Tribol Lett (2013) 49:251–262
DOI 10.1007/s11249-012-0062-1

ORIGINAL PAPER

Relating Friction on the Human Skin to the Hydration and Temperature of the Skin

N. K. Veijgen · M. A. Masen · E. van der Heide

Received: 2 August 2012 / Accepted: 20 October 2012 / Published online: 2 November 2012

Abstract The human skin is constantly in interaction with materials and products. Therefore, skin friction is relevant to all people. In the literature, the frictional properties of the skin have been linked to a large variety of variables, like age, gender and hydration. The present study compares the data of 450 skin friction measurements with the skin hydration and skin temperature on four locations on the body, measured with four materials: stainless steel (SST), aluminum (Al), PE and PTFE. The median skin temperature was 32.1 °C and the median skin hydration was 25.5 AU, as measured with a Corneometer. The median coefficient of friction was 0.52 for the static coefficient of friction and 0.36 for the dynamic coefficient of friction. There was a linear relationship between those two types of coefficient of friction. The coefficient of friction was highest for SST and lowest for PTFE. The frictional properties depend on the skin hydration and skin temperature. Gender differences were found for both skin hydration and coefficient of friction. Most of the variation in the coefficients of friction could be explained by the differences in hydration.

N. K. Veijgen (✉) · M. A. Masen · E. van der Heide
Laboratory for Surface Technology and Tribology, University of Twente, Drienerlolaan 5, 7522 NB Enschede, The Netherlands
e-mail: n.k.veijgen@utwente.nl

M. A. Masen
e-mail: m.a.masen@utwente.nl

E. van der Heide
e-mail: e.vanderheide@utwente.nl

E. van der Heide
TNO, Materials Performance Centre, De Rondom 1, 5612 AP Eindhoven, The Netherlands

Keywords Biotribology · Skin hydration · Human skin · Friction coefficient

1 Introduction

The interest in measuring the friction between the skin and other materials has grown considerably in the past decades. A better understanding of the frictional behavior of skin is relevant to all people, as the skin interacts with a large variety of materials in people's environment. Insight into skin friction can be useful for product development and in contact situations in which the skin gets damaged. Ideally an objective measure like friction could be used as an indicator for comfort or skin damaging. Knowledge of skin friction can also be used to enhance the experience and functionality of products.

The frictional properties of the skin have been associated with variables like the person's age, the relative humidity of the environment and the hydration of the skin. Some variables are related to each other. For example, the hydration of the skin is assumed to be related to the air humidity [1–4].

The skin friction measurements described in the literature are diverse in character [5–31]: the measurements differ not only in the skin sample and contact material, but also in the type of movement between the skin and contact material, the normal load and relative velocity between the materials. The large differences make it difficult to compare the studies and to identify important variables influencing the friction in skin–object interactions. Nevertheless, it has been possible to identify some trends in the results. One of the trends observed in skin friction research is that the coefficient of friction increases after water is applied onto the surface of the skin [15–24]. For variables like age and gender, no persistent trends have been observed and, therefore, these variables are believed not to influence the coefficient of friction [14–18]. Although the anatomic location on which the friction measurement is executed is held to be an important influencing factor for skin friction, it is unknown how skin friction results are influenced and what causes these differences.

The objective of this study is to contribute to a better understanding of skin friction by coupling the data of skin friction measurements to the results of skin hydration and temperature, and to compare the results to those reported in other studies. Veijgen et al. [5] recently developed a mobile device to measure the friction between a material of choice and the skin. The device enables the researcher to measure the skin at all anatomical locations at the glabrous and hairy skin of human subjects. The effort required from the subjects is limited by the portability of the device and the short measurement duration. The mobile device allows the researcher to take it to the subjects instead of requiring the subjects to visit a laboratory, and the short measurement duration (20 s for a standard single test, and approximately 10 min for a full program of repeated measurements on several anatomical locations) makes it acceptable to participate for most people. The results of a comprehensive panel test are presented in this paper and the results of skin friction, hydration and temperature are compared to results from the literature.

2 Methods

2.1 Equipment

The device used for the friction measurements is the portable handheld device described by Veijgen et al. [5]. The device measures the friction between the human skin and a cylindrical contact material of choice. The medical ethics committee of the MST hospital in Enschede, The Netherlands, advised that no medical ethics examination is required for this research.

The device is equipped with a cylinder of the contact material of interest, which is installed before measurement. The contact material rotates with its axis parallel to the surface of the skin. As the device remains stationary to the skin, the surface area of the cylinder slides over the skin. The velocity between the skin and contact material can be set before the measurement starts to a constant value of 1, 2, 5 or 10 mm/s.

The normal load is applied by a spring and is adjustable between 0.5 and 2 N. The friction and normal forces are registered in time and stored on the internal memory, with a standard sample frequency of 2.5 kHz. The variation in both the velocity and the normal load during a friction measurement are typically less than ±5 % of the pre-set value.

2.2 Contact Material

The mobile device was equipped with a cylinder of 20 mm in diameter and 10 mm wide. The edges of the cylinder were rounded with a 1 mm radius. Cylinders of four solid materials were used: stainless steel (SST), aluminum (Al), polyethylene (PE) and polytetrafluorethylene (PTFE). The properties of the samples are summarized in Table 1. The surface roughness (R_a) was measured with a confocal laser scanning microscope (Type VK-9710 K, Keyence Corporation, Osaka, Japan). At least 10 min before a series of measurements, the samples were cleaned with isopropanol (IPA).

2.3 Participants

The test panel of subjects was composed on several days in the spring of 2012 at the University of Twente in Enschede, The Netherlands. Before the measurements started, the objective of the study and the procedure of the measurements were explained to the volunteers. The subjects gave their informed consent and provided information about their age.

The sample of subjects in this study was 31 healthy volunteers (22 male, nine female). The age of the subjects was tested for normality with a Kolmogorov–Smirnov test (K–S), which indicated that the data was not normally distributed ($p < 0.01$). Therefore, age is presented as range, median and interquartile range (IQR). The range in the participants' age is indicated with the minimum and maximum value, the median refers to the middle value, or 50th percentile, meaning that 50 % of the values is higher and 50 % lower. The IQR represents the difference between the 25th and 75th percentile. The range in the age of the subjects was 23–56 years, with a median of 26 years and IQR was 8 years.

The device enables friction measurements on many anatomical sites. In this study, the skin on four anatomical sites is assessed: two locations on the hand and two on the lower arm (Fig. 1a). The axis of rotation was perpendicular to the length of the arm, hand or finger, and the direction of

Table 1 Material parameters of the cylindrical samples used

Sample	Material	R_a (μm)
SST	DIN1.4406 (AISI316LN)	0.57
Al	Al 6063	0.45
PE	LDPE	4.27
Polytetrafluorethylene	PTFE	6.39

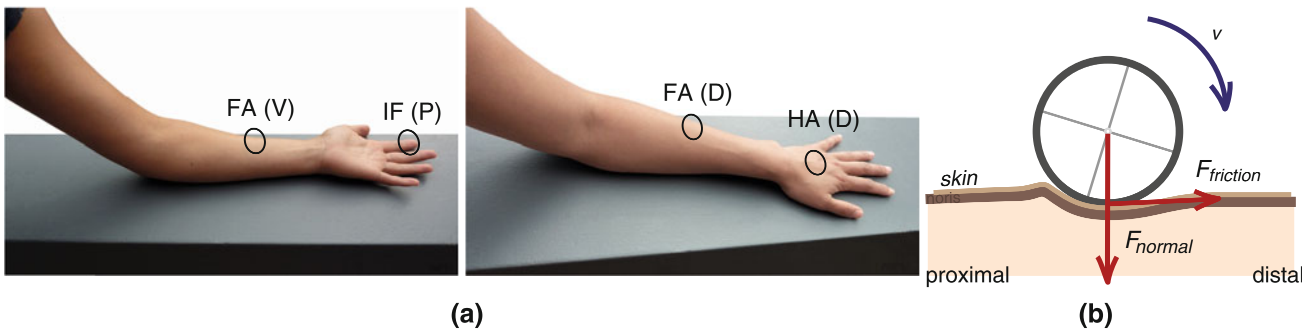

Fig. 1 The anatomical locations tested

the rotation is indicated in Fig. 1b. Proximal indicates the part closer to the shoulder, and distal further away from the shoulder.

The subjects were asked to participate in the study just before the measurements were executed. As cleaning or treating the skin just before measuring the skin would probably influence the skin friction results, the skin samples were not treated or cleaned in a specific way. The subjects followed their usual skin care routine and they indicated whether they had washed the skin areas of interest and whether they treated the skin area with skin care products within 1 h before the measurements.

2.4 Measurements and Contact Parameters

Before executing the skin friction measurements, the temperature and hydration level of the skin were measured at the skin area of interest. An indication for the hydration of the skin was obtained with a Corneometer (CM825; Courage + Khazaka Electronic GmbH, Cologne, Germany). The Corneometer uses the capacitance as an indicator for the hydration of the outer 10 µm of skin, and the results are expressed in arbitrary units (AU). The temperature of the skin area was measured with a commercial fever thermometer, which uses infrared to measure the temperature. Measuring the skin hydration and temperature before skin friction measurements was preferred because it could be done at the same time as the subject provided information on some personal characteristics. A pilot study demonstrated that the measured values before and after skin friction measurements for both variables did not differ significantly.

Together with the self-reported characteristics of the subjects, the applied test settings and the ambient conditions were logged. Before starting a measurement, the device was adjusted for the desired normal load and velocity. The normal load and velocity were pre-set and remained constant during the skin friction measurements. The constant value for the normal load varied between 0.5 and 2.0 N and the velocity between the skin and contact material was varied between 1, 2, 5 or 10 mm/s. The ambient conditions were described in terms of air temperature and relative air humidity, Table 2.

Table 2 An overview of the definitions used

Number	31
Male	22
Female	9
Age, range	23–56 years
Median	26
Interquartile range	8

After the conditions were logged and the desired settings were applied, the device was pushed onto the skin and held in that position. Subsequently, the motor started the relative motion between the contact material and the skin. After 20 s, the measurement stopped automatically and the device was removed from the skin.

Each measurement condition was repeated three times in order to check the consistency of the measurement. While downloading the data into the computer, there was a cursory inspection of the data. If the raw results displayed a large variation, the condition was measured three times again. The measurements were all executed by the same researcher.

The ambient conditions were not normally distributed (K–S, $p < 0.001$), and are therefore presented as range, median, and IQR. The measurements were executed at an air temperature ranging from 20.8 to 25.3 °C (median: 24.2 °C; IQR: 0.8 °C) and a relative air humidity of 32–57 % (median: 43 %; IQR: 18 %).

2.5 Data Processing and Statistics

The normal load and friction force, which were sampled at the minimum sample frequency of 2.5 kHz, were downloaded from the internal data acquisition system into the computer after each measurement. Data were processed with Matlab (version R2011b; The MathWorks Inc. Massachusetts, USA).

Table 3 An overview of the definitions used

μ	Coefficient of friction, calculated as the quotient of the friction force and normal load
μ_s	Static coefficient of friction. In this study defined as the peak value in the coefficient of friction in the first second after the movement was initiated. In cases in which no peak was visible, the μ_s and μ_d were assumed to be equal in this study
μ_d	Dynamic coefficient of friction. Defined as the mean value of the data points after the coefficient of friction had stabilized
F_f	Friction force, the force caused by the resistance against the motion between the skin and contact material
F_n	Normal load: the force between the skin and contact material
v	The velocity of the rotating cylinder sliding over the skin

For the statistical analyses, PASW statistics sofare was used (release 18.0; IBM Inc, Armonk, USA). The definitions used in this study are displayed in Table 3. The level of confidence was set on 95 %. Therefore, α, which represents the probability that the measured effects were caused by chance alone, is 0.05.

All variables were tested for normality with a K–S test. The outcome, p value, indicates the probability that the hypothesis (that the data in a certain variable are normally distributed) is caused by chance alone. Values for $p < 0.05$ are used to conclude that the data for that variable are not normally distributed.

The non-normal character of the data requires the use of non-parametric tests for the statistical analyses. The variables were compared using either a Mann–Whitney U test (M–W) or an independent-samples Kruskal–Wallis test (K–W). These are non-parametric tests for analyzing the differences between two (M–W test) or more (K–W test) groups. For example, a M–W test was used for determining the difference between men and women (two groups), and a K–W test for the four anatomical locations. For both tests, p-values smaller than 0.05 indicate that there are significant differences between the groups. Spearman's rank order correlation coefficient rho (denoted by r_s) was used to indicate the dependence between two variables. A positive value for r_s indicates that the relationship between the variables is proportional: for example, in a relationship between X and Y, larger values for X result in larger values for Y. When r_s is negative, the relationship is inversely proportional, and increasing X will lead to a decrease in Y. The magnitude of r_s indicates how the spread or distribution of the data is around the best fit line, rather than the direction of this line.

Table 4 Measurement results of the temperature and hydration of the skin

	Skin temperature (°C)		Skin hydration (AU)	
	Range	Median (IQR)	Range	Median (IQR)
Total	21.4–35.1	32.1 (2.7)	4–112	25.5 (3.1)
Ventral forearm	29.1–34.9	32.2 (2.6)	13–56	41.0 (10.0)
Dorsal forearm	30.7–34.6	32.4 (1.6)	4–47	29.0 (19.3)
Index finger pad	21.4–35.1	30.2 (6.2)	22–112	78.4 (47.0)
Dorsum hand	30.3–33.2	32.1 (2.8)	10–43	25.5 (3.1)

3 Results

The results of the friction measurements and the measured skin hydration and skin temperature data will be related to each other. Before comparing the results, first the data of skin hydration, skin temperature, and friction will be discussed separately. The distribution of the measurement results (coefficients of friction, skin hydration, and skin temperature) was not normal (K–S $p \leq 0.003$). Therefore, non-parametric tests are used, and the data are presented as range, median (IQR), unless stated differently.

3.1 Skin Hydration and Skin Temperature

The results of the skin temperature and skin hydration are displayed in Table 4. The distribution of both the skin temperature and skin hydration were significantly different across the anatomical locations with $p < 0.001$ for both variables. The variation in both skin hydration and skin temperature for the location index finger pad was relatively large compared to the other anatomical locations.

Spearman's rho between the skin temperature and hydration of the skin on the forearm were significant with a LOC of 95 %, but not for the hand. For the ventral forearm, $r_s = -0.467$ ($p < 0.001$) and for the dorsal side of the forearm, $r_s = -0.346$ ($p = 0.042$).

The hydration of the index finger pad was significantly correlated with the relative humidity (r_s: 0.361; $p = 0.028$), though for other locations no significant correlation was found. The temperature of the ventral forearm was significantly correlated with the ambient temperature (r_s: 0.492; $p < 0.001$), though not for the other body regions.

For the two locations on the forearm, the skin temperature for men was significantly higher than for women (M–W $p < 0.0001$ and $p = 0.002$ for the ventral and dorsal forearm, respectively). The hydration was significantly different for men and women on all anatomical locations (M–W $p \leq 0.03$). Figure 2a shows a box plot of the skin hydration as measured on the four anatomical locations. The boxes indicate the IQR, with an indicator for the median. The T-bars at both ends of the bar indicate the minimum and maximum. When measured values deviated more than 1.5 times the IQR from the quartile, the T-bars

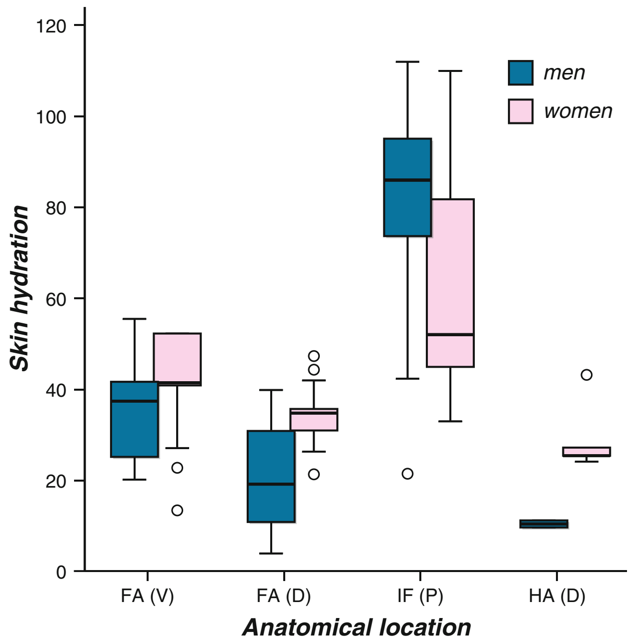

Fig. 2 The hydration level of the skin depends on the anatomical locations

indicate 1.5 * IQR, and the deviating values are indicated separately by dots. The dark bars indicate the hydration levels for men, and the light bars those for women. The figure displays that the skin hydration for men, compared to women, is higher on the pad of the index finger. On the other anatomical locations measured in the present study, the hydration was lower for men compared to women.

3.2 Coefficients of Friction

Both static and dynamic coefficients of friction were calculated from the measured friction and normal forces. The correlation between the dynamic and static coefficient of friction was high: r_s was 0.923 ($p < 0.001$) for all friction measurements. There was a linear relationship between the static and dynamic coefficient of friction: the static coefficient of friction is a factor 1.17 larger than the dynamic coefficient of friction.

3.2.1 Anatomical Location

The results for both static and dynamic coefficient of friction are displayed in Table 5. The coefficients of friction were significantly different across the parts of the body (K–W $p < 0.001$ for both μ_s and μ_d) and other skin variables (K–W $p < 0.001$ for both skin hydration and skin temperature).

The correlations between the coefficient of friction and the skin temperature and skin hydration were significant (all $p < 0.001$). The Spearman's correlation coefficients were −0.375 and 0.564 for μ_s, and −0.327 and 0.553 for μ_d for skin temperature and skin hydration, respectively. Figure 3 displays the static and dynamic coefficients of friction for all body regions.

Table 5 The coefficients of static and dynamic friction for different body regions

	Static coefficient of friction (–)		Dynamic coefficient of friction (–)	
	Range	Median (IQR)	Range	Median (IQR)
Total	0.03–3.86	0.52 (0.73)	0.02–3.64	0.36 (0.60)
Ventral forearm	0.05–3.86	0.53 (0.55)	0.02–3.64	0.42 (0.53)
Dorsal forearm	0.03–0.90	0.23 (0.27)	0.03–0.62	0.15 (0.19)
Index finger pad	0.20–1.91	1.04 (0.93)	0.28–1.75	0.90 (0.90)
Dorsum hand	0.05–0.65	0.40 (0.34)	0.05–0.48	0.19 (0.30)

3.2.2 Contact Material

The coefficient of friction not only depends on the skin, but also on the contact material (Fig. 4). The coefficient of friction with SST is higher than for the other materials, while the coefficient of friction for PTFE is lower (both $p < 0.001$). The coefficients of friction obtained with Al and PE were not significantly different. The differences in μ between anatomical locations were observed for all anatomical locations together as well as for the locations separately.

The conversion rate between the dynamic and static coefficient of friction were significantly different between the anatomical regions. For SST and Al, the conversion rates were similar (1.13), but the rates were significantly higher for PTFE and PE (1.58 and 1.77, respectively).

3.2.3 Gender

The differences for the dynamic coefficient of friction between men and women are shown in Fig. 5. The differences in the dynamic coefficient of friction are significant for the locations index finger pad and dorsum of the hand (M–W U $p = 0.007$ and $p = 0.032$, respectively). The static coefficient of friction behaves similarly and is also significantly different for these locations (M–W U $p = 0.032$ and $p = 0.028$, respectively).

3.2.4 Operational Conditions and Environment

The velocity between the skin and the contact material was varied between 1, 2, 5, and 10 mm/s. There was no effect

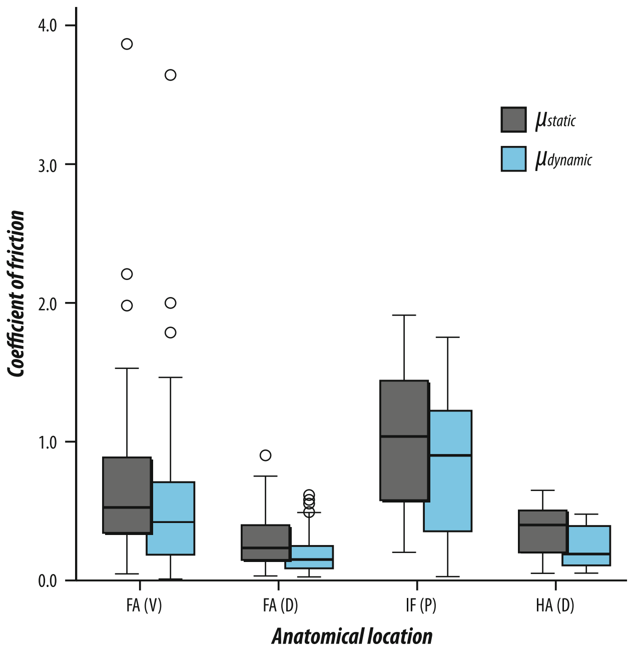

Fig. 3 The coefficient of friction varies over the four anatomical locations

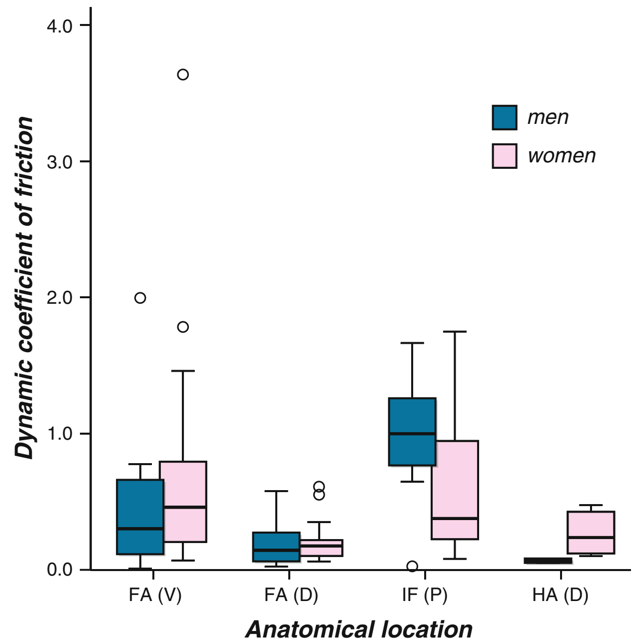

Fig. 5 The influence of gender on the dynamic coefficient of friction varies over the anatomical locations

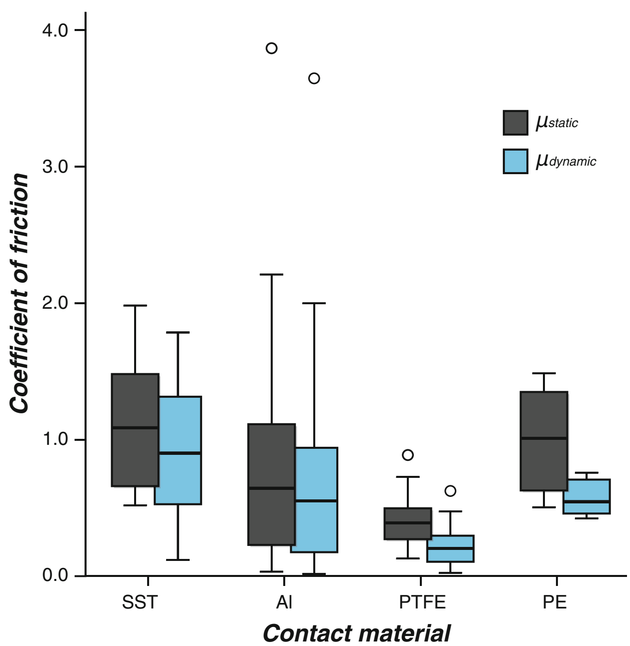

Fig. 4 Measurements with the four materials yield different coefficients of friction

observed for the sliding velocity on the coefficient of friction for the different body regions. The normal load in this study was varied between 0.5 and 2 N. There was a significant correlation between the normal load and the coefficient of friction, for both μ_s and μ_d. Spearman's correlation coefficient was -0.398 ($p < 0.001$) and -0.439 ($p < 0.001$) for μ_s and μ_d, respectively, which indicated that the coefficient of friction was higher for lower loads. Regression analysis could not give a definite answer to the nature of the relationship between the variables: curve fitting based on regression analysis returned linear and logarithmic models as the best fit options, although for both models the explained variance with both linear and logarithmic models was low ($R^2 < 15$ %).

4 Discussion

The objective of this paper was to compare data of the skin friction, hydration, and temperature measurements on four anatomical regions on the human skin. The skin friction measurements were performed with four materials. The measurement data were obtained with a test panel of 31 people: 22 male and 9 female.

4.1 Skin Temperature and Skin Hydration

This study obtained a median skin temperature of 32.1 °C and a median skin hydration of 25.5 AU. Other studies found comparable values for the skin hydration. Bettinger [25] obtained higher values for the hydration on the proximal forearm, with a median skin hydration of 79.3 AU for untreated skin. The hydration of the index finger measured in the current study of 78.4 is comparable to the Corneometer values of 70 AU reported by Kuilenburg et al. [6]. The median Corneometer value for the dorsum of the hand in the current study was 25.5 AU. Zhu et al. [24] reported medians ranging from 25 to 35 AU, at this anatomical location for the age corresponding to that of the subjects participating in the current study.

It was expected that the hydration of the skin would be related to the air humidity and that the temperature of the skin would correlate to the ambient temperature. Although, only for the hydration of the skin on the index finger pad, there was a significant correlation with the air humidity, the air humidity was rather correlated with the temperature of the skin. In the literature reporting on the relationship between skin hydration and air humidity [1–4], the values for the air humidity were more extreme (RH $>$ 80 %) rather than the humidity of 43 % in the present study. This may explain why the expected relationship, as reported in the literature, was not found in the current study.

4.2 Coefficients of Friction

4.2.1 Comparing Coefficient of Friction

The coefficients of friction obtained in this study range between 0.03 and 3.86 for μ_s and 0.02 and 3.64 for μ_d. The range in the coefficients of friction is large. The lowest coefficients of friction ($\mu < 0.1$) are obtained in persons with many hairs on the skin area of interest, or with lower values for the skin hydration and at a higher air humidity. The lower coefficients of friction were mainly obtained with PTFE. Typically, all coefficients of friction smaller than 0.1 were obtained on male subjects, whereas the higher coefficients of friction (over 1.5) were mostly obtained on females, with a skin with a higher hydration level and most often measured with SST.

The coefficients of friction reported in the literature also display a large variation: 0.11–3.4 [7, 8] and 0.07–5.0 [9, 10] for μ_s and μ_d, respectively. In most skin friction research, the dynamic coefficient of friction is used to discuss the friction involving the human skin and is the term hydration used for conditions in which water is added in between the skin and contact surface. The effect of hydration to friction is simulated by adding water in between the materials. Nevertheless, in the current study, the differences in the Corneometer readings are attributed to inter-personal differences rather than to skin treatment or application of water to the skin.

This study describes the results of skin friction measurements in relation to the skin hydration and skin temperature, based on a relatively large sample of subjects. There are few studies that compare to the current study, regarding the contact parameters (e.g., normal load, velocity, and type of movement) and environmental conditions (e.g., temperature and air humidity). Therefore, it is more useful to compare the trends observed in the current study to those reported in the literature, rather than comparing the measured values for the coefficients of friction. Moreover, in some studies, the frictional properties are not expressed as the coefficient of friction but in AU [21] or in an custom expression [14].

4.2.2 Relationship Between Skin Temperature and Coefficient of Friction

The effect of skin temperature on the frictional properties of the skin has not been described in the literature. The results of the present study indicate a linear relationship between the temperature of the skin and the dynamic coefficient of friction, although it must be noted that the explained variance is rather low ($R^2 = 0.11$). Figure 6 shows that there is also a linear relationship between the skin hydration and skin temperature ($R^2 = 0.23$). Regression analysis shows that both variables contribute significantly to the variation in the coefficient of friction, which indicates that the skin temperature is, besides the hydration of the skin, an important variable to influence skin friction.

4.2.3 Relationship Between Hydration and Coefficient of Friction

One of the hypotheses in the current study was that there would be a relationship between the hydration and coefficient of friction. In the literature, a more hydrated skin (or higher Corneometer readings) has been associated with an increase of the adhesion between the skin and contact material, and consequently increase in the measured friction [14–16, 22]. The explanation could be

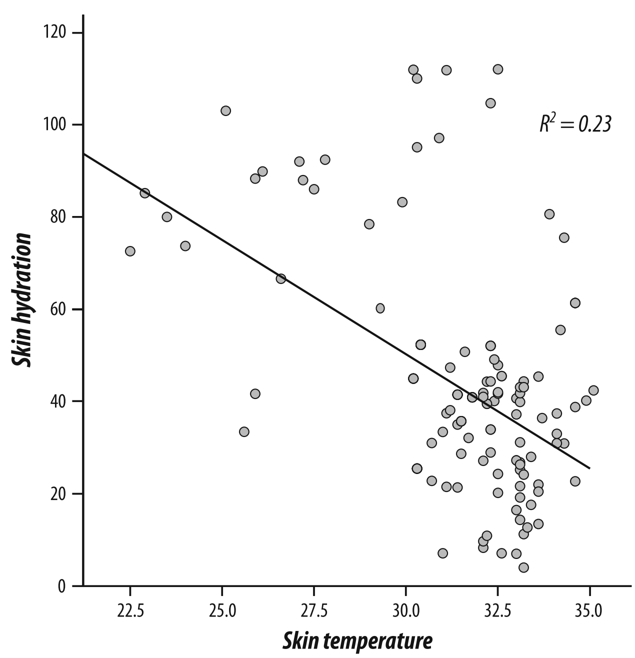

Fig. 6 The linear relationship between the skin hydration and skin temperature

found in the decreased stiffness of the skin, leading to larger real contact area between the contact material and hydrated skin. Therefore, it was expected that higher hydration levels would lead to higher coefficients of friction.

The results in the current study confirm that there is a significant positive correlation between the hydration of the skin and the coefficient of friction and curve fitting returns that the relationship is either linear or exponential, although the explained variance does not give a decisive answer on the nature of the relationship. Figure 7 shows a scatter plot of the coefficient of friction and the hydration of the skin. The line indicates the linear regression line. Gerhardt et al. [16] and Cua et al. [17] reported a linear relationship between hydration and friction, whereas Kwiatkowska et al. [24] found that the relationship was rather exponential. Hendriks and Franklin [23] found both linear and exponential relationships, depending on the environmental conditions. The results on the relationship between the skin hydration and skin temperature reported in the literature support the relationship observed in the current study, although the literature could not give a definite answer about the nature of this relationship.

The results of the present study indicate that skin hydration is an important influencing variable for skin friction. Increasing hydration levels lead to higher coefficients of friction. This effect is observed for each of the four contact materials and for each anatomical location.

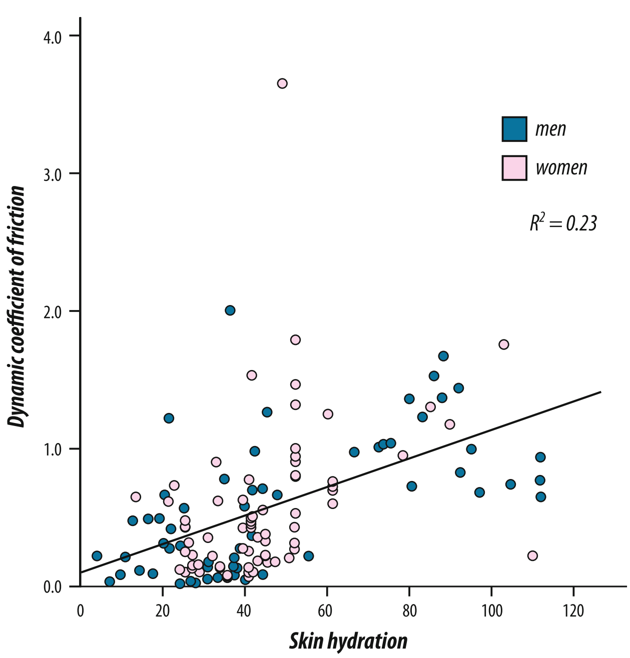

Fig. 7 The linear relationship between the coefficient of friction and the skin hydration

4.2.4 Gender Differences

The coefficients of friction were significantly higher for men than for women at the index finger pad, whereas it was significantly lower at the dorsum of the hand. The hydration of the index finger skin is also significantly higher for men than for women, and at the dorsum of the hand, the hydration is also significantly lower for men than from women. The temperature on these skin locations was not significantly different between men and women.

The skin hydration on the locations on the forearm is lower for men, compared to for women for both locations, while the skin temperature, on the contrary, at these locations is higher for men compared to women. For both locations on the arm, there are no significant gender differences for the coefficient of friction.

The significant differences in coefficient of friction between men and women can be related to the differences in hydration. Regression analysis demonstrates that practically all of the variability in the coefficient of friction can be explained by the differences in hydration and not by gender differences.

In the current study, the coefficient of friction was lower for men compared to women for PTFE. This is supported by Zhu et al. [21], who also found significant differences for the friction on the dorsum of the hand ($p < 0.001$), measured with PTFE for a corresponding age category.

4.2.5 Body Region

One of the trends observed in the current study is that the coefficient of friction is highest on the index finger, followed by the ventral forearm, and for the four locations reported in this study, the lowest coefficients of friction were obtained on the dorsum of the hand and the dorsal forearm. Derler and Gerhardt [15] summarized in their review that the coefficient of friction is higher for the ventral forearm compared to the dorsal forearm, which supports the trend found in the current study.

The spread in the skin hydration and skin temperature was high for the index finger. This is reflected in the higher spread in the coefficient of friction. Figure 8 shows a scatter plot of the skin hydration to the dynamic coefficient of friction for all measurements. The colored areas group the results of the four anatomical locations. From the plot, it can be concluded that the hydration of the skin varies over the four measured anatomical locations. The hydration of the skin is an important variable for the coefficient of friction. The differences in skin hydration and body region indicate that it is important to measure the anatomical site of interest for skin friction measurements, and that skin friction results on one anatomical location are not necessarily representative for skin friction on other anatomical locations.

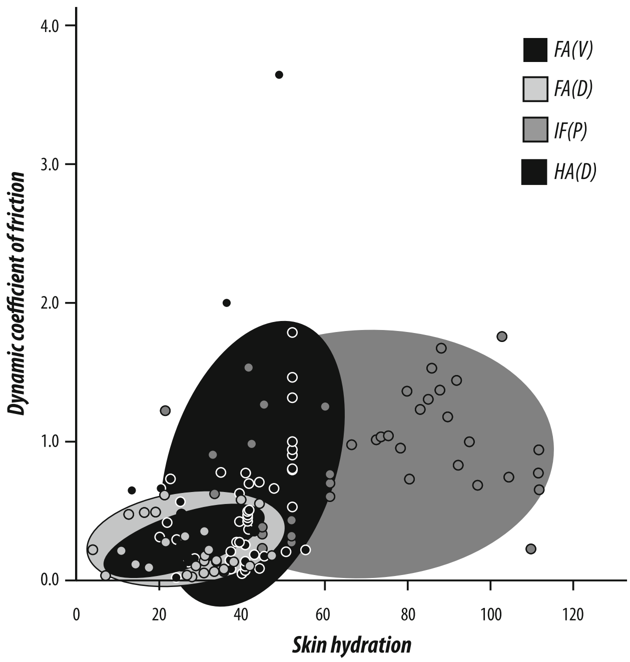

Fig. 8 The dynamic coefficient of friction and the skin hydration depend on the anatomical location

4.2.6 *Contact Material*

Another trend observed in the current study is that for all anatomical locations, the friction between the skin and SST is highest of the four materials, and PTFE is lowest. The difference between μ_d obtained in the interaction between the skin and Al or PE depends on the body region, while the static coefficient of friction for all anatomical locations of PE is higher than that of Al. The differences in the coefficients of friction are attributed to material and surface roughness. Bullinger et al. [20] did not support this trend: they found higher values for Al than for steel, although another type of steel was used with different surface roughness. Gee et al. [27] and Comaish and Bottoms [28] support the trend observed in the current study: Gee et al. [27] found higher coefficients of friction for steel than for PE, and Comaish and Bottoms [28] found higher values for PE compared to PTFE.

4.2.7 *Relationship Coefficient of Friction and Normal Load*

The friction involving the human skin is often described in a model based on Hertz's theory. The model assumes an exponential relationship between the normal and friction force rather than a linear relationship, which can be seen in the friction between two metal surfaces. The relationship between F_f and F_n can simplified into

$$F_{\mathrm{f}} \sim c * (F_n)^n \quad (1)$$

The variable c is determined by the properties of the interacting materials, like the geometry and the roughness, and the real area of contact between the skin and contact material. With the Hertz theory, the exponent n has a value of 2/3 for adhesive contacts and 4/3 when the friction force is determined by sub-surface deformations [11, 29]. The values for n reported in the literature range from 0.66 to 1.0 [8, 9, 11, 30, 31]. The results of the current study yield with $n = 0.69$ a comparable value.

4.3 Equipment

4.3.1 *Other Measures for the Frictional Behavior*

The measured signal for the friction force and coefficient of friction displayed some noise. The amplitude of this noise was relatively larger for the center of the ventral forearm and was smaller for the pad of the index finger. Figure 9 displays unfiltered coefficient of friction in time, and clearly shows the difference in the amplitudes of the coefficient of friction for the index finger pad and the ventral forearm.

The amplitude in the friction force was used as an indicator for the frictional behavior of skin in two other studies [11, 12]. Koudine et al. [8] found larger amplitudes for the dorsal forearm, compared to the ventral forearm. In the current study, from the tested anatomical locations, the amplitude for the ventral forearm was lowest, followed by the dorsal forearm and the dorsum of the hand, and was highest for the pad of the index finger. Koudine et al. [8] ascribe the amplitude to microscale deformations due to the roughness of the skin. This could explain the larger amplitude at the index finger pad with the roughness caused by the fingerprints. Asserin et al. [12] only uses the amplitude of the signal to show the differences between an older and younger subject. These age distinction was not found in the current study.

The development of the friction in time differed between body regions. Typically, the friction is high directly after the start of the measurement and decreases to a plateau value. For the dorsal forearm, the friction force stabilized relatively fast compared to the other anatomical locations. More noticeable is the effect of contact material on the time to reach the dynamic coefficient of friction. Figure 10 shows that the course of the coefficient of friction in time is different for the PTFE sample compared to the Al sample. Both measurements were executed at the mid-ventral forearm. The material and location dependency shown in Figs. 9 and 10 are representative for the differences seen in all measurements.

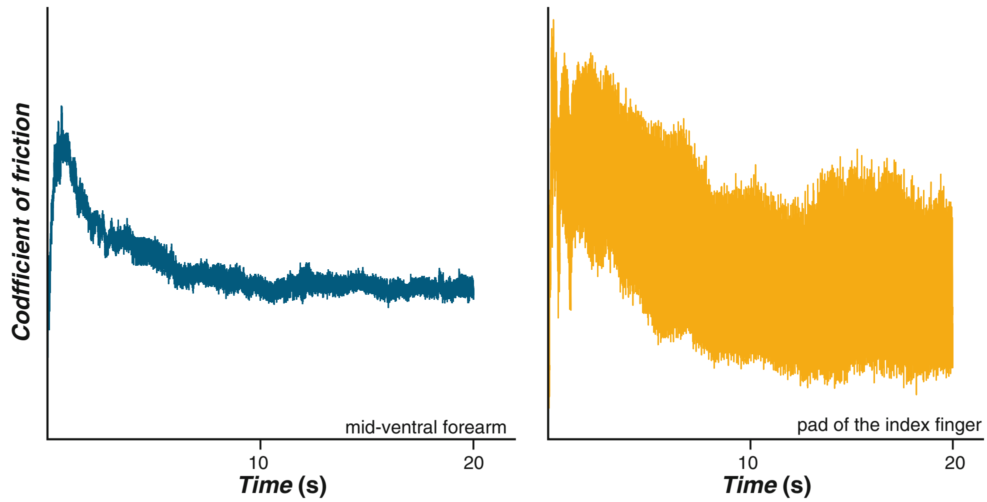

Fig. 9 The amplitude of the fluctuations in the coefficient of friction varies with anatomical location

The time to reach the plateau of the dynamic coefficient of friction has not often before been reported as a measure for the frictional behavior of human skin before. Hendriks and Franklin [23] mentioned a plateau value which was reached after about 60 s, but in their measurements, the coefficient of friction increased to a plateau value.

4.3.2 Type of Movement

The contact geometry used in the current study has also been used by Highley et al. [19] and Bullinger et al. [20]. Bullinger et al. [20] measured the friction between the index finger pad and steel (Fe360) and aluminum, and obtained coefficients of friction of approximately 1.9 for aluminum and 1.6 for steel. Highley et al. [19] measured the friction between the untreated skin on the mid-ventral forearm in contact with PA.

In the review study of Derler and Gerhardt [15], the coefficients of friction obtained in many studies are summarized. They conclude that the measurement technique influences the measured skin friction coefficient: in rotational movements, the high contact pressures in combination with the occlusion of the skin area of interest cause the skin to sweat and consequently increases the friction. Though, when comparing the coefficients of friction, the values obtained with rotational movements are lower than those obtained with linear movements. An explanation for the higher values for the linear movements can be explained by the effect of plowing of the contact material through the skin, which is less in rotational movements [15, 26]. This can be attributed to the fact that with linear movement, the contact material constantly deforms a new area of skin, while in the described rotational movement, only a small area of skin is deformed at the start of the measurement. The coefficients of friction in the current study compared more to those with other rotational movements than to coefficients of friction obtained with linear movements. This can also be attributed to the fact that only a small area of skin is deformed for the entire measurement, instead of constantly deforming a different skin area.

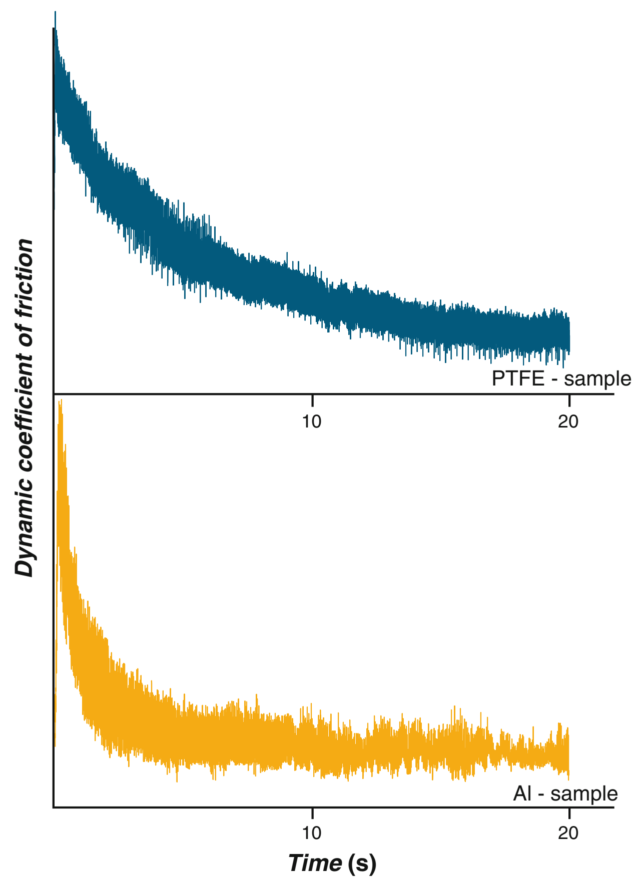

Fig. 10 The time for the coefficient of friction to stabilize depends on the type of material

It can be concluded that the type of movement used in the new mobile device is suitable to measure the friction on the human skin. The measured coefficients of friction compare to the results reported in the literature. The advantage of the rotational movement used in the present study is that large travelled paths can be attained on small areas of skin.

4.3.3 Extreme Coefficients of Friction

It could be argued that values of the coefficient of friction over 1.5 are outliers. Nevertheless, as the conclusions were not influenced considerably by those values, they are left in the dataset to indicate that the interpersonal differences in coefficient of friction are substantial. The results are assumed not to be caused by defects in the measurement equipment, as all trials gained the same coefficient of friction.

4.4 Other Considerations

Experiments on human subjects require the willingness of people to cooperate. During the present study, it was remarkable that subjects were willing to cooperate as long the measurements did not take them more than 10–15 min and that they refused to cooperate if they had to remove for example their shoes and socks. Therefore, the anatomical locations reported here were limited to the four locations at the forearm and hand, although the device can be used for skin friction measurements at any site on the human body.

5 Conclusions

The coefficient of skin friction as well as the hydration and temperature of the skin vary for the four measured anatomical locations at the forearm and hand. The static and dynamic coefficient of friction are highly correlated. There is a linear relationship between μ_s and μ_d. There were significant differences in the coefficient of friction, temperature and hydration between men and women. The differences in the coefficient of friction between men and women could rather be explained by the differences in hydration than gender differences. An inverse relationship was observed between the normal load and coefficient of friction, whereas there was no significant effect of the sliding velocity.

References

1. Atmaca, I., Yigit, A.: Predicting the effect of relative humidity on skin temperature and skin wettedness. J. Therm. Biol. **31**(5), 442–452 (2006)
2. Bouwstra, J.A., Groenink, W.W., Kempenaar, J.A., Romeijn, S.G., Ponec, M.: Water distribution and natural moisturizer factor content in human skin equivalents are regulated by environmental relative humidity. J. Investig. Dermatol. **128**, 378–388 (2008)
3. Papir, Y.S., Hsu, K.H., Wildnauer, R.H.: Mechanical properties of stratum corneum. 1. The effect of water and ambient temperature on the tensile properties of newborn rat stratum corneum. Biochim. Biophys. Acta **399**(1), 170–180 (1975)
4. James, W.D., Davis, L.B., Quick, C.M., Siegel, S.E. (eds.): Military Dermatology. Office of the Surgeon General at TMM Publications, Washington (1994)
5. Veijgen, N.K., Masen, M.A., van der Heide, E.: A novel approach to measuring the frictional behaviour of human skin in vivo. Tribol. Int. **54**, 38–41 (2012)
6. van Kuilenburg, J., Masen, M.A., Groenendijk, M.N.W., Bana, V., van der Heide, E.: An experimental study on the relation between surface texture and tactile friction. Tribol. Int. **48**, 15–21 (2012)
7. Lewis, R., Menardi, C., Yoxall, A., Langley, J.: Finger friction: grip and opening packaging. Wear **263**, 1124–1132 (2007)
8. Koudine, A.A., Barquins, M., Anthoine, P., Aubert, L., Lévèque, J.L.: Frictional properties of skin: proposal of a new approach. Int. J. Cosmet. Sc. **22**, 11–20 (2000)
9. El-Shimi, A.F.: In vivo skin friction measurements. J. Soc. Cosmet. Chem. **28**(2), 37–52 (1977)
10. Pailler-Mattéi, C., Pavan, S., Varigiolu, R., Pirot, F., Falson, F., Zahouani, H.: Contribution of stratum corneum in determining bio-tribological properties of the human skin. Wear **263**, 1038–1043 (2007)
11. Adams, M.J., Briscoe, B.J., Johnson, S.A.: Friction and lubrication of human skin. Tribol. Lett. **26**(3), 239–253 (2007)
12. Asserin, J., Zahouani, H., Humbert, P., Couturaud, V., Mougin, D.: Measurement of the friction coefficient of the human skin in vivo. Quantification of the cutaneous smoothness. Colloids Surf. B **19**, 1–12 (2000)
13. Masen, M.A.: A system based experimental approach to tactile friction. J. Mech. Behav. Biomed. Mater. **4**, 1620–1626 (2011)
14. Egawa, M., Oguri, M., Hirao, T., Takahashi, M., Miyakawa, M.: The evaluation of skin friction using a frictional feel analyzer. Skin Res. Technol. **8**, 41–51 (2002)
15. Derler, S., Gerhardt, L.C.: Tribology of skin: review and analysis of experimental results for the friction coefficient of human skin. Tribol. Lett. **45**, 1–27 (2012)
16. Gerhardt, L.C., Strässle, V., Lenz, A., Spencer, N.D., Derler, S.: Influence of epidermal hydration on the friction of human skin against textiles. J. R. Soc. Interface **5**, 1317–1328 (2008)
17. Cua, A.B., Wilhelm, K.P., Maibach, H.I.: Frictional properties of human skin: relation to age, sex and anatomical region, stratum corneum hydration and transepidermal water loss. Br. J. Dermatol. **123**, 473–479 (1990)
18. Tomlinson, S.E., Lewis, R., Liu, X., Texier, C., Carre, M.J.: Understanding the friction mechanisms between the human finger and flat contacting surfaces in moist conditions. Tribol. Lett. **41**(1), 283–294 (2011)
19. Highley, D.R., Comey, M., DenBeste, M., Wolfram, L.J.: Frictional properties of skin. J. Investig. Dermatol **69**(3), 303–305 (1977)
20. Bullinger, H.J., Kern, P., Solf, J.J.: Reibung zwischen hand und griff. Bundesanstalt für Arbeitsschutz und Unfallforschung, Dortmund (1979)
21. Zhu, Y.H., Song, S.P., Luo, W., Elias, P.M., Man, M.Q.: Characterization of skin friction coefficient, and relationship to stratum corneum hydration in a normal Chinese population. Skin Pharmacol. Physiol. **24**, 81–86 (2011)
22. Lodén, M., Olsson, H., Axell, T., Linde, Y.W.: Friction, capacitance and transepidermal water loss (TEWL) in dry atopic and normal skin. Br. J. Dermatol. **126**(2), 137–141 (1992)

23. Hendriks, C.P., Franklin, S.E.: Influence of surface roughness, material and climate conditions on the friction of human skin. Tribol. Lett. **37**, 361–373 (2010)
24. Kwiatkowska, M., Franklin, S.E., Hendriks, C.P., Kwiatkowski, K.: Friction and deformation behaviour of human skin. Wear **267**, 1264–1273 (2009)
25. Bettinger, J., Gloor, M., Vollert, A., Kleesz, P., Fluhr, J., Gehring, W.: Comparison of different non-invasive test methods with respect to the effect of different moisturizers on skin. Skin Res. Technol. **5**, 21–27 (1999)
26. Tang, W., Ge, S., Zhu, H., Cao, X., Li, N.: The influence of normal load and sliding speed on frictional properties of skin. J. Bionic Eng. **5**, 33–38 (2008)
27. Gee, M.G., Tomlins, P., Calver, A., Darling, R.H., Rides, M.: A new friction measurement system for the frictional component of touch. Wear **259**, 1437–1442 (2005)
28. Comaish, S., Bottoms, E.: The skin and friction: deviations from Amonton's laws, and the effects of hydration and lubrication. Br. J. Dermatol. **84**, 37–43 (1971)
29. Wolfram, L.J.: Friction of skin. J. Soc. Cosmet. Chem. **34**, 465–476 (1983)
30. Gitis, N., Sivamani, R.: Tribometrology of skin. Tribol. Trans. **47**, 461–469 (2004)
31. Sivamani, R.K., Goodman, J., Gitis, N.V., Maibach, H.I.: Friction coefficient of skin in real-time. Skin. Res. Technol. **9**, 235–239 (2003)