https://www.grandviewresearch.com/industry-analysis/in-vitro-diagnostics-ivd-market, accessed: 01.08.2023.

[89] S. Mühlfriedel, G. Knebel, The establishment of *in vivo*-like tissue culture conditions in ThinCert™ tissue culture products, BioTechniques, Vol. 43, No. 6, 2007, pp. 812-813, DOI: 10.2144/000112701

[90] S. Abadie, P. Bedos, J. Rouquette, A human skin model to evaluate the protective effect of compounds against UVA damage, International Journal of Cosmetic Science, Vol. 41, No. 6, 2019, pp. 594-603, DOI: 10.1111/ics.12579

[91] K.L. Johnson, Contact Mechanics, Cambridge University Press, Cambridge, 1985.

[92] J. van Kuilenburg, M.A. Masen, M.N.W. Groenendijk, V. Bana, E. van der Heide, An experimental study on the relation between surface texture and tactile friction, Tribology International, Vol. 48, 2012, pp. 15-21, DOI: 10.1016/j.triboint.2011.06.003

[93] S. Comaish, E. Bottoms, The skin and friction: Deviations from Amonton's laws, and the effects of hydration and lubrication, British Journal of Dermatology, Vol. 84, No. 1, 1971, pp. 37-43, DOI: 10.1111/j.1365-2133.1971.tb14194.x

[94] L.J. Wolfram, Friction of skin, Journal of the Society of Cosmetic Chemists, Vol. 34, No. 8, 1983, pp. 465-476.

[95] M.J. Adams, B.J. Briscoe, S.A. Johnson, Friction and lubrication of human skin, Tribology Letters, Vol. 26, No. 3, 2007, pp. 239-253, DOI: 10.1007/ s11249-007-9206-0

[96] A.F. El-Shimi, *In vivo* skin friction measurements, Journal of the Society of Cosmetic Chemists, Vol. 28, No. 2, 1977, pp. 37-51.

[97] A.A. Koudine, M. Barquins, P.H. Anthoine, L. Aubert, J.-L. Lévêque, Frictional properties of skin: Proposal of a new approach, International Journal of Cosmetic Science, Vol. 22, No. 1, 2000, pp. 11-20, DOI: 10.1046/j.1467-2494.2000.00006.x

[98] R.K. Sivamani, J. Goodman, N.V. Gitis, H.I. Maibach, Friction coefficient of skin in real-time, Skin Research and Technology, Vol. 9, No. 3, 2003, pp. 235-239, DOI: 10.1034/j.1600-0846.2003.20361.x

[99] N. Gitis, R. Sivamani, Tribometrology of skin, Tribology Transactions, Vol. 47, No. 4, 2004, pp. 461-469, DOI: 10.1080/05698190490493355

[100] K. Subramanyan, M. Misra, S. Mukherjee, K.P. Ananthapadmanabhan, Advances in the materials science of skin: A composite structure with multiple functions, MRS Bulletin, Vol. 32, No. 10, 2007, pp. 770-778, DOI: 10.1557/mrs2007.163

[101] P.F.D. Naylor, The skin surface and friction, British Journal of Dermatology, Vol. 67, No. 7, 1955, pp. 239-248, DOI: 10.1111/j.1365-2133.1955.tb12729.x

[102] J.S. Comaish, P.R.H. Harborow, D.A. Hofman, A hand-held friction meter, British Journal of Dermatology, Vol. 89, No. 1, 1973, pp. 33-35, DOI: 10.1111/j.1365-2133.1973.tb01914.x

[103] D.R. Highley, M. Coomey, M. DenBeste, L.J. Wolfram, Frictional properties of skin, The Journal of Investigative Dermatology, Vol. 69, No. 3, 1977, pp. 303-305, DOI: 10.1111/1523-1747.ep12507530

[104] O.S. Dinc, C.M. Ettles, S.J. Calabrese, H.A. Scarton, Some parameters affecting tactile friction, Journal of Tribology, Vol. 113, No. 3, 1991, pp. 512-517, DOI: 10.1115/1.2920653

[105] R. Lewis, C. Menardi, A. Yoxall, J. Langley, Finger friction: Grip and opening packaging, Wear, Vol.

263, No. 7-12, 2007, pp. 1124-1132, DOI: 10.1016/j.wear.2006.12.024

[106] O. Bobjer, S.-E. Johansson, S. Piguet, Friction between hand and handle. Effects of oil and lard on textured and non-textured surfaces; perception of discomfort, Applied Ergonomics, Vol. 24, No. 3, 1993, pp. 190-202, DOI: 10.1016/0003-6870(93)90007-V

[107] A.B. Cua, K.-P. Wilhelm, H.I. Maibach, Frictional properties of human skin: Relation to age, sex and anatomical region, *stratum corneum* hydration and transepidermal water loss, British Journal of Dermatology, Vol. 123, No. 4, 1990, pp. 473-479, DOI: 10.1111/j.1365-2133.1990.tb01452.x

[108] M.G. Gee, P. Tomlins, A. Calver, R.H. Darling, M. Rides, A new friction measurement system for the frictional component of touch, Wear, Vol. 259, No. 7-12, 2005, pp. 1437-1442, DOI: 10.1016/j.wear.2005.02.053

[109] J. Asserin, H. Zahouani, P. Humbert, V. Couturaud, D. Mougin, Measurement of the friction coefficient of the human skin *in vivo*: Quantification of the cutaneous smoothness, Colloids and Surfaces B: Biointerfaces, Vol. 19, No. 1, 2000, pp. 1-12, DOI: 10.1016/S0927-7765(99)00169-1

[110] W. Li, M. Kong, X.D. Liu, Z.R. Zhou, Tribological behavior of scar skin and prosthetic skin *in vivo*, Tribology International, Vol. 41, No. 7, 2008, pp. 640-647, DOI: 10.1016/j.triboint.2007.11.009

[111] H.-J. Bullinger, P. Kern, J.J. Solf, Reibung zwischen Hand und Griff: der Einfluss von Material und Oberfläche auf das Reibungsverhalten zwischen Hand und Arbeitsmittelhandseite [Friction between hand and handle: The influence of material and surface on the friction behaviour between the hand and the handle of the tool], Wirtschaftsverlag NW, Bremerhaven, 1979 [in German].

[112] A. Ramalho, C.L. Silva, A.A.C.C. Pais, J.J.S. Sousa, *In vivo* friction study of human palmoplantar skin against glass, Tribologia, Vol. 25, No. 3, 2006, pp. 14-23.

[113] A. Ramalho, C.L. Silva, A.A.C.C. Pais, J.J.S. Sousa, *In vivo* friction study of human skin: Influence of moisturizers on different anatomical sites, Wear, Vol. 263, No. 7-12, 2007, pp. 1044-1049, DOI: 10.1016/j.wear.2006.11.051

[114] W. Li, S.X. Qu, Z.R. Zhou, Reciprocating sliding behaviour of human skin *in vivo* at lower number of cycles, Tribology Letters, Vol. 23, No. 2, 2006, pp. 165-170, DOI: 10.1007/s11249-006-9111-y

[115] C.P. Hendriks, S.E. Franklin, Influence of surface roughness, material and climate conditions on the friction of human skin, Tribology Letters, Vol. 37, No. 2, 2010, pp. 361-373, DOI: 10.1007/s11249-009-9530-7

[116] S.E. Tomlinson, R. Lewis, X. Liu, C. Texier, M.J. Carré, Understanding the friction mechanisms between the human finger and flat contacting surfaces in moist conditions, Tribology Letters, Vol. 41, No. 1, 2011, pp. 283-294, DOI: 10.1007/s11249-010-9709-y

[117] F.-X. Li, S. Margetts, I. Fowler, Use of 'chalk' in rock climbing: Sine qua non or myth?, Journal of Sports Sciences, Vol. 19, No.6, 2001, pp. 427-432, DOI: 10.1080/026404101300149375

[118] N. Nakazawa, R. Ikeura, H. Inooka, Characteristics of human fingertips in the shearing direction, Biological Cybernetics, Vol. 82, No. 2, 2000, pp. 207-214, DOI: 10.1007/s004220050020

[119] Y. Nonomura, T. Fujii, Y. Arashi, T. Miura, T. Maeno, K. Tashiro, Y. Kamikawa, R. Monchi, Tactile impression and friction of water on human skin, Colloids and Surfaces B: Biointerfaces, Vol. 69, No. 2, 2009, pp. 264-267, DOI: 10.1016/j.colsurfb.2008.11.024

[120] M. Uygur, P.B. de Freitas, S. Jaric, Frictional properties of different hand skin areas and grasping techniques, Ergonomics, Vol. 53, No. 6, 2010, pp. 812-817, DOI: 10.1080/00140131003734237

[121] M. Besser, M. Marpet, H. Medoff, Barefoot-pedestrian tribometry: *In vivo* method of measurement of available friction between the human heel and the walkway, Industrial Health, Vol. 46, No. 1, 2008, pp. 51-58, DOI: 10.2486/indhealth.46.51

[122] B.L. Davis, Foot ulceration: Hypotheses concerning shear and vertical forces acting on adjacent regions of skin, Medical Hypotheses, Vol. 40, No. 1, 1993, pp. 44-47, DOI: 10.1016/0306-9877(93)90195-V

[123] M. Zhang, A.F.T. Mak, *In vivo* friction properties of human skin, Prosthetics and Orthotics International, Vol. 23, No. 2, 1999, pp. 135-141, DOI: 10.3109/03093649909071625

[124] M. Kwiatkowska, S.E. Franklin, C.P. Hendriks, K. Kwiatkowski, Friction and deformation behaviour of human skin, Wear, Vol. 267, No. 5-8, 2009, pp. 1264-1273, DOI: 10.1016/j.wear.2008.12.030

[125] P. Humbert, F. Fanian, H.I. Maibach, P. Agache (Eds.), Agache's Measuring the Skin, Springer, Cham, 2017, DOI: 10.1007/978-3-319-32383-1

[126] G. Boyer, L. Laquièze, A. Le Bot, S. Laquièze, H. Zahouani, Dynamic indentation on human skin *in vivo*: Ageing effects, Skin Research and Technology, Vol. 15, No. 1, 2009, pp. 55-67, DOI: 10.1111/j.1600-0846.2008.00324.x

[127] U. Jacobi, M. Chen, G. Frankowski, R. Sinkgraven, M. Hund, B. Rzany, W. Sterry, J. Lademann, *In*

vivo determination of skin surface topography using an optical 3D device, Skin Research and Technology, Vol. 10, No. 4, 2004, pp. 207-214, DOI: 10.1111/j.1600-0846.2004.00075.x

[128] L. Li, S. Mac-Mary, D. Marsaut, J.M. Sainthillier, S. Nouveau, T. Gharbi, O. de Lacharriere, P. Humbert, Age-related changes in skin topography and microcirculation, Archives of Dermatological Research, Vol. 297, No. 9, 2006; pp. 412-416, DOI: 10.1007/s00403-005-0628-y

[129] T. Fujimura, K. Haketa, M. Hotta, T. Kitahara, Loss of skin elasticity precedes to rapid increase of wrinkle levels, Journal of Dermatological Science, Vol. 47, No. 3, 2007, pp. 233-239, DOI: 10.1016/j.jdermsci.2007.05.002

[130] K. Nakajima, H. Narasaka, Evaluation of skin surface associated with morphology and coefficient of friction, International Journal of Cosmetic Science, Vol. 15, No. 4, 1993, pp. 135-151, DOI: 10.1111/j.1468-2494.1993.tb00594.x

[131] S. Derler, R. Huber, H.-P. Feuz, M. Hadad, Influence of surface microstructure on the sliding friction of plantar skin against hard substrates, Wear, Vol. 267, No. 5-8, 2009, pp. 1281-1288, DOI: 10.1016/j.wear.2008.12.053

[132] S.E. Tomlinson, R. Lewis, M.J. Carré, The effect of normal force and roughness on friction in human finger contact, Wear, Vol. 267, No. 5-8, 2009, pp. 1311-1318, DOI: 10.1016/j.wear.2008.12.084

[133] M.A. Masen, A systems based experimental approach to tactile friction, Journal of the Mechanical Behavior of Biomedical Materials, Vol. 4, No. 8, 2011, pp. 1620-1626, DOI: 10.1016/j.jmbbm.2011.04.007

[134] S.E. Tomlinson, M.J. Carré, R. Lewis, S.E Franklin, Human finger contact with small, triangular ridged surfaces, Wear, Vol. 271, No. 9-10, 2011, pp. 2346-2353, DOI: 10.1016/j.wear.2010.12.055

[135] D.F. Moore, The Friction and Lubrication of Elastomers, Pergamon Press, Oxford, 1972.

[136] A. El Khyat, A. Mavon, M. Leduc, P. Agache, P. Humbert, Skin critical surface tension, Skin Research and Technology, Vol. 2, No. 2, 1996, pp. 91-96, DOI: 10.1111/j.1600-0846.1996.tb00066.x

[137] A.B Gupta, B Haldar, M. Bhattacharya, A simple device for measuring skin friction, Indian Journal of Dermatology, Vol. 40, No. 3, 1995, pp. 116-121.

[138] A. Mavon, H. Zahouani, D. Redoules, P. Agache, Y. Gall, P. Humbert, Sebum and *stratum corneum* lipids increase human skin surface free energy as determined from contact angle measurements: A study on two anatomical sites, Colloids and Surfaces B: Biointerfaces, Vol. 8, No. 3, 1997, pp. 147-155, DOI: 10.1016/S0927-7765(96)01317-3

[139] C. Pailler-Mattei, S. Nicoli, F. Pirot, R. Vargiolu, H. Zahouani, A new approach to describe the skin surface physical properties *in vivo*, Colloids and Surfaces B: Biointerfaces, Vol. 68, No. 2, 2009, pp. 200-206, DOI: 10.1016/j.colsurfb.2008.10.005

[140] R.K. Sivamani, G.C. Wu, N.V. Gitis, H.I. Maibach, Tribological testing of skin products: gender, age, and ethnicity on the volar forearm, Skin Research and Technology, Vol. 9, No. 4, 2003, pp. 299-305, DOI: 10.1034/j.1600-0846.2003.00034.x

[141] M. Lodén, H. Olsson, T. Axéll, Y. Werner Linde, Friction, capacitance and transepidermal water loss (TEWL) in dry atopic and normal skin, British Journal of Dermatology, Vol. 126, No. 2, 1992, pp. 137-141, DOI: 10.1111/j.1365-2133.1992.tb07810.x

[142] Y.H. Zhu, S.P. Song, W. Luo, P.M. Elias, M.Q. Man, Characterization of skin friction coefficient, and relationship to *stratum corneum* hydration in a normal Chinese population, Skin Pharmacol Physiol, Vol. 24, No. 2, 2011, pp. 81-86, DOI: 10.1159/000321993

[143] P. Kenins, Influence of fiber type and moisture on measured fabric-to-skin friction, Textile Research Journal, Vol. 64, No. 12, 1994, pp. 722-728, DOI: 10.1177/004051759406401204

[144] P. Eisner, D. Wilhelm, H.I. Maibach, Frictional properties of human forearm and vulvar skin: Influence of age and correlation with transepidermal water loss and capacitance, Dermatologica, Vol. 181, No. 2, 1990, pp. 88-91, DOI: 10.1159/000247892

[145] S.M. Pasumarty, S.A. Johnson, S.A. Watson, M.J. Adams, Friction of the human finger pad: Influence of moisture, occlusion and velocity, Tribology Letters, Vol. 44, No. 2, 2011, pp. 117-137, DOI: 10.1007/s11249-011-9828-0

[146] L.-C. Gerhardt, V. Strässle, A. Lenz, N.D. Spencer, S. Derler, Influence of epidermal hydration on the friction of human skin against textiles, Journal of The Royal Society Interface, Vol. 5, No. 28, 2008, pp. 1317-1328, DOI: 10.1098/rsif.2008.0034

[147] S. Derler, L.-C. Gerhardt, A. Lenz, E. Bertaux, M. Hadad, Friction of human skin against smooth and rough glass as a function of the contact pressure, Tribology International, Vol. 42, No. 11-12, 2009, pp. 1565-1574, DOI: 10.1016/j.triboint.2008.11.009

[148] K.A. Flack, M.P. Schultz, J.M. Barros, Skin friction measurements of systematically-varied roughness: Probing the role of roughness amplitude and skewness, Flow, Turbulence and Combustion, Vol. 104, No. 2-3, 2020, pp. 317-329, DOI: 10.1007/s10494-019-00077-1

[149] F.P. Bowden, D. Tabor, F. Palmer, The friction and lubrication of solids, American Journal of

Physics, Vol. 19, No. 7, 1951, pp. 428-429, DOI: 10.1119/1.1933017
[150] B.J. Briscoe, D. Tabor, Shear properties of thin polymeric films, The Journal of Adhesion, Vol. 9, No. 2, 1978, pp. 145-155, DOI: 10.1080/00218467808075110
[151] S. Derler, L.-C. Gerhardt, Tribology of skin: Review and analysis of experimental results for the friction coefficient of human skin, Tribology Letters, Vol. 45, No. 1, 2012, pp. 1-27, DOI: 10.1007/s11249-011-9854-y
[152] J.A. Greenwood, J.B.P. Williamson, Contact of nominally flat surfaces, Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences, Vol. 295, No. 1442, 1966, pp. 300-319, DOI: 10.1098/rspa.1966.0242
[153] D. Dowson, Tribology and the skin surface, in K.-P. Wilhelm, P. Elsner, E. Berardesca, H.I. Maibach (Eds.), Bioengineering of the Skin, CRC Press, Boca Raton, 1997, pp. 159-179.
[154] S.A. Johnson, D.M. Gorman, M.J. Adams, B.J. Briscoe, The friction and lubrication of human *stratum corneum*, in D. Dowson, C.M. Taylor, T.H.C. Childs, M. Godet, G. Dalmaz (Eds.), Thin Films in Tribology, Elsevier, Amsterdam, 1993, pp. 663-672, DOI: 10.1016/S0167-8922(08)70419-X
[155] J.A. Greenwood, D. Tabor, The friction of hard sliders on lubricated rubber: The importance of deformation losses, Proceedings of the Physical Society, Vol. 71, No. 6, 1958, 989-1001, DOI: 10.1088/0370-1328/71/6/312
[156] S. Derler, U. Schrade, L.-C. Gerhardt, Tribology of human skin and mechanical skin equivalents in contact with textiles, Wear, Vol. 263, No. 7-12, 2007, pp. 1112-1116, DOI: 10.1016/j.wear.2006.11.031
[157] J.E. Sanders, J.M. Greve, S.B. Mitchell, S.G. Zachariah, Material properties of commonly-used interface materials and their static coefficients of friction with skin and socks, Journal of Rehabilitation Research and Development, Vol. 35, No. 2, 1998, pp. 161-176.
[158] J.F. Archard, Elastic deformation and the laws of friction, Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences, Vol. 243, No. 1233, 1957, pp. 190-205, DOI: 10.1098/rspa.1957.0214
[159] T. Soneda, K. Nakano, Investigation of vibrotactile sensation of human fingerpads by observation of contact zones, Tribology International, Vol. 43, No. 1-2, 2010, pp. 210-217, DOI: 10.1016/j.triboint.2009.05.016
[160] B.N.J. Persson, Theory of rubber friction and contact mechanics, The Journal of Chemical Physics, Vol. 115, No. 8, 2001, pp. 3840-3861, DOI: 10.1063/1.1388626
[161] B.N.J. Persson, Capillary adhesion between elastic solids with randomly rough surfaces, Journal of Physics: Condensed Matter, Vol. 20, No. 31, 2008, Paper 315007, DOI: 10.1088/0953-8984/20/31/315007
[162] B.N.J. Persson, O. Albohr, C. Creton, V. Peveri, Contact area between a viscoelastic solid and a hard, randomly rough, substrate, The Journal of Chemical Physics, Vol. 120, No. 18, 2004, pp. 8779-8793, DOI: 10.1063/1.1697376
[163] K.R. Shull, Contact mechanics and the adhesion of soft solids, Materials Science & Engineering R: Reports, Vol. 36, No. 1, 2002, pp. 1-45, DOI: 10.1016/S0927-796X(01)00039-0
[164] L.D. Landau, E.M. Lifschitz, Elastizitätstheorie [Theory of Elasticity], Verlag Harri Deutsch, Frankfurt, 1991 [in German].
[165] M. Amontons, De la resistance causée dans les machines [About Resistance and Force in Machines], Mémoires de l'Académie Royale des Sciences, 1969, pp. 206-222 [in French].
[166] D. Dowson, History of Tribology, Professional Engineering Publishing, London, 1998.
[167] B. Derjaguin, Molekulartheorie der äußeren Reibung [Molecular Theory of External Friction], Zeitschrift für Physik, Vol. 88, No. 9-10, 1934, pp. 661-675, DOI: 10.1007/BF01333114 [in German].
[168] S.J. Eder, A. Vernes, G. Betz, On the Derjaguin offset in boundary-lubricated nanotribological systems, Langmuir, Vol. 29, No. 45, 2013, pp. 13760-13772, DOI: 10.1021/la4026443
[169] J. Gao, W.D. Luedtke, D. Gourdon, M. Ruths, J. N. Israelachvili, U. Landman, Frictional forces and Amontons' law: From the molecular to the macroscopic scale, The Journal of Physical Chemistry B, Vol. 108, No. 11, 2004, pp. 3410-3425, DOI: 10.1021/jp036362l
[170] A.M. Homola, J.N. Israelachvili, M.L. Gee, P.M. McGuiggan, Measurements of and relation between the adhesion and friction of two surfaces separated by molecularly thin liquid films, Journal of Tribology, Vol. 111, No. 4, 1989, pp. 675-682, DOI: 10.1115/1.3261994
[171] G. Bogdanovic, F. Tiberg, M.W. Rutland, Sliding friction between cellulose and silica surfaces, Langmuir, Vol. 17, No. 19, 2001, pp. 5911-5916, DOI: 10.1021/la010330c
[172] A.A. Feiler, P. Jenkins, M.W. Rutland, Effect of relative humidity on adhesion and frictional properties of micro- and nano-scopic contacts, Journal of Adhesion Science and Technology, Vol. 19, No. 3-5, 2005, pp. 165-179, DOI: 10.1163/1568561054352595
[173] A. Feiler, M.A. Plunkett, M.W. Rutland, Atomic force microscopy measurements of adsorbed

polyelectrolyte layers. 1. Dynamics of forces and friction, Langmuir, Vol. 19, No. 10, 2003, pp. 4173-4179, DOI: 10.1021/la026570p
[174] A.A. Feiler, J. Stiernstedt, K. Theander, P. Jenkins, M.W. Rutland, Effect of capillary condensation on friction force and adhesion, Langmuir, Vol. 23, No. 2, 2007, pp. 517-522, DOI: 10.1021/la060456f
[175] S. Yamada, J. Israelachvili, Friction and adhesion hysteresis of fluorocarbon surfactant monolayer-coated surfaces measured with the surface forces apparatus, The Journal of Physical Chemistry B, Vol. 102, No. 1, 1998, pp. 234-244, DOI: 10.1021/jp972875e
[176] A. Berman, C. Drummond, J. Israelachvili, Amontons' law at the molecular level, Tribology Letters, Vol. 4, No. 2, 1998, pp. 95-101, DOI: 10.1023/A:1019103205079
[177] R. D'Amato, A. Ruggiero, Skin tribology: Overview and insights on frictional properties of human skin, in S. Marcos-Pablos, J.A. Juanes-Méndez (Eds.), Technological Adoption and Trends in Health Sciences Teaching, Learning, and Practice, IGI Global, Hershey, 2022, pp. 1-25, DOI: 10.4018/978-1-7998-8871-0.ch001
[178] F.P. Bowden, D. Tabor, Mechanism of metallic friction, Nature, Vol. 150, No. 3798, 1942, pp. 197-199, DOI: 10.1038/150197a0
[179] Y. Martin, C.C. Williams, H.K. Wickramasinghe, Atomic force microscope-force mapping and profiling on a sub 100-Å scale, Journal of Applied Physics, Vol. 61, No. 10, 1987, pp. 4723-4729, DOI: 10.1063/1.338807
[180] G. Binnig, C.F. Quate, C. Gerber, Atomic force microscope, Physical Review Letters, Vol. 56, No. 9, 1986, pp. 930-934, DOI: 10.1103/PhysRevLett.56.930
[181] R.S. Johansson, Tactile sensibility in the human hand: Receptive field characteristics of mechanoreceptive units in the glabrous skin area, The Journal of Physiology, Vol. 281, No. 1, 1978, pp. 101-125, DOI: 10.1113/jphysiol.1978.sp012411
[182] I. Brody, The ultrastructure of the epidermis in *psoriasis vulgaris* as revealed by electron microscopy: 1. The dermo-epidermal junction and the stratum basale in parakeratosis without keratohyalin, Journal of Ultrastructure Research, Vol. 6, No. 3-4, 1962, pp. 304-323, DOI: 10.1016/S0022-5320(62)80037-9
[183] M. Klaassen, E.G. de Vries, M.A. Masen, The static friction response of non-glabrous skin as a function of surface energy and environmental conditions, Biotribology, Vol. 11, 2017, pp. 124-131, DOI: 10.1016/j.biotri.2017.05.004
[184] W.A. Ducker, T.J. Senden, R.M. Pashley, Measurement of forces in liquids using a force microscope, Langmuir, Vol. 8, No. 7, 1992, pp. 1831-1836, DOI: 10.1021/la00043a024
[185] W.A. Ducker, T.J. Senden, R.M. Pashley, Direct measurement of colloidal forces using an atomic force microscope, Nature, Vol. 353, No. 6341, 1991, pp. 239-241, DOI: 10.1038/353239a0
[186] H.-J. Butt, Measuring electrostatic, van der Waals, and hydration forces in electrolyte solutions with an atomic force microscope, Biophysical Journal, Vol. 60, No. 6, 1991, pp. 1438-1444, DOI: 10.1016/S0006-3495(91)82180-4
[187] A. Tomala, H. Göçerler, I.C. Gebeshuber, Bridging nano- and microtribology in mechanical and biomolecular layers, in B. Bhushan (Ed.), Scanning Probe Microscopy in Nanoscience and Nanotechnology 3, Springer, Berlin, 2012, pp. 431-483, DOI: 10.1007/978-3-642-25414-7_16
[188] J.E. Sader, I. Larson, P. Mulvaney, L.R. White, Method for the calibration of atomic force microscope cantilevers, Review of Scientific Instruments, Vol. 66, No. 7, 1995, pp. 3789-3798, DOI: 10.1063/1.1145439
[189] C.P. Green, H. Lioe, J.P. Cleveland, R. Proksch, P. Mulvaney, J.E. Sader, Normal and torsional spring constants of atomic force microscope cantilevers, Review of Scientific Instruments, Vol. 75, No. 6, 2004, pp. 1988-1996, DOI: 10.1063/1.1753100
[190] C.P. Green, J.E. Sader, Torsional frequency response of cantilever beams immersed in viscous fluids with applications to the atomic force microscope, Journal of Applied Physics, Vol. 92, No. 10, 2002, pp. 6262-6274, DOI: 10.1063/1.1512318
[191] W. Tang, B. Bhushan, Adhesion, friction and wear characterization of skin and skin cream using atomic force microscope, Colloids and Surfaces B: Biointerfaces, Vol. 76, No. 1, 2010, pp. 1-15, DOI: 10.1016/j.colsurfb.2009.09.039
[192] A. Potter, G. Luengo, R. Santoprete, B. Querleux, *Stratum corneum* biomechanics, in A.V. Rawlings, J.J. Leyden (Eds.), Skin Moisturization, Informa Healthcare, New York, 2009, pp. 259-278.
[193] Y. Yuan, R. Verma, Measuring microelastic properties of *stratum corneum*, Colloids and Surfaces B: Biointerfaces, Vol. 48, No. 1, 2006, pp. 6-12, DOI: 10.1016/j.colsurfb.2005.12.013
[194] R. Álvarez-Asencio, V. Wallqvist, M. Kjellin, M.W. Rutland, A. Camacho, N. Nordgren, G.S. Luengo, Nanomechanical properties of human skin and introduction of a novel hair indenter, Journal of the Mechanical Behavior of Biomedical Materials, Vol. 54, 2016, pp. 185-193, DOI: 10.1016/j.jmbbm.2015.09.014
[195] B.V. Derjaguin, V.M. Muller, Y.P. Toporov, Effect of contact deformations on the adhesion of particles, Journal of Colloid and Interface

Science, Vol. 53, No. 2, 1975, pp. 314-326, DOI: 10.1016/0021-9797(75)90018-1

[196] F. Xu, T. Lu, Introduction to Skin Biothermomechanics and Thermal Pain, Springer, Berlin, 2011, DOI: 10.1007/978-3-642-13202-5

[197] P.G. Agache, C. Monneur, J.L. Leveque, J. De Rigal, Mechanical properties and Young's modulus of human skin *in vivo*, Archives of Dermatological Research, Vol. 269, No. 3, 1980, pp. 221-232, DOI: 10.1007/BF00406415

[198] M. Indrieri, M. Suardi, A. Podestà, E. Ranucci, P. Ferruti, P. Milani, Quantitative investigation by atomic force microscopy of supported phospholipid layers and nanostructures on cholesterol-functionalized glass surfaces, Langmuir, Vol. 24, No. 15, 2008, pp. 7830-7841, DOI: 10.1021/la703725b

[199] M. Indrieri, A. Podestà, G. Bongiorno, D. Marchesi, P. Milani, Adhesive-free colloidal probes for nanoscale force measurements: Production and characterization, Review of Scientific Instruments, Vol. 82, No. 2, 2011, Paper 023708, DOI: 10.1063/1.3553499

[200] A. Podestà, G. Fantoni, P. Milani, Quantitative nanofriction characterization of corrugated surfaces by atomic force microscopy, Review of Scientific Instruments, Vol. 75, No. 5, 2004, pp. 1228-1242, DOI: 10.1063/1.1710692