Experimental Tribology of Human Skin

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Abstract The interaction behavior of the human skin is of relevance for the functional performance of a wide range of products and, as a result, the topic is widely studied in both industry and academia. However, the key underlying mechanisms determining the interaction behavior of skin are at present not well understood.

Skin is a living material and thus will respond and may adapt to mechanical interaction, for instance by producing sweat, releasing biomarkers and even developing a blister or a wound. In addition, the properties of skin strongly depend on personal traits and characteristics. This makes predictive modelling of the interaction behaviour of skin challenging, and therefore there is a continued need for experimental investigations.

In literature a large range of experimentally obtained friction values have been reported. These have been measured using a wide variety of tribometers. When commencing tribological testing it is essential to ensure that the investigations are performed using the appropriate tribo-system, meaning that contact conditions such as pressures, sliding velocities and environmental conditions are representative for the final application, as any of these factors will have a significant effect on the obtained tribological result. Additionally, many studies use the volar forearm as measurement site; whilst this area provides ease of measurement, it may not always be highly representative of the actual skin site of interest.

Because of the complex nature of skin interactions, much of the underlying fundamental physical mechanisms remain to be discovered. Focused in-depth experimental investigations will be key to achieving a better understanding in skin tribology.

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1 Introduction

Our skin is the outermost layer of the human body and is in continuous interaction with the outside world. This interaction comes in the form of a large range of cues, of which the field of tribology covers those aspects related to contact mechanics. This includes normal and shear forces and the resulting pressures as well as shear stresses and friction.

Tribology is defined as the science and engine?ering of interacting surfaces in relative motion, and in that respect 'skin tribology' can be loosely defined as the study of interacting surfaces in which one of the interacting surfaces is the human skin or, alternatively, a substitute for human skin. The latter is pertinent when investigating damage mechanisms. The tribological behavior of skin is important for a wide variety of applications, ranging from touch perception and haptics of products such as consumer electronics and personal care and cosmetics, to the prevention of damage following more intense contact conditions, such as in the case of a sliding tackle during sports or the in the contact of skin with medical devices.

2 Tribological System

It is essential to recognize that the tribology of skin, or any other material, is not a material property, but depends strongly on the entire system of two materials in contact, the presence of a lubricating medium (gaseous, liquid or solid), the loading conditions in terms of forces and sliding velocities as well as the (micro-) environment in which the contact operates. For a skin tribo-system this is schematically illustrated in Fig. 1.

As briefly mentioned before, output parameters of the tribological system include shear forces that are the result of the friction between the two bodies, and the

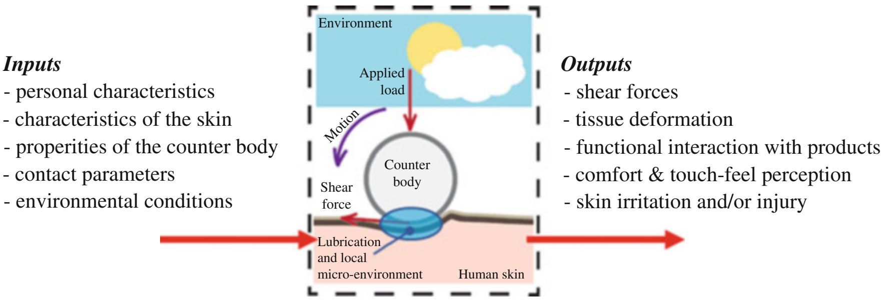

Fig. 1 The tribological system for skin-object interaction; the observed interaction phenomena depend on a multitude of inputs that include the mechanical and geometrical properties of both bodies in contact, the motion and loading characteristics and the surrounding environmental conditions, both globally and locally (after Veijgen [1])

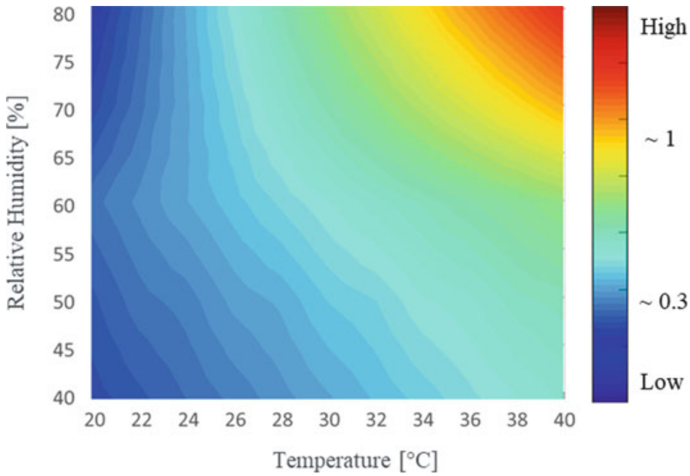

Fig. 2 Effect of temperature and humidity on friction [2]

response of the tissue to interaction. Other outputs are more affective and perception based and include touch/feel as triggered through strains and vibrations in the mechanoreceptors in the skin, and related to these, the perceived comfort or lack thereof. Another possible output is irritation and or damage to skin. It needs to be noted that any of these effects can be triggered as a result of either static friction, which is sometimes referred to as 'grip', or in medicine as 'shear', and dynamic friction, which involves macroscopic sliding and relates to the rubbing contact between two bodies.

An illustrative example of the importance of this system approach is the effect of the environment on skin interactions: compare the stickiness experienced during a hot and humid summer day to the dryness of a cold day in the winter. Whilst the skin and the counter surface may be (more or less) the same, the contact and friction behavior has completely changed due to the change in temperature and humidity. This is also illustrated in Fig. 2, from Klaassen [2], which shows the measured static coefficient of friction (represented as a heat-map) as a function of the temperature and the relative humidity.

An additional factor to consider when dealing with living tissue is the response of the tissue to the physical contact. Such responses may occur at the subject level, the tissue level as well as at the cell level: the subject may respond to interaction by preventing it from (re-)occurring, such as when someone feels discomfort because of a blister developing and subsequently adapts their gait. The response of the tissue to interaction will be deformation, possibly resulting in the restriction of blood flow through the capillary vessels, but also in the release of sweat. At the cells level the response to loading could be an anti-inflammatory reaction Cornelissen [3]. Any of these will have a marked effect on the tribo-system and thus on the output as they affect the loads, sliding velocities, the (micro-environment in which the contact operates and/or the characteristics of the two interacting bodies.

3 Experimental Methods Used in Skin Tribology

The main focus in most published skin tribology studies has been on friction, even though friction itself (maximizing, minimizing or optimizing) is hardly ever the main topic of interest in skin interactions. However, in many cases, friction is seen as a key determining component of the final objective, which could be the perception and comfort experienced whilst handling a product, the grip between the hand and a grabrail or the prevention of damage to tissue during prolonged contact.

A wide range of tribometers with corresponding have been utilized for tribological studies of the skin. Some examples are shown in Fig. 3. These tribometers can be classified into four groups based on the type of relative motion they employ, as listed below and shown in Fig. 4:

- Linear sliding or linearly reciprocating tribometers, as shown in Fig. 4a and the top row of Fig. 3. Naylor [4] was one of the first to use a linear reciprocating probe sliding against the skin. In such a configuration the alignment of the skin with the plane of motion may present a challenge, however this can be overcome to a certain degree by measuring the friction in both directions of motion. Obviously, the length of a stroke is limited. Additionally, this reciprocating configuration allows studying the point at which full sliding motion is initiated, and as such the possible occurrence of a static friction peak.
- Rotating tribometers with the axis of rotation perpendicular to the skin surface, Fig. 4b and the second row of Fig. 3, see e.g. Prall. Early versions of these tribometers were based on rotational rheometers. An obvious characteristic of such a measurement set-up is that the in-plane anisotropy of the skin cannot be assessed. Additionally, the sliding velocity in the contact increases with radial distance from the centre of motion with a zero-velocity pole at the centre of rotation. An annulus or ring-shaped specimen will prevent this from happening. Two examples of small hand-held versions of such a configuration were presented by Comaish [13] and Hendriks [9].
- Rotating tribometers with the axis of rotation parallel to the skin surface, Fig. 4c and the third row of Fig. 3. Highley [10] employed a configuration where the probe rotates against the skin with the axis of rotation parallel to the surface of the skin. Such a setup allows for continuous motion in one direction, meaning the in-plane anisotropic properties of the skin can also be taken into account. Veijgen [1] built a small, handheld version for use outside of the laboratory.
- A fourth type of set-up was introduced in the early nineties by Dinç [14], who employed a force transducer to measure the friction between the tip of the finger

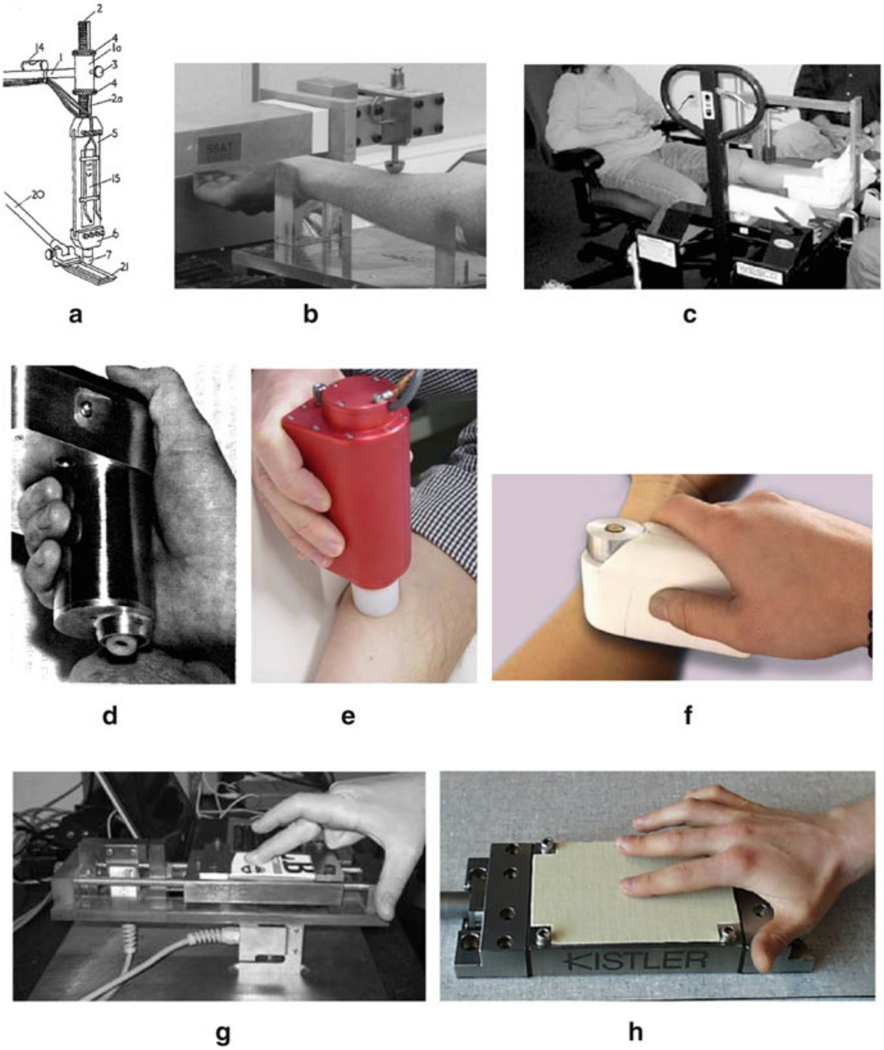

Fig. 3 A selection of skin tribometers reported in literature. (**a**) Naylor [4]. (**b**) Adams [5]. (**c**) Polliack [6]. (**d**) Comaish [8]. (**e**) Hendriks [9]. (**f**) Veijgen [1]. (**g**) Lewis [11]. (**h**) Derler [12]

sliding over a flat sample of material. Often a specimen made of a certain material is fixed onto the force transducer and the subject is asked to slide or rub the skin (often the finger, but hand, arm and feet have also been tested) against the specimen. The force transducer measures both the applied load and the resulting shear load. The input conditions such as applied load and the sliding velocity in these set-ups depend strongly on the subject and are therefore typically not very accurately controlled, or constant during the test. This means that such

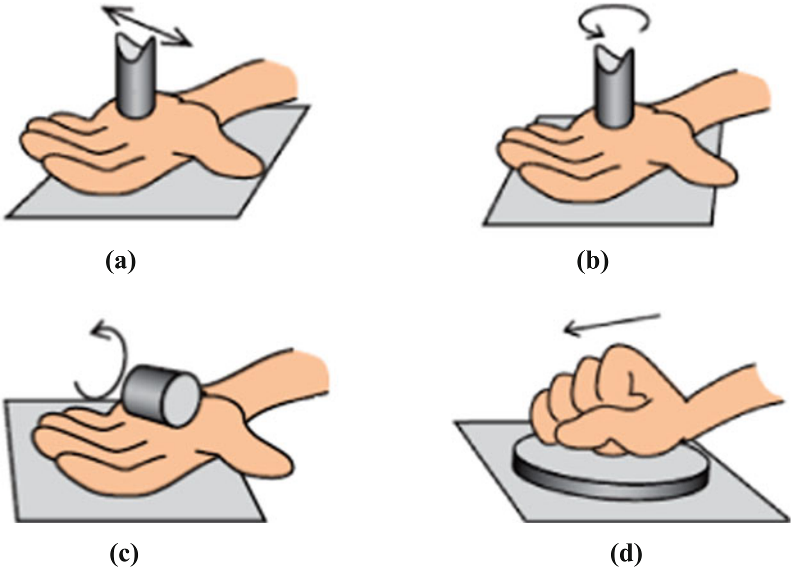

Fig. 4 Various contact configurations used in tribometry [1]. (**a**) Linear contact. (**b**) Perpendicular rotating contact. (**c**) Parallel rotating contact. (**d**) User controlled motion

a set-up is less suited for investigations focused to understanding of the basic interaction phenomena. However, they provide a testing methodology that is often somewhat closer to the application that the previously mentioned three set-ups, and therefore can provide highly relevant information. Similar setups have been successfully applied in psychophysics investigations, see e.g. Smith [15] and Gee [16].

Next to these tribometers, which are often based on traditional tribometers, but customized for use on skin and on life subjects, e.g. by reducing the applied load and velocity as well as enabling insertion of body parts, a range of commercial tribometers, in various states of development are now available for use on skin and artificial skin substitutes. A prototype version of a 'BioTriboMeter' (BTM, PCS Instruments Ltd., London, UK) is shown in Fig. 5. Biotribometers typically allow more complex motion profiles than traditional tribometers, whilst allowing a dynamic applied load and recording forces at high (>100 Hz) temporal resolution, to match the triggering frequencies of the mechanoreceptors in the skin.

Given the wide range of set-ups used by various researchers, results reported in the literature for skin friction measurements are obtained using a large range of measurement conditions: besides the possible variations in the motion type of the tribometer that were discussed above, a fairly large range for both the applied load and the sliding velocity have been used. Loads vary between 10 mN and 100 N whilst velocities range from the order of 100 μm/s to several metres per second. As

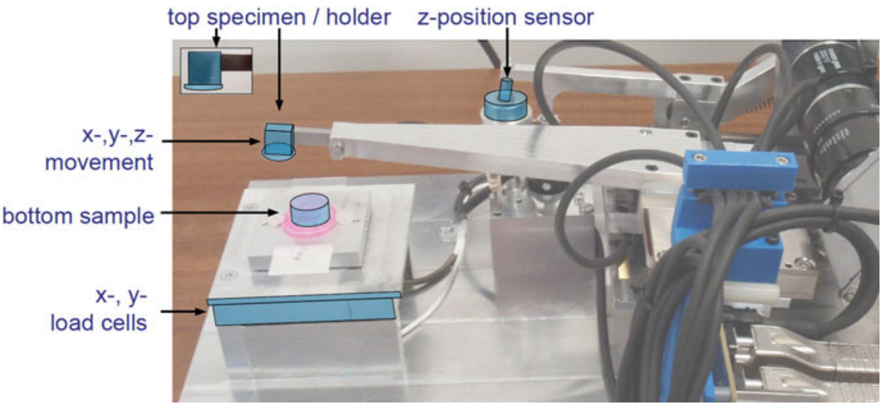

Fig. 5 Prototype biotribometer for use on a variety of tissue and tissue mimics, Porte [17]

discussed by Sivamani [18, 19], Derler [20] and Veijgen [1], coefficient of friction values for skin reported in literature range from less than 0.2 to over 2.

4 Key Factors Affecting Dynamic Friction

An excellent overview of the key factors and their effects on the friction behavior of skin that have been reported in literature has been provided by Derler [20]. A brief overview of their findings is provided in Table 1. From this overview it can be concluded that many of the key underlying factors in skin tribology are at present still not very well understood, and that many investigators obtained conflicting results.

5 Hydration of the Skin

Although there currently is no clear consensus between researchers on which parameters are affecting the tribological behavior of skin, most researchers agree that the moisture content, or the hydration, of the skin appears to be one of the most important parameters determining friction. This also aligns with intuition and everyday experience that, preventing full film lubrication or '*aquaplaning*', the friction under moist or damp conditions is significantly higher than in dry conditions.

A range of researchers, including Comaish [13], Highley [10], Wolfram [21], Johnson et al. [22] and Adams [5] studied the friction under 'dry' and 'wet' conditions and found a significant increase in wet conditions. El-Shimi [23] and Sivamani [18, 19] observed a correlation between the hydration level and the coefficient of friction. Gerhardt [24] showed that this correlation was indeed valid for individuals when the moisture content of the skin is carefully controlled, but also

Table 1 Factors affecting the friction of skin, as reported in a review paper by Derler [20] and experiments by Veijgen [1]

Factor	Effect on friction		
	Derler [20]		Veijgen [1]
Hydration of the skin	Increase or increase up to a maximum, followed by a decrease		Positive correlation
Temperature of the skin	Not mentioned		Negative correlation
Ambient temperature	Not mentioned		Positive correlation
Amount of sebum on the skin	No effect or a slight increase		No significant effect
Skin surface roughness	No effect		Not included
Roughness of counter body	Unclear: Decrease, increase or decrease until a minimum followed by increase all reported		Negative correlation
Surface free energy of counter body	Unclear, both increase and decrease reported		Positive correlation
Age of subject	No effect, constant		Positive correlation
Height of subject	Not mentioned		Negative correlation
Body region	*High*:	Forehead and behind ear	Finger pad significantly higher than other sites
	↓	Volar forearm and upper back	
		Dorsal forearm	
		Ankle and palm	
		Lower back	
		Thigh	
	Low:	Abdomen	Temple significantly lower than other sites

that the moisture content of a person's skin as measured using capacitive methods appears not to be a generally applicable predictive parameter for the friction of the skin. This is further evidenced by the large deviations for the friction for each value of the moisture content in Fig. 6.

It appears reasonable to suspect the moisture content of the skin to be one of the driving factors behind friction. Indeed, Johnson [22] already identified the role of water, and Adams investigated the effects of occlusion to the friction. Klaassen [2], suggested that the amount of water available to the contact drives the observed friction coefficient. Klaassen [25] employed an alternative characterization of the moisture content of skin, based on the work of Bomannan [26] and Lucassen [27] in which he employed Fourier Transform InfraRed (FTIR) spectroscopy using an Attenuated Total Reflectance (ATR) crystal to ensure appropriate measurements on the skin.

They found a high correlation between the friction and the moisture content of the skin as expressed in terms of the ratio of the Amide I and Amide 2 peaks in

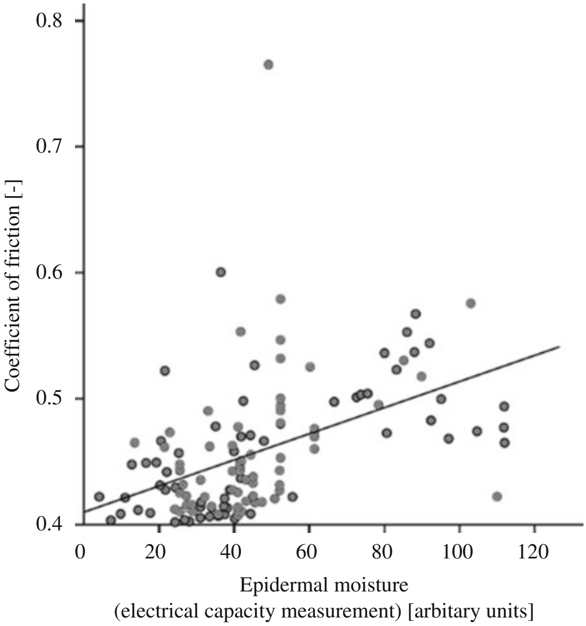

Fig. 6 Skin moisture content or hydration related to friction for 50 people, as reported by Veijgen [1]

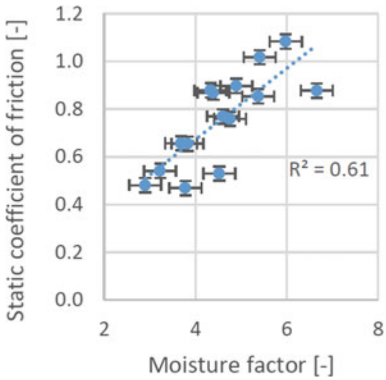

Fig. 7 Friction as a function of in-vivo measured skin moisture factor, defined as the ATR-FTIR Amide I to Amide II ratio

an ATR-FTIR spectrum of the skin (Fig. 7). The coefficient of friction correlates well to this skin moisture factor, with a coefficient of determination of $R^2 = 0.61$. Whilst for most engineering application this value would be considered fairly low, for applications involving living subjects, this value is reasonable.

6 Static Friction and Dynamic Friction

As stated before, the static friction has a close relationship with aspects such as grip and the contact between medical devices and skin, whereas the dynamic friction relates to rubbing and the perception of touch and feel. There is an ongoing

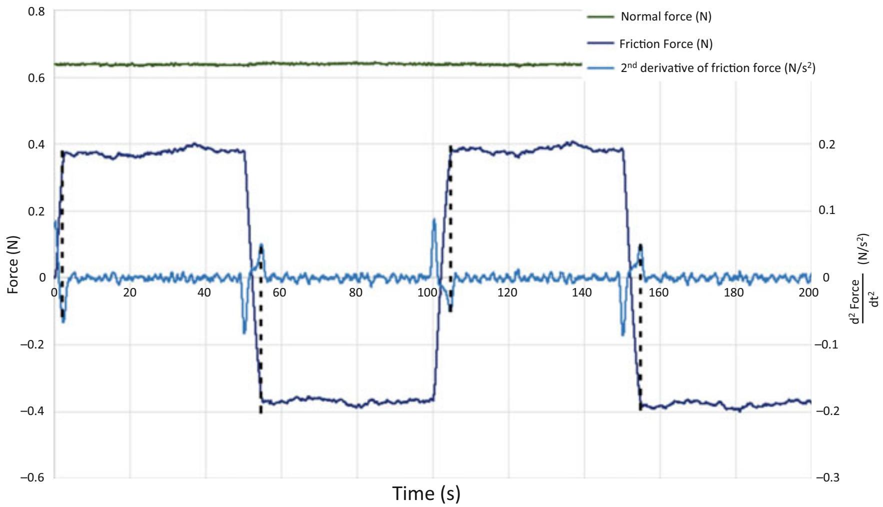

Fig. 8 Measured friction force signal obtained in a linear reciprocating tribometer, and the second time derivative of the friction force to define the onset of macroscopic sliding

debate if skin actually exhibits a 'traditional' static friction peak and if so, how to define this phenomenon unambiguously. As a result, many researchers develop their own definition of a static and a dynamic friction and how to deduce this from a measured signal. At present, there appears a significant amount of ambiguity, and any differences in values for the coefficients of friction reported in literature based may very well be based on non-similar definitions, compare e.g. Gitis [28], Koudine [29] and Klaassen [25]. A more firm definition of the reported friction values would be extremely useful.

Gitis [28] defined the static coefficient of friction as the maximum value in their measured signal and take the mean value as the dynamic coefficient of friction. They also use the ratio between the amplitude and the mean as a measure for the 'stickiness' of the skin. Koudine [29] refers to the fluctuation in the frictional force which they attribute the variation to the non-uniformity of the skin's surface Klaassen [25] suggests defining the transition between the static and the dynamic regime by taking the second time derivative of the friction signal (Fig. 8), and defining the maximum static friction as the maximum friction value measured in a period of 0.2 s around this transition point. Although the use of a 0.2 s band might be random, this is a fairly unambiguous definition.

Finally, Veijgen [30] observed that the dynamic coefficient of friction for skin contact is on average 0.85 times the static coefficient of friction, as shown in Fig. 9.

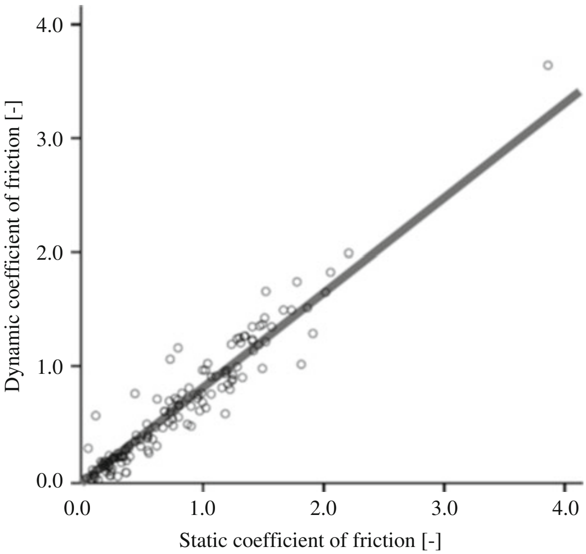

Fig. 9 Statistical relationship between static and dynamic coefficient of friction

7 Concluding Remarks

Interest in the tribology of skin is growing and over the past two decades an abundance of research papers has been published discussing the frictional behavior of skin. However, much remains to be discovered as the key underlying mechanisms are still not well understood. A large range of friction values have been reported in literature. In various cases the volar forearm has been assumed to be representative for skin on other body sites, but this appears to be an assumption that is mainly focused towards an ease of measurement. Recently, several small tribometers have been developed that can be used on multiple body sites, and a small selection was shown in Fig. 3. Additionally, a number of commercial tribometers allow testing of tissue and tissue mimics under a wide range of conditions. These devices also allow friction measurements to be recorded at high temporal resolution, typically in the order of 1000 Hz, linking the measurement with the typical trigger rates of the mechanoreceptors that are distributed in the skin.

A complicating factor in skin friction research is that many studies do not fully define the tribological system in unambiguous terms: many studies will lack information about the subjects, normal load or pressure, the relative velocity, the properties or finish of the contact material and the environmental conditions. Quite often the skin is rather simplistically described in terms of the anatomical location and the age of the subject. However, the skin is a living material and its properties depend on many more variables, including, but not limited to the thickness of the skin layers, gender, ethnicity, dietary habits, the season as well as the ambient temperature and the humidity. Indeed, scientific literature shows a broad range of results with a variety of, often conflicting, conclusions. It seems likely that this may result from differences in materials, methods and/or experimental conditions. It is rather obvious that two studies cannot use the exact same skin samples, as even when experiments are done on the same subjects, a range of other parameters will have changed. Therefore, it is impossible to exactly reproduce studies and results, even when measured under the same circumstances.

When commencing tribological testing it is absolutely essential to ensure that experimental investigations are done using the appropriate tribo-system, meaning contact conditions such as pressures, sliding velocities and environmental conditions are representative for the final application, as any of these factors could have a significant effect on the tribological result.

Because of the complex nature of skin interactions, much of the underlying fundamental mechanisms remains to be discovered. Focused in-depth experimental investigations will be key to achieving a better understanding in skin tribology.

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