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On the role of adhesive forces in the tribo-mechanical performance of *ex vivo* human skin

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ABSTRACT

The frictional performance of *ex vivo* skin was studied in a range of pressures between 0.5 and 20 kPa. Modifications in the coefficient of friction under different conditions stressed the important role of adhesion. The friction coefficient of "untreated" skin was obtained between 2.3–0.5, between 5.5 and 0.65 for wet skin and in a range between 0.65 and 0.35 for oil-covered skin. The contribution of capillary adhesion under wet conditions was analysed by the Hertzian and JKR contact models. The high coefficient of friction obtained under wet conditions could not be explained by the softening effect of the stratum corneum and capillary adhesion only. The results suggested a further influence of water in the physicochemical properties of the stratum corneum with a subsequent effect on friction.

1. Introduction

Human skin is a multi-layered structure whose outermost layer, the so-called Stratum Corneum (SC), plays an important role in the adhesive properties of the skin because of its specific composition. The stratum corneum is usually referred to as "brick and mortar", a biphasic layer of "brick" regions surrounded by the "mortar". The "bricks" are tightly packed flattened anucleated cells (corneocytes) full of keratin, which is mainly responsible for the hydration properties of this layer. The "mortar" is an organized lamellar periodic bilayer of fatty acids, ceramides, cholesterol and water phases [1,2]. On top of the stratum corneum there is a film composed of sebum, secreted by the exocrine glands, and other lipids which form the Skin Surface Lipid Film (SSLF) [2–4]. This natural lubricant layer is fundamental to understanding the tribological performance of the skin at the meso level and it plays an essential role in hydration control of the skin [3,5,6]. The application of creams and moistures, which are emulsions of oil in water or water in oil, affects the adhesive properties of the stratum corneum and subsequently has an effect on the frictional response of the skin.

The tribo-mechanical behaviour of the human skin has been extensively reviewed in connection with different applications [7–11]. In previous research the effects of hydration, skin topography and elastic properties as well as the role of sebum or other components on the skin surface have been presented as the most relevant factors influencing skin friction [12–18]. As has been demonstrated before, adhesion has a major role in the tribological performance of the skin and therefore changes in friction due to viscoelastic skin deformation can be neglected [11,12,14]. When a smooth spherical ball contacts a flat slice of human skin under certain pressure, already, at very low forces, the true area of contact reaches the nominal one due to the strong differences in the elasticity of the contacting materials. In this case, the effect of skin roughness on friction can be ignored and the friction force due to adhesion can be evaluated by means of the surface condition of the skin. If the skin is "untreated", friction would occur mainly because of the properties of its Skin Surface Lipid Film (SSLF), whereas if the skin is "treated" the role of the adhesion forces needs to be approached according to the likely physicochemical changes emerging on the surface. Under dry conditions, the skin shows a coefficient of friction typically between 0.25 and 0.5 depending on the body location, the contacting material, and the age of the individual or indenter size, among other things [12]. Conversely, in the hydrated case, the coefficient of friction increases as a consequence of the softening effect of the stratum corneum and the changes in adhesion

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[12,19–21]. When the skin is subjected to substances such as oils, creams or moisturizers, a similar effect occurs with a subsequent modification in the adhesive properties of the skin. Although the increase in friction with hydration either by the direct application of water or by the moisturizing effect of creams has been extensively analysed [14,21–25], the mechanism behind the high friction has not yet been completely understood. For normal skin, Hertz's theory gives a correct approximation as regards the contact area between the skin and a spherical ball. However, it has been extensively shown in previous research that an increase in the friction force under hydrated conditions cannot be explained based only on the Hertzian approach [26]. Thus, other mechanisms have been proposed to explain the increase in the coefficient of friction. To include the effect of the adhesive forces due to Van der Waal interactions between the contacting materials, a modified Hertz's model was proposed by Johnson, Kendall and Roberts [27]. Further, a hypothesis put forward by Persson [28,29] suggested the role of the capillary forces in the contact between a hard surface and a smooth soft face under wet conditions. According to this reference, the softening effect of water causes a decrease in the elastic modulus linked to an increase in the capillary adhesion, which addresses the issue of the increase in the area of contact and, therefore, the increase in the friction force. It has been suggested in previous research that capillary adhesion affects the frictional performance of the skin, especially under hydrated conditions [14,18,30,31]. However, its effect has not yet been introduced in the models to predict skin friction. Hence, to enhance understanding of the mechanisms behind the changes of friction due to the application of substances, and particularly under hydrated conditions, an evaluation of the adhesive forces arising on the skin is addressed in this work.

This is why the main focus of this work was to evaluate the role of the adhesive forces in the tribo-mechanical performance of human skin – object interactions by means of an experimental and a theoretical approach using untreated, wet and oil-covered *ex vivo* human skin. Three samples taken from the abdomen of one individual were evaluated at the meso scale (that is, in a range of forces between 1 mN to 80 mN). The measurements were performed on *ex vivo* human skin to avoid both the effect of pre-stretching the skin and the influence of the underlying tissue of *in vivo* skin in the results. Modifications in the elastic properties of *ex vivo* skin can occur as a consequence of the effect of ageing yet, for fresh *ex vivo* skin, these changes should be minimal compared to the effect of pre-stretching on *in vivo* skin. Furthermore, although the results on *ex vivo* tissue are subject to similar variables as *in vivo* skin, no roughness effects on friction were taken into consideration since all the samples came from the same individual. Consequently, the number of parameters possibly affecting skin friction were minimized in order to evaluate the role of the adhesive properties of the skin under different conditions.

2. Theoretical models

According to the “Two-term friction model” [14,22,33], the friction force is defined by the contribution of two non-interacting parts: the adhesive and the deformation components. Adhesion is generally considered the main constituent of the friction of human skin, whereas the deformation component seems to have a minor influence on it [11,14]. The deformation component is proportional to the viscoelastic loss fraction, β, due to the viscoelastic behaviour of the skin, the applied force, F, and the relative indentation into the skin, $\frac{a}{R}$:

$$F_{\mu,def}=\frac{3}{16}\beta\frac{a}{R}F \tag{1}$$

The adhesive component of friction is defined as a function of the area of contact, A_{real}, and the interfacial shear strength, τ, between the contacting surfaces:

$$F_{\mu,adh}=\tau A_{real} \tag{2}$$

Commonly, the total friction force is described as a power law of the normal force, as indicated by Eq. (3), with an exponent, m, that varies with the applied conditions. Thus, m includes information about the relative contribution of each component to the total friction.

$$F_{\mu}=k\bullet F^{m} \tag{3}$$

When m approaches values close to 1, friction is defined according to Amontons' law. Typically, values between 0.6 and 1.1 can be obtained from the literature in the case of the human skin [14,34–38].

To determine the area of contact, A_0, for the case of the contact between a spherical ball and a flat surface representing the skin, Hertz's theory can be used [36,39,40]. Based on Hertz's theory, the contact radius, a_H, is a function of the applied force, F, the radius of the probe, R, and the Effective Elastic modulus, E^*, a combination of the elasticity of the contacting materials.

$$a_H=\left(\frac{3RF}{4E^*}\right)^{1/3} \tag{4}$$

However, Hertz's theory does not account for the adhesive forces on the contact area [41,42] due to the attractive forces between solids. Certainly, the adhesive phenomena appear as a consequence of dispersive Van der Waal forces between two contacting surfaces. Thus, to evaluate the adhesive behaviour of the skin it might be required to include these forces in the contact model. Johnson-Kendall-Roberts [27,43,44] proposed a modified Hertz model which includes the force of adhesion due to Van der Waals interactions between the contacting materials. Then, the apparent force acting on the material's surface is:

$$F_{app}=F+2F_{adh}+2\sqrt{F_{adh}\left(F+F_{adh}\right)} \tag{5}$$

With F_{adh} the adhesive force defined as:

$$F_{adh}=\quad\frac{3}{2}\pi RW_{12} \tag{6}$$

where W_{12} is the work of adhesion between the two contacting surfaces, see [41,45,46].

Additionally, it has also been proposed that the role of capillary forces which act on the contact surface could influence the frictional behaviour of the skin [29]. The capillary force can be derived from the capillary pressure given by the Young-Laplace [44] as indicated in Eq. (7):

$$F_{cap}=\quad-2\pi R\gamma_L\left(cos\theta_1+cos\theta_2\right) \tag{7}$$

R, radius of the sphere, γ_L, the surface tension of water and θ_1, θ_2, the contact angles of the surfaces.

The influence of this force on the frictional performance of the skin has not yet been analysed for object – skin interactions. The introduction of these forces in the friction model would increase the area of contact, especially at low forces, and it might be a better approach to describe the frictional performance of the skin. The negative sign of Eq. (7) shows that the force is attractive, so that to include the capillary force in the JKR model the sign would be positive and the apparent normal force would be given by:

$$F_{app}^{cap}=(F+F_{cap})+2F_{adh}+2\sqrt{F_{adh}\left[(F+F_{cap})+F_{adh}\right]} \tag{8}$$

3. Material and methods

3.1. Ex vivo *human skin samples*

Ex vivo human skin samples from abdominal surgery of an anonymous donor were used to perform indentation and friction experiments. The samples, provided by the Radboud Hospital of Nijmegen, were taken with the consent of the patient and the corresponding agreements of the Ethical Committees of the Hospital and the University of Twente. The adipose tissue was completely removed from the samples, so that the friction data corresponded to the response of Epidermis and Dermis only. The average thickness of the samples was 1.2 mm. In general, the source of skin samples is subject to availability; it is expected that differences associated with the anatomical location fall within deviations among donors, which are consistent according to the results of Lewis et al. [47]. In this case, all the measurements were performed using abdominal samples from one individual so no roughness effects on friction were taken into consideration. In previous research, the contact between the fingertip and a counter surface was modelled with a ratio of 1:1 between the apparent to the real contact area with an apparent contact area between 45% and 55% of the nominal contact area [48,49]. Therefore, in this research the real area of contact was considered as 80% of the nominal area of contact with a ratio of 1:1 between the apparent and the real contact areas.

3.2. Experimental methods

3.2.1. Surface characterization

The surface of the *ex vivo* skin was analysed with a laser confocal microscope VK 9700 from Keyence at a magnification of 10x and z-axis resolution of 1 nm. The samples were cut into square shapes of 20×20 mm and they were glued in a Petri dish. The surface characterization of the skin was done as received; that is, only in the dry condition. 2D and 3D confocal images of one of the *ex vivo* samples are presented in Fig. 1. Additionally, as indicative value, the average surface roughness of the 3 *ex vivo* human skin samples is given in Table 1.

3.2.2. Tribo-mechanical performance

A series of pull-off and friction measurements were carried out by a Vacuum Adhesive and Friction Tester (VAFT) created at the University of Twente [50]. Indentation tests were performed with a relatively large indenter made of Chrome Steel AISI-52100 of 6 mm diameter to ensure that the contact area was larger than the diameter of the individual cells of the stratum corneum [32]. The forces applied during the measurements ranged from 1 up to 50 mN and they were selected to ensure values between 0.5 and 20 kPa; that is, within the range of the applications on which our study focuses [7–10]. The indentation measurements were performed at a velocity of 50 μm/s. and the results corresponded to indentation depths between 3 and 350 μm, which is in the meso scale, to assess the layered structure of the skin. Thus, using this type of indenter the overall performance of the skin could be evaluated and the influence of the holder's material was avoided. The adhesive forces of “untreated” and “treated” skin with water and rapeseed oil were obtained from pull-off experiments at $z=z_0$ during an indentation test. Subsequently, the work of adhesion was calculated based on the JKR model as defined in Eq. (6). These measurements were performed on “untreated” skin and “treated” skin with deionized water (DW) and rapeseed oil from Grease Factory of Lanzhou (China). Moreover, the adhesive forces obtained from the experimental results were compared to the capillary forces calculated for the skin treated with water and rapeseed oil.

Table 1
Summary of the average roughness parameters of the ex vivo skin samples.

R_{pv} (μm)	R_a (μm)	R_q (μm)	R_{sk} (μm)
74.03 ± 3	46.20 ± 4	57.67 ± 3	−0.53 ± 0.05

Furthermore, friction measurements were performed with a Vacuum Adhesive and Friction Tester (VAFT) in a load range of 1–80 mN at a velocity of 10 μm/s and a sliding distance of 400–2000 μm. The skin samples were glued inside a Petri dish with Loctite (Loctite, Germany). Friction measurements were conducted on untreated skin and after applying between 3 and 4 drops of water and oil onto the skin surface. The fluids were spread on the surface and the excess was removed with a paper tissue after 2 min to ensure a boundary lubrication regime. Next, the coefficient of friction was obtained and compared to the average friction obtained previously on normal skin.

3.3. Theoretical methods

The results of the coefficient of friction under different conditions were compared to the results obtained from the theoretical models described in the “Theoretical models” section. To better understand the role of the adhesive forces in skin friction, the Hertzian and the JKR models were applied to describe the contact situation of “untreated” and wet skin. In addition, although it was previously mentioned that the capillary force had a role in the increased coefficient of friction under hydrated conditions, it has not yet been completely proved whether it has a role or not [51]. The effect of the capillary force on the adhesive forces of the skin can cause an increase in the area of contact at low forces, which might affect the interfacial shear strength as well and, in turn, the coefficient of friction. Thus, the effect of the capillary forces was included in both models according to Eqs. (7) and (8) to evaluate its likely effect on skin friction. The resulting contact parameters were introduced later in the “Two-term friction model” to predict the coefficient of friction under each condition. Lastly, the theoretical coefficient of friction was given as a power law function of the applied force and the role of the obtained m exponents was analysed in relation to the role of adhesion and capillarity in skin friction. The parameters used to obtain the capillary forces under normal and dry conditions are presented in Table 2.

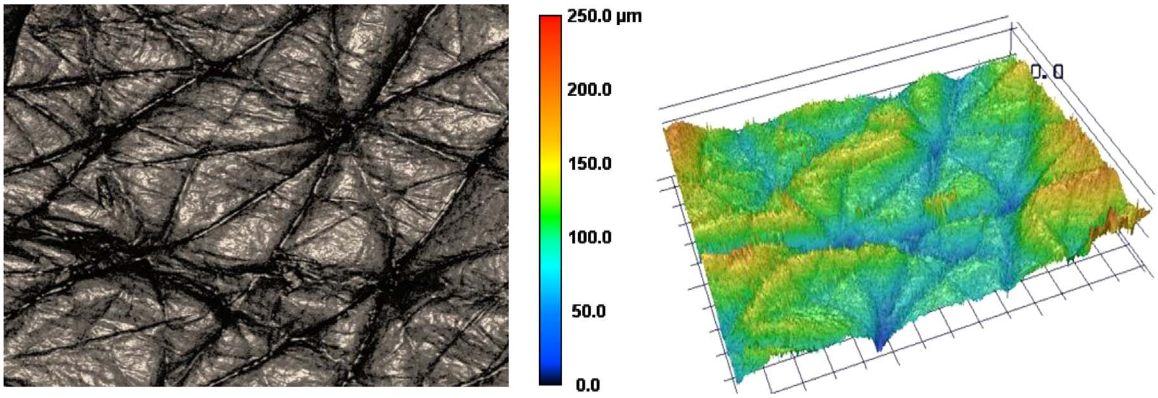

Fig. 1. Confocal microscope images of excised human skin. At the left is presented a 2D image of the skin and at the right a 3D image with a depth scale (size: 1 mm×1.4 mm).

Table 2
Surface tensions for normal skin, water and rapeseed oil. The contact angles between the skin and sebum, water and oil as well as the corresponding values for steel in contact with those substances are also given in the table.

	NORMAL SKIN		*WET SKIN*	
Surface tension (mN/m)	43		72	
Contact angle (rad)	Skin - sebum	1.58	Skin - water	1.55
	Steel - sebum	1.43	Steel - water	0.96

4. Results and discussion

4.1. Adhesive properties of ex vivo human skin

The adhesive properties of the skin samples obtained from pull-off measurements are presented in Fig. 2 for a range of forces from 1 to 50 mN. From the data of these measurements the work of adhesion was calculated according to Eq. (6) based on the JKR model as a function of the applied force. These results presented in Fig. 3 point out a lower work of adhesion at low normal forces, whereas from 10 mN it rises to values around −60 mN and slightly higher at 50 mN of normal force. This might be owing to the increase in the area of contact at higher forces due to Van der Waals interactions, whereas at lower forces it is likely that the adhesion is only due to capillary forces. The higher pull-off forces could also be related to the viscoelastic increase in the contact area due to the increase in load and longer contact times. The average work of adhesion was 47.5 ± 4 N m^{-1} which is in accordance with previous research on *in vivo* skin [26].

4.2. Frictional performance of ex vivo human skin

4.2.1. Experimental results

The frictional performance of 3 *ex vivo* skin samples is presented in Fig. 4 over a range of forces between 1 and 80 mN. The average friction obtained from the given results is also presented in the figure. The coefficient of friction at 1 mN was about 2.3 ± 1 and it decreased according to a power law to values of 0.5 ± 0.1 from 30 mN onwards. The standard deviation of the average friction was large, mainly at low forces, as a consequence of the variability of the human samples and the low number of samples studied. This fact can be seen as a limitation of the experimental part of this research, yet it also reveals that the existing differences in the coefficient of friction at low forces cannot be explained only by means of roughness or other intrinsic surface properties of the skin since all the samples were taken from the same individual and the same anatomical location. Thus, external factors might have an influence on the surface properties of the skin, which, especially at low applied forces, would explain the scattered results for the coefficient of friction. In addition, the high standard deviation at low normal forces could also be due to the error introduced by the equipment, which is much more relevant at low forces.

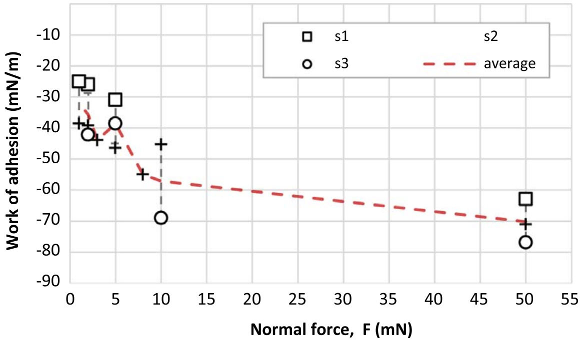

Fig. 3. Work of adhesion of human skin as a function of the force for 3 *ex vivo* samples (square markers in red, blue and green); the black line represents the average values of three samples with the corresponding standard deviation at each force. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

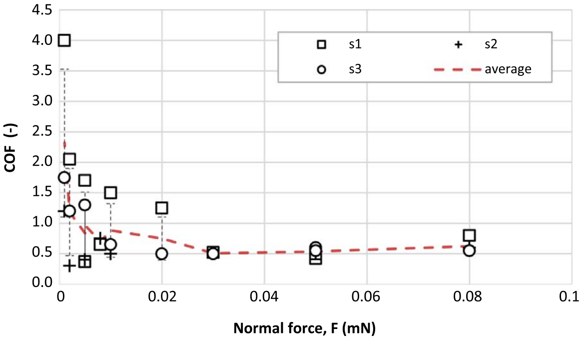

Fig. 4. Evolution of the friction coefficient of the excised human samples at the meso scale, evaluated from 1 to 80 mN. In the figure, the values of three samples are presented with black markers whereas the average friction is indicated with a dashed red line. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The adhesive properties of the skin in sliding friction have been found to be influenced mainly by the properties of the SSLF or, in general, by the condition of the skin's surface [12–14,25,26,42,43,52,53]. The frictional results at the meso scale are displayed in Fig. 5 as a function of the normal force for "untreated" skin

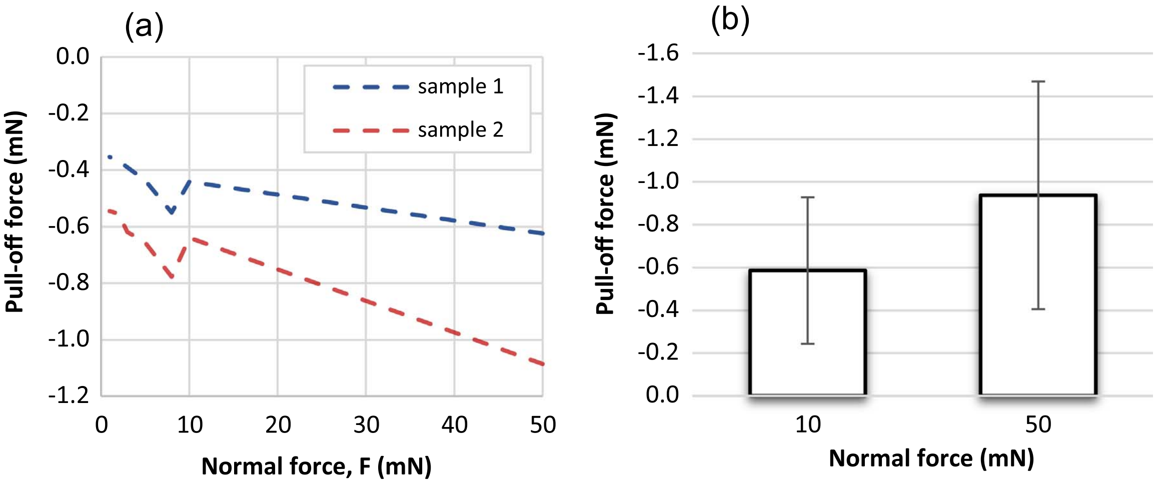

Fig. 2. Pull-off forces obtained after pull-off measurements on human skin: image (a) displays the results of two of the tested samples as a function of the force; image (b) presents the average values for the adhesion at forces of 10 and 50 mN.

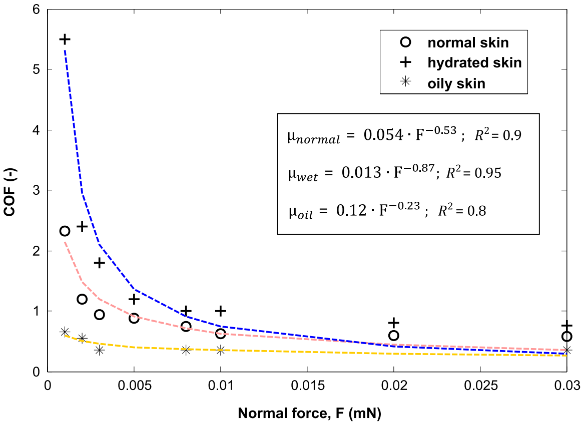

Fig. 5. Coefficient of friction of human skin as a function of the applied force for “untreated” skin (black circles), wet skin (black crosses) and oil-covered skin (black stars). The lines correspond to the fit of the experimental data according to a power law of the force as is also presented in the figure: normal skin (red dashed line), wet skin (blue dashed line) and oil-covered skin (yellow dashed line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

and “treated” skin with water and oil. Wet skin indicated a higher coefficient of friction than “untreated” skin, whereas the skin coated with oil presented a lower coefficient of friction than “untreated” skin. Further, at low forces, the coefficient of friction presented higher values than those obtained at higher forces for “untreated” and “treated” skin. Since the samples measured were all taken from the same person, from the same body site and they were not pre-stretched, the role of roughness in the measured friction should have the same impact.

The higher coefficient of friction indicated by the sample treated with water could, in part, be explained based on the effect of capillary adhesion on the surface and/or a modification in the interfacial shear strength, which, according to Persson [28,29], is also related to the changes due to capillary effects. Besides, the effect of water causes a decrease in the stratum corneum stiffness and a subsequent increase in the area of contact. This interpretation has extensively been used to explain the higher coefficient of friction of the skin under hydrated conditions, albeit the larger area of contact cannot solely justify the friction values observed experimentally. Therefore, other mechanisms might also contribute to the increase in skin friction under hydrated conditions. In fact, the effect of water causes structural modifications in the stratum corneum, such as replacement of lipid covalent bonds by weak hydrogen bonds [54], with a likely effect on the physicochemical properties of the skin surface, such as the surface tension or the dielectrical properties. Changes in the resistance and capacitance of the human skin have been measured after the application of water [55], which reveal an effect of water on the electrical properties of the skin. In the same article, a decrease in the output voltage with the time when the skin was immersed in water and, subsequently, exposed to environmental conditions, is presented. Thus, the specific composition and surface properties of the skin are altered when they are in contact with water in such a way that, according to these results, the dielectric properties of the stratum corneum are modified [56]. Then, the interaction with a counter surface might be affected by the electrical changes occurring on the skin surface after the application of water. Additionally, the analysis of similar and dissimilar metal contacts in sliding friction have demonstrated the role of ploughing and debris in the frictional performance of these systems [57]. According to the previous reference, a hard metal sliding on a soft metal is influenced by both the ploughing effect and the generated debris, with a subsequent effect on the coefficient of friction. Skin abrasion has been pointed out by frictional and immunohistological analysis when contacting natural and artificial turf surfaces [58]. This debris from the stratum corneum might also influence the coefficient of friction as in the case of metals. Moreover, segregation of compounds and roughness modifications in the stratum corneum were observed in our previous research after sliding contact of several materials on *ex vivo* skin [59]. Consequently, during the sliding contact between the skin and a steel ball a transfer of debris (stratum corneum removal and sebum) from the skin surface to the ball might also cause an increase in friction which, under hydrated conditions, would be higher due to the increase in adhesion. Therefore, the increase in the coefficient of friction under hydrated conditions might be explained based on the sum of several suppositions:

1. *Modification in the physicochemical properties of the stratum corneum with a subsequent contribution of other adhesive mechanisms beyond the dispersive forces (such as hydrogen bonding).*
2. *Increase in the area of contact due to the softening of the stratum corneum*
3. *Effect of the capillary force and capillary pressure at each contact point.*
4. *Effect of the electrostatic forces at the contact due to the presence of water ions (hydroxide and hydronium) and the molecular changes in the stratum corneum due to hydration.*
5. *Increase in debris due to a higher adhesion and sticky performance of the hydrated stratum corneum.*

Therefore the noticeable differences in the coefficient of friction presented in Fig. 5 have to be influenced by the aspects listed above.

Additionally, the viscoelastic loss fraction, β, was also obtained from the indentation measurements. The average value was 0.35 ± 0.01, which showed a good agreement with the values from the literature [22,35,60,61], and it was used to calculate the deformation component of friction. Moreover, the elastic modulus for dry skin was considered 120 kPa whereas for wet skin the modulus was 50 kPa. A summary of the input parameters used in the model is presented in Table 3.

4.2.2. Theoretical analysis

A fit of the experimental coefficient of friction of normal, wet and oil-covered skin is presented in Fig. 5 as a power law of the normal force. The differences in the m exponent for the three cases revealed the influence of adhesion in the prediction of friction. Further, Fig. 6(a) and (b) presents the contact radius obtained as a function of the normal force under dry and wet conditions, respectively, according to the theoretical models described in the “Theoretical methods” section. Thus, a comparison of the theoretical models with the experimental data under dry and wet conditions was done to evaluate the possible role of the capillary forces in predicting friction, especially under wet conditions. Therefore, Fig. 7(a) and (b) displays the results of the coefficient of friction under both dry and wet conditions, respectively, in comparison with the theoretical results from the Hertzian and the JKR models and their modified versions which include the capillary effect. From these figures it is noticeable that the coefficient of friction at low forces was only approached by the JKR and the modified JKR model already under dry conditions. Similarly, under wet conditions the results showed the same disposition with coefficient of friction values especially high at low forces, only reached by the aforemen-

Table 3
Parameters used in the friction model. The elastic modulus at dry and wet conditions was obtained according to ref. [57] for a skin model composed of stratum corneum, viable epidermis and dermis. The interfacial shear strength, τ, was the fitting parameter in this model.

	DRY CONDITIONS	*WET CONDITIONS*
Elastic modulus (kPa)	*120*	*50*
Interfacial shear strength (kPa)	*E/28*	*E/18*
Viscoelastic loss fraction, β (−)	*0.35*	

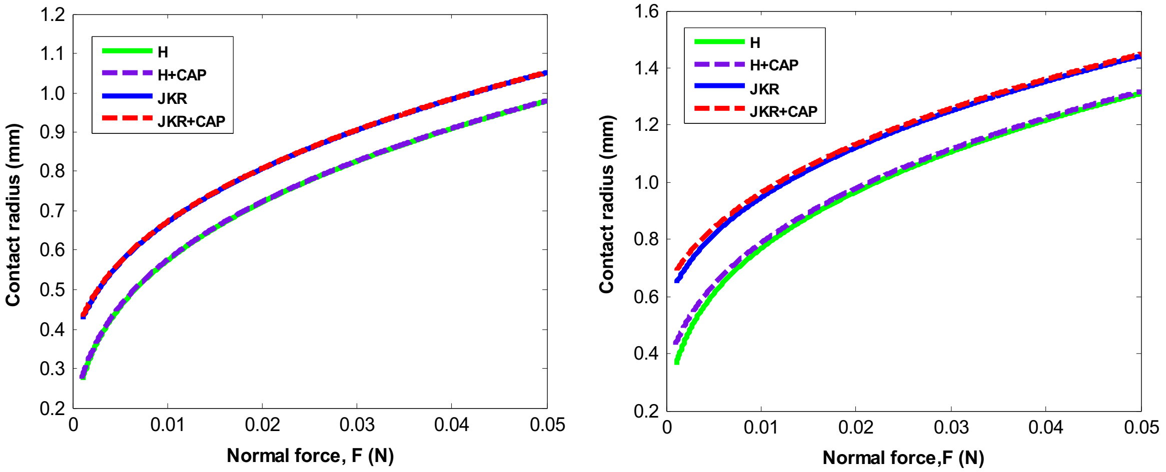

Fig. 6. Evolution of the contact area calculated according to the Hertzian and JKR cases with and without considering the capillary forces: (a) dry conditions; (b) wet conditions.

tioned models. To determine which model estimates better the experimental result under each condition, the corresponding power law functions were calculated for the cases presented in Fig. 7 and they are presented in Table 4. This table also shows the standard error (SE) when estimating the experimental results. Thus, according to the results presented above, the JKR model, which includes the capillary force, exhibits the lowest error for both dry and wet conditions. The error for the best cases is still considerably high since it is 13% and 16% for the dry and wet conditions, respectively. Therefore, as mentioned previously in the discussion, this suggests the necessity of considering other mechanisms to explain the interaction between the human skin and other surfaces, particularly under hydrated conditions, where the coefficient of friction yields especially high values. Moreover, the differences with respect to the experimental data can also be due to deviations in the values of some applied parameters, such as the elastic modulus. Additionally, the theoretical coefficient of friction presented as a function of the normal force decreases according to a power law function, whereas at a certain load the experimental coefficient of friction keeps steady at around 0.4 by suggesting a different regime at higher forces. So the error of 13.3% and 16.2% for the modified JKR model was mainly due to the differences with respect to the experimental data at the highest forces. Furthermore, the m exponent obtained for the experimental data presented high values under both dry and wet conditions, which indicated an important contribution from the adhesive forces to the coefficient of friction. A value of −0.53 for the experimental data was properly assessed under dry conditions by the JKR model, which presented an m exponent of −0.52. The value of the m exponent for the experimental data indicated an increase in the adhesive forces under wet conditions, in comparison to the dry case. Under wet conditions, the experimental results addressed the issue of an increase in the m exponent, which reached −0.87. The theoretical m exponents for the Hertzian and JKR models were −0.32 and −0.57 which were too low compared to the experimental result. Thus, the Hertzian and the JKR models were inadequate to simulate the high adhesion displayed on *ex vivo* skin under wet conditions. The comparison of the function fits, including the capillary force, showed a better agreement of the experimental results with the modified JKR model given by Eq. (8). The modified version of the JKR model presented an m exponent of −0.62, still lower than that obtained from the experimental results. Consequently, the contribution of the adhesive forces at low normal loads and in particular under wet conditions requires the consideration of adhesive and capillary forces to approach the frictional performance of the skin. Hence, this analysis suggests that both adhesive and capillary forces need to be taken into consideration for the frictional performance of the skin under wet conditions, whereas the JKR model represented properly the tribological behaviour of the skin under dry conditions. Thus, the increase in the adhesion at the meso scale under wet conditions can be explained

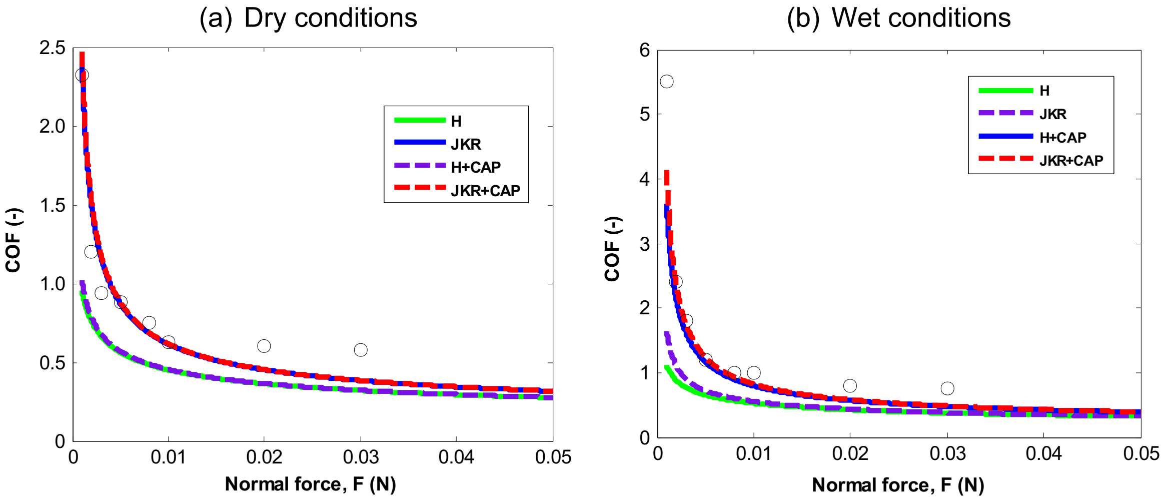

Fig. 7. Coefficient of friction as a function of the normal force for *ex vivo* skin at normal (a) and wet (b) conditions. The experimental data is presented by black circular markers. The coefficient of friction based on the models is presented with a green line for the Hertzian case, blue line for the JKR, violet dashed line for the modified Hertzian case and red dashed line for the modified JKR case. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 4
Summary of the coefficient of friction as a power law function of the normal force at dry and wet conditions according to each of the cases investigated: Hertz, JKR and the modified version of those two models.

Dry conditions		*SE*	***Wet conditions***		*SE*
Experimental	$\mu = 0.05 \bullet F^{-0.53}$		***Experimental***	$\mu = 0.01 \bullet F^{-0.87}$	
Hertz	$\mu = 0.11 \bullet F^{-0.32}$	*42.6%*	*Hertz*	$\mu = 0.12 \bullet F^{-0.32}$	*55.5%*
Hertz + cap	$\mu = 0.11 \bullet F^{-0.33}$	*42.6%*	*Hertz + cap*	$\mu = 0.09 \bullet F^{-0.39}$	*49.7%*
JKR	$\mu = 0.06 \bullet F^{-0.51}$	*17.3%*	*JKR*	$\mu = 0.06 \bullet F^{-0.57}$	*17.3%*
JKR + cap	$\mu = 0.06 \bullet F^{-0.52}$	*13.3%*	*JKR + cap*	$\mu = 0.05 \bullet F^{-0.62}$	*16.2%*

in terms of capillary forces due to condensation of water molecules, the effect of creams, moisturizers or other lubricants or as a consequence of modifications in the SSLF of skin.

5. Conclusions

The adhesive properties of *ex vivo* human skin have been analysed in relation to their frictional performance. Pull-off measurements in a range of pressures between 0.5 and 20 kPa indicated an average work of adhesion of 43 ± 15 mN/m which is consistent with the literature. The high standard deviation of these results is due to the scattered results of the pull-off forces. Further, the analysis of the frictional performance of “untreated” and wet skin showed similar values for the coefficient of friction to those observed in previous research. A considerable increase in friction was observed under wet conditions with a maximum coefficient of friction of 5.5 decreasing to about 1 as the force was raised. For “untreated” skin, a maximum coefficient of friction of 2.5 decreased to around 0.45 as the force increased. Experiments on oily-covered skin indicated a steadier coefficient of friction with values between 0.65 and 0.35 in the range of applied forces. Based on these results, the coefficient of friction was described as a power law of the normal force with variations in the m exponent, which confirmed the role of adhesion in skin friction. The analysis of the frictional models indicated a good agreement of the experimental results with the JRK model under dry conditions. The introduction of the capillary forces in the JKR model caused a slight increase in the coefficient of friction, which indicated a better agreement with the experimental results under wet conditions. Nevertheless, a larger coefficient of friction needs to be obtained under wet conditions to resemble the experimental results. Thus, the contribution of other mechanisms to the total adhesion force must be considered. The influence of debris from the stratum corneum removal, the ploughing effect, a higher contribution of deformation or an effect of the electrical potential associated with the physicochemical properties of the contacting materials, especially at low forces, can introduce modifications in the total friction force that are not currently taken into consideration. Moreover, modifications in the interfacial shear strength as a function of the force must also be studied, especially because of the layered structure of the skin. Besides, changes in the skin surface lipid film (SSLF) could also introduce alterations in the location of the shear, with a subsequent effect on friction.

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