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Liu, X., Gad, D., Lu, Z. et al. (3 more authors) (2015) The contributions of skin structural properties to the friction of human finger-pads. Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, 229 (3). 294 - 311. ISSN 1350-6501

https://doi.org/10.1177/1350650114567699

The Contributions of Skin Structural Properties to the Friction of Human Finger-pads

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ABSTRACT

This paper describes three series of tests that were designed to investigate how skin mechanical and structural properties, measured using a “Cutometer” and Optical Coherence Tomography, affect the frictional behaviour of human finger-pads.

Firstly, the skin mechanical properties across all fingers and the palm in participants’ dominant hands were assessed. Results showed that the distensibility of skin (total deformation in a suction test) is associated with stratum corneum thickness and that this in turn affects friction (thicker stratuem corneum leads to higher friction), giving a link between distensibility and friction.

Tape stripping to remove the superficial layer of the skin led to increased moisture (and/or electric charge on the skin surface) led to higher friction. No accompanying changes were seen in structural properties so it was concluded that moisture was the main cause of the adhesion increase. More work is required to isolate moisture and possible changes in electric charge using alternative measurement techniques.

When rubbing with sand paper, the stratum corneum thinned considerably and friction reduced. Moisture was ruled out as a cause of friction changes in this instance. Skin normal stiffness also did not change, but lateral stiffness changes have been seen in previous work when the stratum corneum thickness has been reduced so this is likely to be the cause of the reduced friction. This will be investigated further in future work using dynamic OCT measurements.

Keywords: Skin tribology, Skin properties, Optical Coherence Tomography, Cutometer.

1. INTRODUCTION

As it is the largest organ in human body, skin is always exposed to the external environment, and has to directly contact with a variety of surfaces in human daily activities. Many problems due to the physical or chemical interactions between human skin and contacting materials have been reported. For example, sweating during exercise can result in a slippery surface and can cause sports injuries. This could be prevented by adding powder on the contact interface or using sports equipment with non-slip surfaces to provide high friction force. It is not necessary to retain high friction coefficient in human daily tasks. For instant, high friction forces between human skin and the blades of a hair shaver can lead to a large skin deformation and cause skin "burn" or irritation. Therefore, a lower friction coefficient is required in this case. Consequently, in order to satisfy human needs and improve the quality of human life, knowledge on these problems is required. In recent years, the tribology of human skin has become one of the key topics in the study of biotribology. This topic is also an interdisciplinary subject and closely related to many research areas.

Human skin is mainly composed by two distinct layers: the epidermis (ED) and dermis (DL). The epidermis is the top layer of the skin, which itself consists of five layers, which are in descending order: stratum corneum (SC), stratum lucidum (SL), stratum granulosum (SG), stratum spinsum (SS) and stratum basale (SB). The outermost layer is the stratum corneum, consisting of dead cells. The thickness of the stratum corneum varies at different regions of the body and ranges from 0.03mm to 0.1mm. Beneath the epidermis is the dermis, it consists of papillary and reticular layers, and is much thicker than the epidermis [1-4]. As discussed above, each layer of skin is made up of various types of tissue and possesses different mechanical properties [5]. For example, in the dermis, collagen and elastin fibres form a network that not only supports the structure of skin, but also provides its elasticity. Viscous properties of skin are related to delayed recovery from deformation which are attributed to viscous sliding of fibrous networks. In previous studies, some researchers believed that the contribution of the epidermis to the overall mechanical properties of skin is so small that it can be neglected [6, 7], except for the palm and the feet soles. However, the epidermis is considered important in determining the skin mechanical properties as it is the outmost layer, interfacing with the external environment and influencing the skin conditions directly as it is affected more by exogenous factors, such as temperature, humidity, cosmetics and etc.

There has been a large amount of work carried out on skin friction, however, the different studies involve different subject groups and different test regions. With respect to anatomic site, the friction coefficient shows a huge variety, ranging from 0.12 on the abdomen to 1.4 on the finger pad or palm [8-13]. Ramalho et al. [14] investigated the friction coefficient on the palm and forearm and found that the palm had a higher value (1.2) than that of forearm (0.15~1.0). They assumed that the difference was related to skin thickness. In later studies, Zhang and Mak [9] reasoned it was due to the fact that the palm is rarely sweat free, but the forearm is. Some authors reported that the friction coefficient is also dependent on the water content of skin and TEWL (Transepidermal Water Loss). For example, Cua et al. [8] investigated skin frictional properties with respect to age, sex and anatomical regions using a frictionmeter. They observed that some regions (e.g. lower back, dorsal forearm) with higher capacitance, have lower friction coefficients. There was a correlation between the friction coefficient and TEWL found on the palm and thigh.

On the basis of the above findings it can be concluded that the frictional properties of human skin are intimately associated with its mechanical properties and moisture content. There have been several studies examining the mechanical properties of skin, which have shown that they are highly dependent upon its structural properties. For example, Geerligs et al. [5] developed a finite element model to estimate the Young's modulus of a tested sample with different thicknesses based on a NeoHookean model. They found that the Young's modulus is inversely proportional to the thickness of samples. Therefore, an understanding of mechanical and structure properties can be achieved by examining the morphological features and internal structural of skin. It would therefore be very helpful if the external and internal geometries of human skin could be directly imaged. In order to characterise skin properties and their effects on skin friction, it is necessary to characterise skin's mechanical properties (i.e. Young's modulus) and structural properties in tandem with friction tests.

Though there is a great deal of work on the mechanical properties related to cosmetic or skin-care products, very few of them have addressed on the contribution of skin mechanical properties to its frictional properties. Information concerning this is required as it could be related back to resolving these problems in human daily activities. Pailler-Mattei et al. [15] were the first to investigate the contribution of the stratum corneum on the skin friction of a forearm using a tape stripping technique. They observed that the skin friction coefficient globally increases after a number of tape strippings. They reasoned this could be attributed to the fall in the skin lateral stiffness and other changes in the physico-chemical properties. Recently, they carried out a further study and reported that skin tape stripping can generate electric charge on the skin surface that increases the adhesion force between human skin and objects [16]. In the study of Liu et al. [17], an Optical Coherence Tomography (OCT) system was used to study the potential relationship between skin properties (e.g. the thickness of stratum corneum and the number of sweat ducts) and skin friction on human finger-pads. Variation was achieved by using different test subjects rather than tape stripping. No direct relationship was found between the thickness of stratum corneum and skin friction as might have been expected. This may be due to the fact that with multiple tests candidates there were too many factors influencing the measurement of skin friction, most significantly the different fingers used.

The previous research has produced some interesting findings as to how the skin friction changes with its thickness [15-17]. This study aimed to conduct a detailed investigation of the effects of skin properties on friction. First, skin properties were measured across all finger-pads and the palm using a “Cutometer” and OCT and corresponding friction measurements were taken. Then, skin frictional behaviour was further assessed initially by evaluating the effect of the superficial layer on skin friction using a simple tape stripping method and then by investigating how skin friction changes with the removal of stratum corneum.

2. EXPERIMENTAL DETAILS

2.1 Measurement Apparatus and Methods

2.1.1 Mechanical Properties

Mechanical properties of the skin were determined using a non-invasive "Cutometer" MPA580. The device consists of a handheld probe with a distinctive central suction head (2, 4, 6 and 8 mm in diameter), attached to the main unit. The main unit includes a vacuum pump that can generate constant pressure up to 500 mbar and a non-contact optical measuring system. This device provides two modes: a stress-strain mode and a strain-time mode. A typical strain-time curve of human skin is illustrated in Figure 1. The following deformation parameters used to describe the curve were proposed by Agache et al. [18]: immediate distension-skin extensibility (U_e); delayed distension reflecting the viscoelastic contribution of the skin (U_v); immediate retraction (U_r); final skin deformation – skin distensibility (U_f); total recovery of skin after removing vacuum (U_a); gross elasticity of the skin, including viscous deformation (U_a/ U_f); net elasticity of the skin without viscous deformation (U_r/ U_e); the portion of the viscoelasticity on elastic segment of the curve (U_v/ U_e); biological elasticity (U_r/ U_f) [8, 19]. In the current study, the measurements were performed using the time-strain mode that can be used to estimate the skin properties. A 2 mm diameter measuring probe was used, which applied a constant pressure of 500 mbar to the skin. These tests were carried out at room conditions (humidity: 28% RH and temperature: 24°C), all five fingers and palm were examined. The hand was not treated by any chemical or cosmetic products in the 12 hours prior to the measurement. Apart from those biomechanical parameters that can be directly read from the device, it also permits determination of the normal contact stiffness of skin since the normal force and the corresponding deformation of the skin are known. The normal stiffness of the skin (S) is given by:

$$S = \frac{dN}{d\delta} \tag{1}$$

where N is the applied normal load to the skin and δ is the vertical deformation of the skin. The normal force applied to the skin is defined as the applied pressure p (approximate value of 500 mbar) multiplied by the area of the probe A_P (the diameter of probe used is equal to 2 mm) that is attached to the main apparatus:

$$N = p \times A_P \tag{2}$$

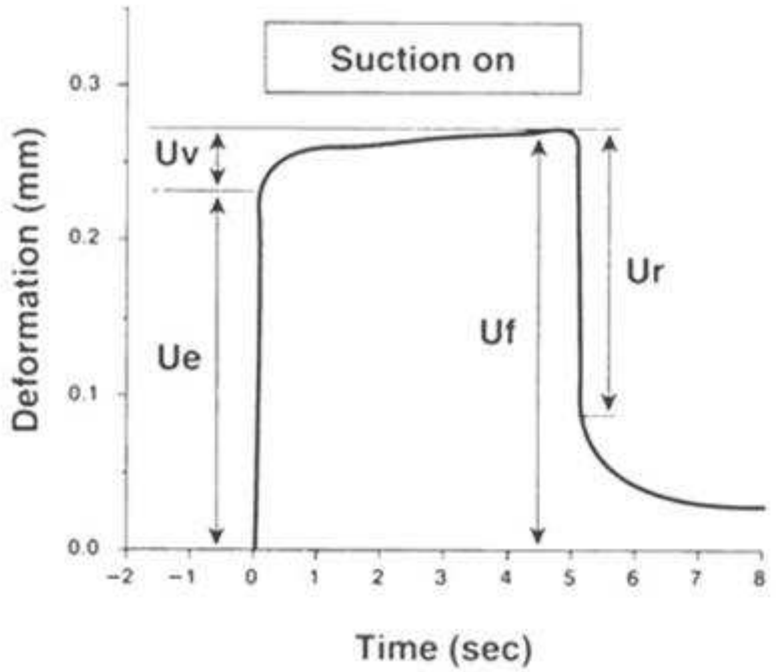


Figure 1: Typical data from a "Cutometer" measurement

2.1.2 Structural Properties

A commercial PS-SS-OCT system (Michelson Diagnostic Ltd.) was introduced to assess the structural properties of skin, see Figure 2. The principle of the OCT technique is based on the interferometric method. The infrared light is split into two paths, one path launches into the sample where it is scattered (sample arm) and the other one goes to a reference mirror (reference arm). These two beams of light signals reflected from the sample and the mirror arms, respectively, are then overlaid. The combination and subsequent inference of these two light paths generates a two dimensional image [20]. In a 2D cross-sectional OCT image, the axial resolution depends on the coherence length and the lateral resolution is determined by the focusing conditions. In this study, the OCT system uses a light source with a centre wavelength of 1300 nm and 110 nm FWHM bandwidth (Santec Ltd.). A generated 2D image has a lateral dimension of 4 mm (up to 6 mm) and a penetration depth of 2 mm. The resolution of the image is 10 μm (axis) x 15 μm (lateral). The average refractive index of the skin on a human finger-pad is assumed to be 1.44 [21].

During image scanning, participants were guided to place their fingers on the work plate with the pad facing the lens (see Figure 2). The work plate was attached to a mechanical stage for adjusting the distance between the skin and the lens. In order to obtain the average value of the thickness of the stratum corneum, the examined hands were fixed in position to ensure images were taken in the same position.

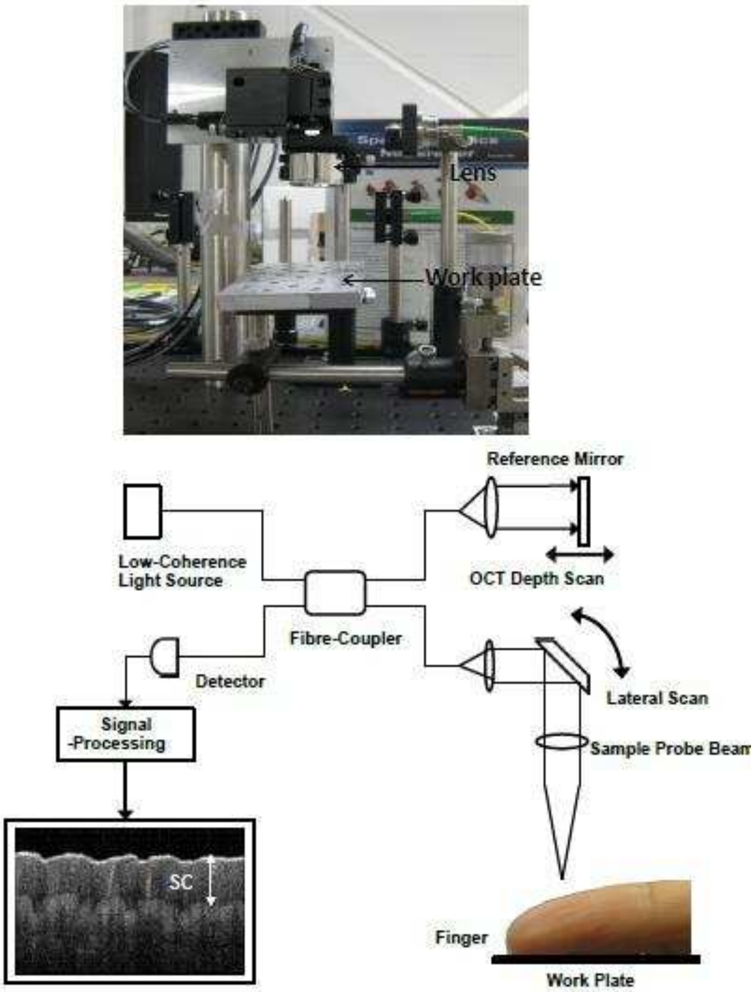


Figure 2: A typical set-up of an OCT system.

Human skin is a complex tissue consisting of several different layers with varying light refractance properties. The scattering light during OCT analysis depends on the size and shape of the particles, the hydration levels in the tissue, etc. Therefore, each layer of the skin displays different light intensity in the vertical depth in each OCT image and can be easily identified by correlating with histology sample images, see Figure 3(a) and (b). The boundary between the whole cornified layer and the living epidermis layer is always distinct, which enables the thickness of the stratum corneum in a finger-pad to be measured. Figure 3(c) shows an intensity profile along the vertical depth of an OCT image of a finger-pad (A-scan), in which two peaks are generated. The first peak can be attributed to the strong light reflection from those dead cells and/or lipid film on the surface of the skin. The second peak is caused by the relatively strong reflection of the fibres in the living epidermis. Therefore, the thickness of the stratum corneum can be determined by measuring the distance between these two peaks. In this study, 16 single slices were collected from each participant; slice Nos. 1, 5, 10, 15 were selected to be assessed individually. For each slice, eight predefined measurement points were used for determining the thickness of the stratum corneum. The measurements were performed manually using the "distance tool" (i.e. ruler) in Matlab. The average data of these predefined points for four slices was calculated to give the thickness of the stratum cornuem [17].

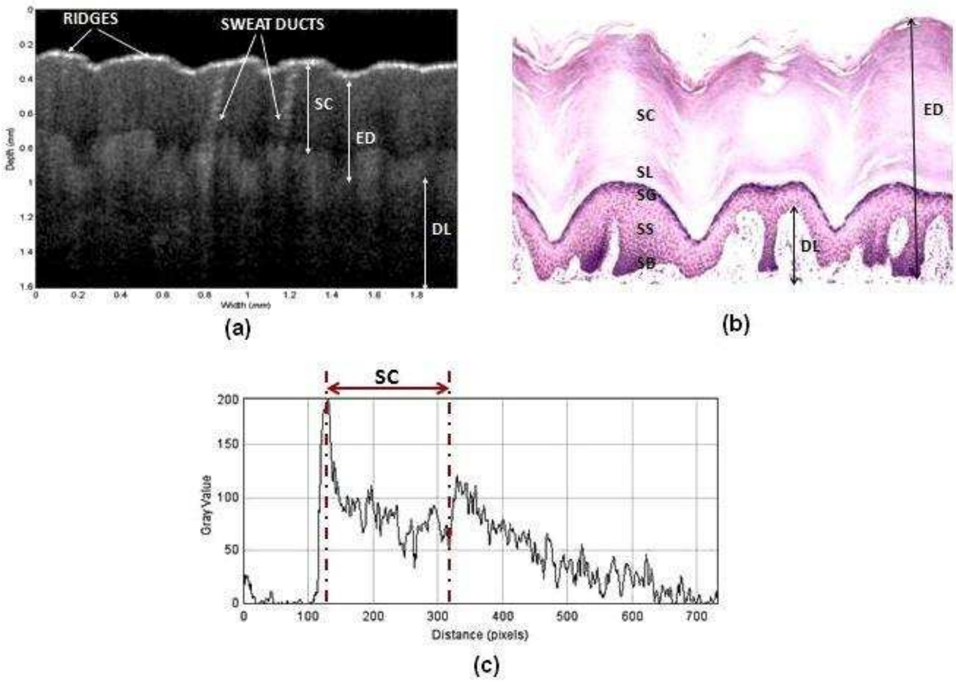


Figure 3: (a) An optical coherence tomography (OCT) image of a finger-pad surface; (b) tissue histology of human skin, used only for indentifying various layers of skin [22]; (c) intensity profile of the OCT image (A-scan).

2.1.3 Friction

With respect to the friction tests, a multi-component force platform system (HE6X6) from Advanced Mechanical Technology Ltd., was used. This test set-up (see Figure 4) is composed of the HE6X6 force plate, a PC, a PJB-101 interface box (AccuGait system posturographic plane) with a RJ cable and a RS-232 cable. The HE6X6 force plate is designed based on the strain gauge flexibility technique, and is able to provide three force components along the X, Y, and Z axes as well as their corresponding moments. This device is ideal for quantifying low loads. The maximum load in the Z axis is 44 N (normal force) and 22 N for X and Y axes (friction forces). The resultant horizontal force in the X-Y plane is considered to be the frictional force, assuming the finger is moving relative to the plate. The ratio of the normal force over the friction force was considered to be the coefficient of friction. For the measurement of friction, each participant was asked to wash their hands and dry them using a paper towel, prior to the test. During measurements, the top of the force plate was covered with a 5 mm wide acetal strip (Ra ≈ 0.5 μm) that is less than a finger-pad width, so that all fingers could experience the same contact area under a certain load, since the contact area is one of the key factors influencing the skin friction. The participant was requested to initially slide the index finger or palm of the dominant hand along the acetal strip at a steady speed (giving approximately 20 mm/s). The angle between the surface and the fingers ranged between 25° and 35°. This test was done at both low load (0 to 2 N) and high load (2 to 12 N) conditions to examine the effect of the skin mechanical properties on the skin friction, individually. The moisture level of the finger-pad skin was measured using a "MoistSense" device immediately prior to the friction tests (for details, see [23]).

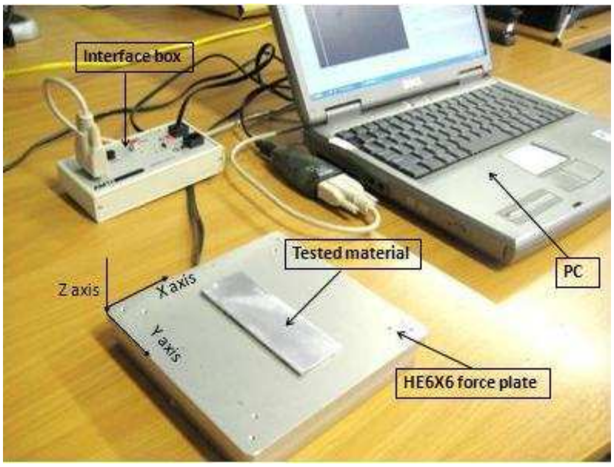


Figure 4: The set-up of the multi-component force platform system.

For measurements of skin roughness, an indirect approach using a surface profilometer (MitutoyoSurftest SV-600) was used. Since finger-pad skin is a non flat and soft material, it is not possible to conduct measurements of finger-pads directly, for this case, a replica of the hand skin was made. Firstly, making moulds of the tested finger-pads using alginate (skin safe chromatic alginate powder). Secondly, making cases of these moulds with Plaster of Paris. Finally, as human skin texture is transferred on these replicas, so that the roughness of human skin can be quantified using a stylus profilometer. In this research, measurements were carried out exactly following Tomlinson's roughness measurement procedure [24], in which the stylus was moved 2 mm along in the same direction as the finger-pad or the palm in the friction tests, with a speed of 0.1 mm^{-1}. In order to gain reliable roughness data, each measurement needs to be repeated at 3 different positions on the tested region and average values calculated.

2.2 Test Details

2.2.1 Measurements of Skin Physical Parameters and Friction

In the first series of tests the mechanical and structural properties and corresponding friction of the finger-pads and palm on the hands of two participants (Participant 1: a 25 year-old male and Participant 2: a 27 year-old female) were assessed using the methods described in Section 2.1. Moisture and roughness measurements were also taken.

2.2.2 The Effect of the Superficial Sweat on Skin Friction

As discussed earlier, a thin film covers the surface of skin, which not only helps maintain the skin in good condition, but also influences some of its physico-chemical properties. To investigate the influence of the superficial layer on skin friction, a simple test was designed, that involved tape stripping. This test was carried out on the left index finger of the same participants. An adhesive tape was adhered to the finger-pad and peeled off after a few seconds. After that, images of the finger-pads using the OCT system were taken and then friction measurements were carried out using the force plate.

2.2.3 The Effect of the Thickness of Stratum Corneum on Skin Friction

The aim of this test was to examine the effect of stratum corneum thickness on skin friction, since the skin thickness was found to be associated with some mechanical properties of the skin (e.g. distensibility). To do this a simple rubbing test was designed and carried out on the right middle finger of the same participants. A sheet of fine grade sand-paper (Pro grade: 240 grit) was used to rub the surface of finger-pads, causing some skin tissue to be removed and hence reduce the thickness of the stratum corneum. OCT was used to take images of the finger-pad to determine stratum corneum thickness.

3. Results

3.1 Measurements of Skin Physical Parameters and Friction

The OCT and "Cutometer" results obtained from Participant 1 for the first series of tests are given in Table 1, which shows some deformation parameters (e.g. skin distensibility, elasticity, viscosity) with respect to the examined regions of hand, as well as the thickness of the stratum corneum from OCT. The distensibility of the skin (total deformation) (R0 or U_f) was found to be linearly dependent on the thickness of the skin (as illustrated in Figure 5. So in this case as thickness increased the deformability (elasticity) of the skin increased. This could have implications for friction as this would imply that thicker skin will form a larger contact area and deform more when loaded against a rough surface, both of which would increase friction force. There were no significant relationships found between the thickness of the stratum corneum and other biological ratios (i.e. R2 (U_a/ U_f), R5 (U_r/ U_e)and R7 (U_r/ U_f)), however.

Table 1: "Cutometer" deformation parameters and the thickness of stratum corneum for different regions of the hand of Participant 1.

Region of Hand	R0 (± SD)	R2 (±SD)	R5 (±SD)	R7 (±SD)	Thickness of SC [mm] (± SD)
Thumb-pad	0.166±0.012	0.727±0.070	0.375±0.085	0.235±0.032	0.21±0.008
Index Finger-pad	0.157±0.008	0.748±0.040	0.368±0.033	0.248±0.027	0.20±0.003
Middle Finger-pad	0.165±0.011	0.697±0.042	0.360±0.074	0.246±0.043	0.20±0.010
Ring Finger-pad	0.149±0.007	0.705±0.047	0.390±0.024	0.254±0.015	0.18±0.007
Little Finger-pad	0.142±0.012	0.691±0.023	0.439±0.083	0.281±0.032	0.16±0.004
Palm	0.078±0.002	0.725±0.049	0.696±0.073	0.336±0.037	0.13±0.007

where **R0** is skin distensibility (or elasticity) (U_f), **R2** is gross elasticity of the skin (U_a/ U_f), **R5** is pure elasticity of the skin (U_r/ U_e) and **R7** is biological elasticity of the skin (U_r/ U_f).

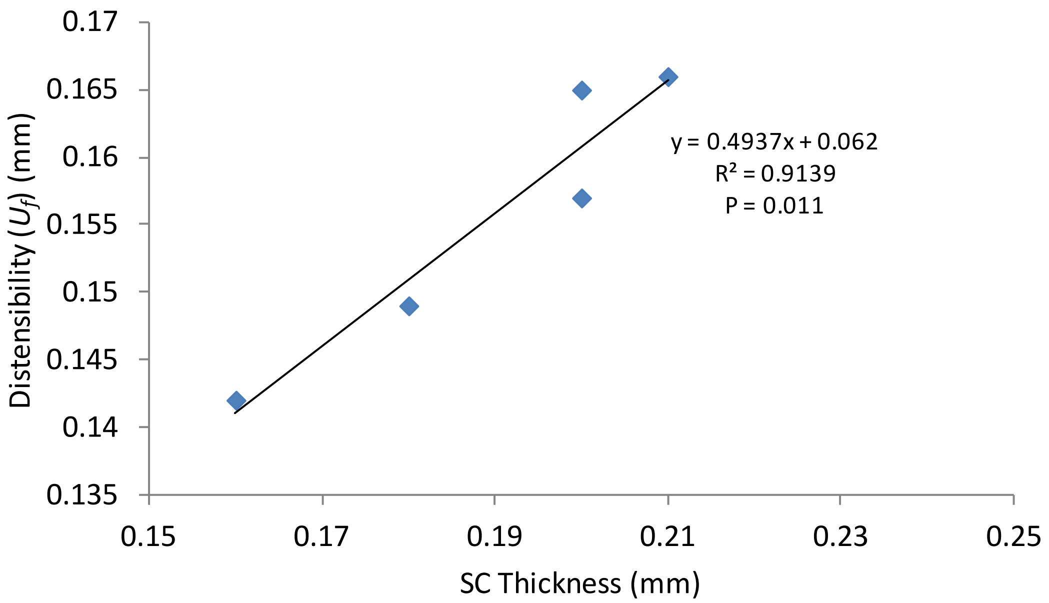


Figure 5: Distensibility (U_f) against SC thickness for Participant 1.

Table 2 displays data of physical parameters measured from all five finger-pads and the palm of Participant 2, as well as the friction coefficients at different load conditions. The moisture levels among all regions examined were very similar and in the range of 39~42 au, except for the ring finger which had a slightly higher reading. This was expected since all fingers and palm examined were taken from the same hand of one participant, so they should have similar temperature and moisture levels under the same body conditions. It was also observed that the thickness of the SC varies among fingers. The thumb and index finger have relatively thick SC compared with other regions which are twice as thick as those of the palm. This difference may be due to these fingers being involved in human daily activities more frequently. Thick SC could help prevent skin from damage or injury.

The measurable roughness of the skin was reported to range from 7 to 30 µm with respect to different regions of the hand. As expected, there was no significant difference among them except for the thumb which compares well with the data in Childs et al. [25]. Most tested regions of the hand had similar frictional behaviours, particularly when they experienced high loads (> 2 N). In this case, except the thumb and the ring finger, the magnitudes of the friction coefficient are around 0.34. At the low load condition, the friction coefficients showed a higher variability among those tested regions compared with those at high load condition, ranging from 0.30 for the palm to 0.42 for the ring finger.

In order to see if the distensibility of the skin affects shear conditions in the skin/surface interface, SC thickness (for Participant 2) (which was shown to be linearly dependent on distensibility for Participant 1, see Figure 5) was plotted against shear stress ((normal force × friction coefficient)/area, where area came from previous measurements at 1N of the same fingers [27]) divided by moisture content. This was an attempt to normalise for area and moisture, both of which themselves affect friction. As can be seen in Figure 6, there are indications that a threshold SC thickness of 0.4mm, below which lower friction occurs. It could be assumed that the same applies for distensibility.

Table 2: Skin surface properties and friction coefficients for different regions of hand of the Participant 2.

Region of Hand	MoistSense [au] (±error)	Thickness of SC [mm] (± SD)	Roughness [µm] (range)	CoF (N = 1 N) (± SD)	CoF (N > 2 N) (± SD)
Thumb-pad	40± 2	0.61±0.018	10-30	0.37±0.046	0.40±0.040
Index Finger-pad	42± 2	0.63±0.025	9.5-16	0.32±0.029	0.34±0.026
Middle Finger-pad	41± 2	0.54±0.023	10-16.5	0.35±0.027	0.35±0.028
Ring Finger-pad	44± 2	0.45±0.014	7-13.4	0.42±0.064	0.43±0.031
Little Finger-pad	39± 2	0.48±0.013	8-15	0.33±0.029	0.35±0.020
Palm	42± 2	0.27±0.008	7-14	0.30±0.018	0.34±0.011

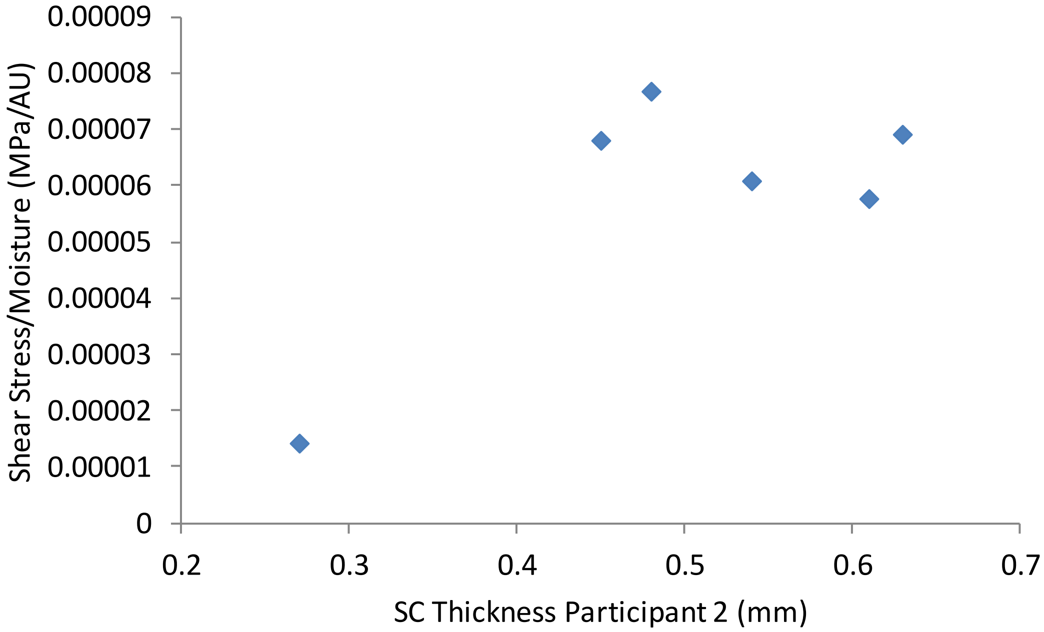


Figure 6: Link between SC thickness and shear conditions in the interfaces for Participant 2.

3.2 The Effect of Superficial Serum/Sweat on Skin Friction

Figure 7 (I) shows OCT images obtained from the tested finger-pad of Participant 1 after the tape strippings. The corresponding changes in the structural properties were quantified and plotted in Figure 7 (II), (III) and (IV) (please note that the "error bars" indicate Standard Deviation here and in all other graphs where shown).

As can be seen in Figure 7 (II), there was a slight reduction in the thickness of the stratum corneum (approximately 30 µm) in the first 5 tape strippings, which may due to the superficial film on the surface of the skin being removed. Afterwards, a further decrease occurred in the thickness of the SC when the number of strippings reached 15, resulting from some dead cells in the SC and serum/sweat film being removed. The thickness of the SC finally reached a plateau for the rest of the strippings. Unfortunately, those changes were too small to be viewed by the naked eye in the OCT images.

Figure 7 (III) shows some corresponding changes occurred on the moisture level of the skin after removal of the superficial film on the skin surface. This can be explained using three phases. In the first phase, the "MoistSense" reading was found to drop slightly (approximately 2 au) within the first 6 strippings, after that it increases to 67 au. In the third phase, the "MoistSense" reading gradually reduces and finally remains constant with further tape stripping. Figure 7 (IV) displays the friction force against the number of tape strippings, in which it was observed to increase until 10 µm of the SC was removed after 10 tape strippings. The general trend in moisture change follows that of the friction force. In Figure 7 (V), it is shown that the friction force generally increases with the "MoistSense" reading.

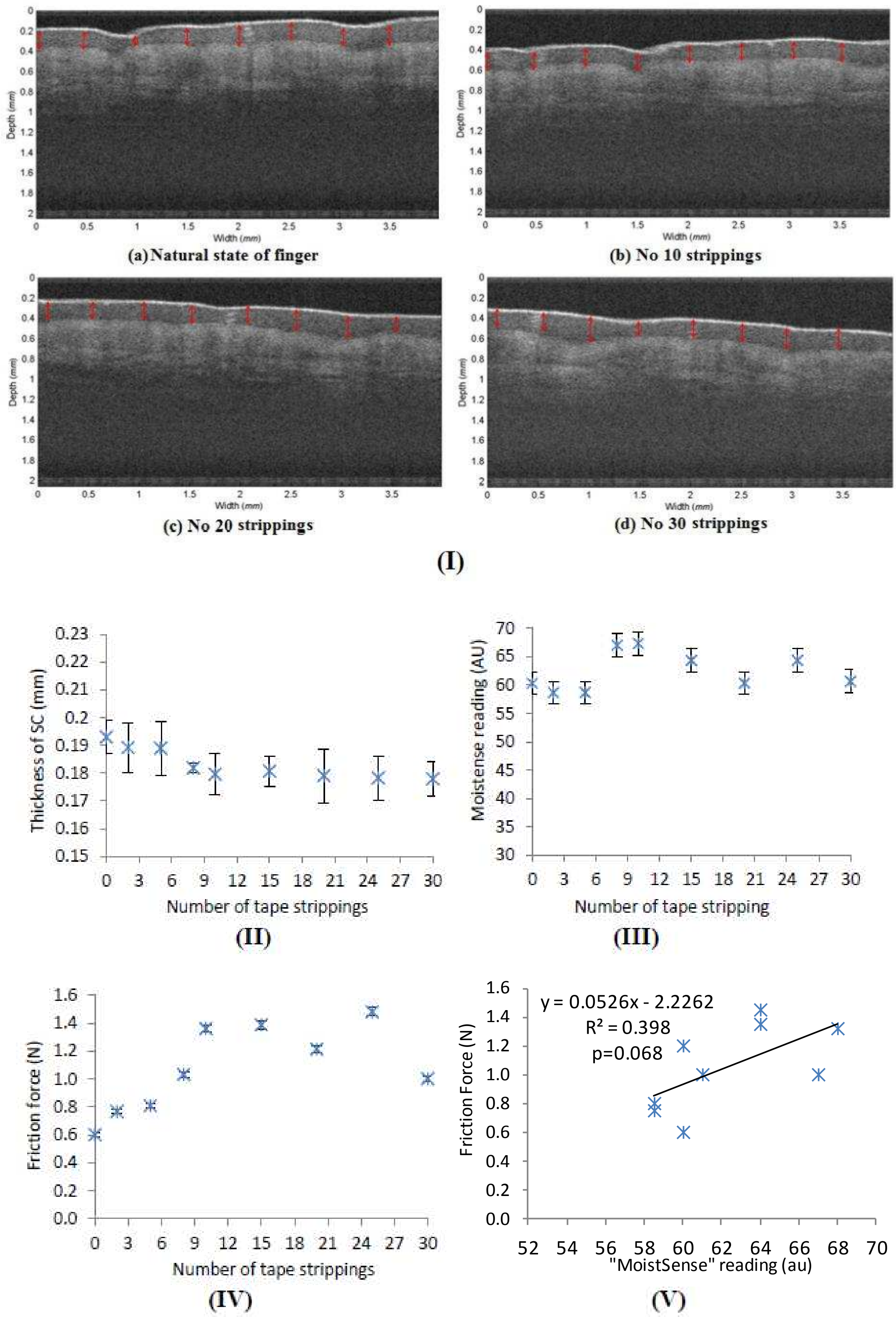


Figure 7: (I) OCT images of the skin of the index finger-pad of Participant 1 taken with various numbers of tape stripping; plots of the corresponding changes in the thickness of the stratun corneum (II), “MoistSense” reading (III) and friction force (IV), as well as the relationship between the friction force and the “MoistSense” reading (V).

OCT images of the skin of the index finger of Participant 2 are shown in Figure 8 (I), where changes in the skin structure with numbers of tape strippings are difficult to observe as expected. The corresponding thickness of the stratum corneum was found to have a rapid decrease in the first 3 tape strippings, after that it begins to plateau (see Figure 8 (II)). In contrast with Participant 1, the thickness of stratum corneum removed from Participant 2 was relatively high (around 120 µm).

From Figure 8 (III) it can be seen that there is a decrease in the "MoistSense" reading from 43 au to 40 au with tape stripping, followed by an increase beyond 8 tape strippings. The high similarities in the thickness of the stratum corneum and the moisture level of skin relating to tape stripping between both participants helped to confirm the assumption that only the surface film and dead cells were being removed by tape stripping. The corresponding results of the friction force shown in Figure 8 (IV) present a different trend compared to the case of the Participant 1 though. There was a slight drop of 2% in the friction force with 8 tape strippings, after that, the friction force was found to rise to 0.36. Moreover, it can be seen that the moisture level of Participant 2 was relatively low compared to Participant 1. This may be why the changes in the friction force were not as great as with Participant 2. Despite the differences between Participant 1 and 2 in absolute terms, though, for both, the moisture change follows that of the friction force as strippings increase and a linear relationship between the friction force and skin moisture level was also observed in Participant 2 (Figure 8 (V)).

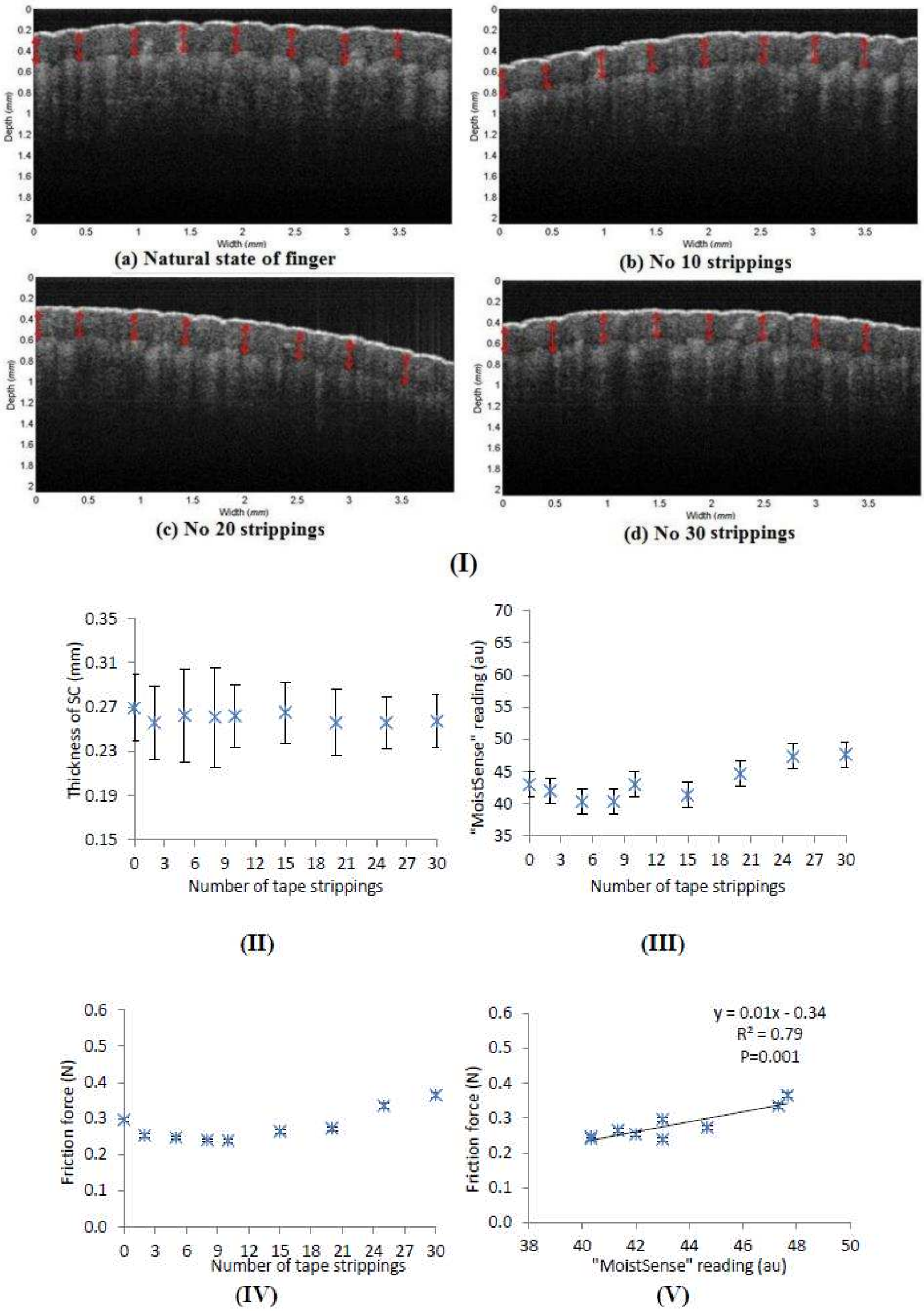
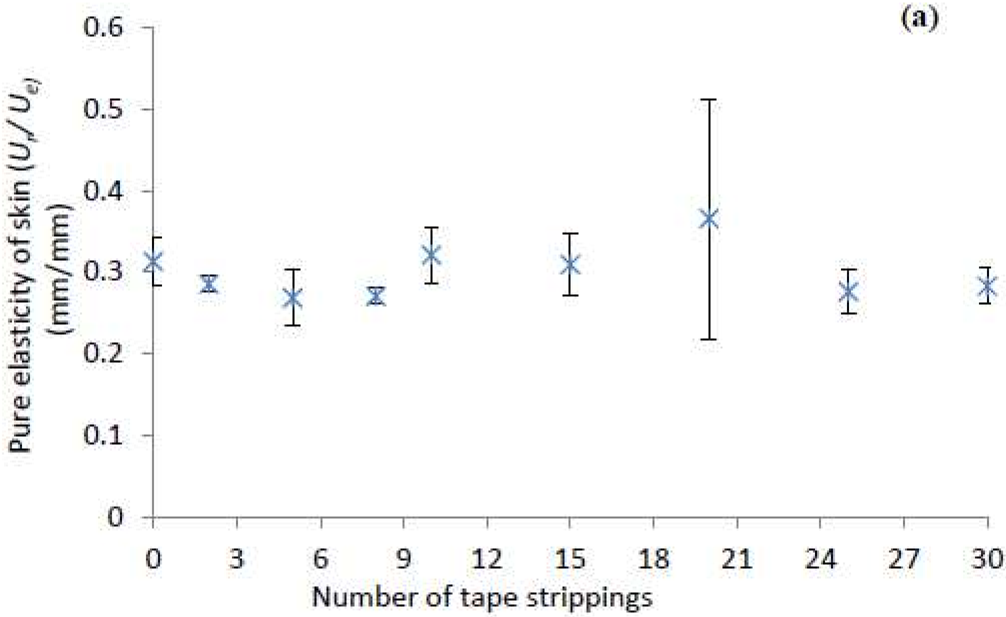


Figure 8: (I) OCT images of the skin of the index finger-pad of Participant 2 taken with various numbers of tape stripping; plots of the corresponding changes in the thickness of the stratum corneum (II), "MoistSense" reading (III) and friction force (IV), as well as the relationship between the friction force and the "MoistSense" reading (V). [Note: the scale of friction force is different to Figure 8].

Figure 9(a) shows measurements of pure elasticity (R5:U_r/ U_e) of the skin taken in Participant 1 using the "Cutometer". There is no significant change in the elasticity of the skin with the tape stripping, it can be assumed that skin elasticity is unlikely affected by tape stripping. A similar phenomenon is also found in Figure 9(b) where the general trend of the normal stiffness appears to be approximately constant. The change in friction as the strippings increase therefore must be related to the change in moisture or some other surface effect such as change in electric charge.



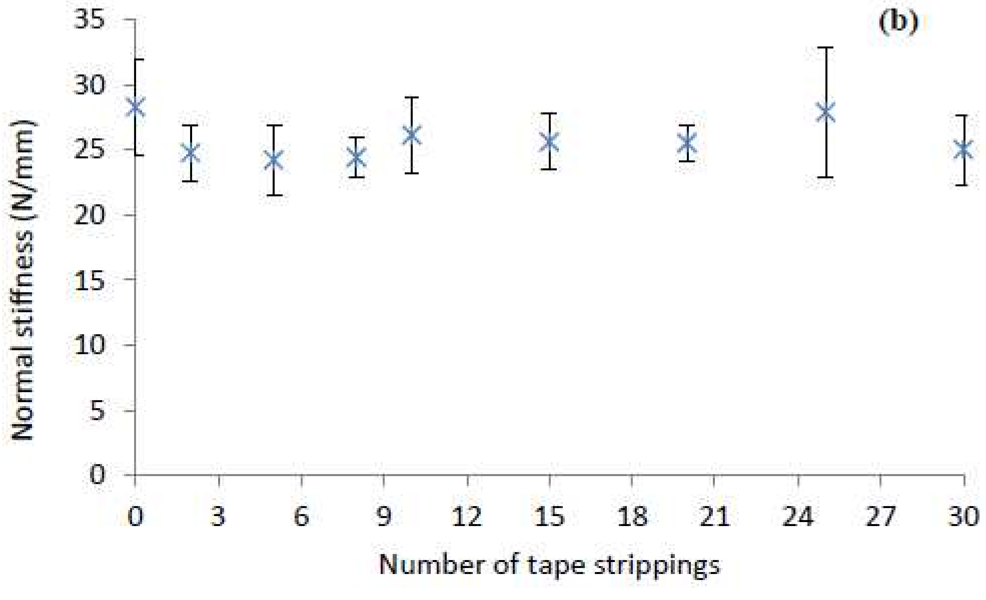


Figure 9: Changes in pure elasticity and normal stiffness of the skin at the finger-pad of Participant 1 for various numbers of tape strippings.

3.3 The Effect of the Thickness of Stratum Corneum on Skin Friction

In the OCT images shown in Figure 10 (I) and Figure 11 (I), the layers of the SC taken from both participants are clearly visible and corresponding changes in the thickness with various numbers of rubbings can be observed. It was also found that the skin in both subjects gradually becomes relatively smooth and this was attributed to the fact that the ridges on the skin surface were worn down by the sand-paper. It is clear to see that the thickness of the SC significantly decreases (approximately 0.03 mm in Participant 1 and 0.06 mm in Participant 2) when the finger-pad is rubbed by sand-paper, particularly in the first 6 rubbings (see Figure 10 (II) and Figure 11 (II)). There was no further decrease when increasing the number of rubbings from 8 to 12, the reason may lie in the fact that the sand-paper surface was contaminated with skin cells after being used for a period of time and therefore was less effective.

The moisture level of the natural skin in Participant 2 (approximately 36 au) was lower than half of the moisture level in Participant 1 (approximately 91 au) as before (see Figure 10 (III) and Figure 11 (III)). For both participants after an initial change over the first couple of rubbings the moisture value stayed fairly constant and this was clearly not the main parameter driving change in the friction force.

These results differ from those for the stripping where friction force followed the same trend as moisture for each participant. Here the friction forces followed the same trend as the SC thickness. The friction force was observed to drop by 29% in Participant 1 and 34% in Participant 2, respectively across the test duration. For example, as can be seen in Figure 10 (IV), the friction force was 3.1 N for the natural skin and reduced to 2.3 N after 6 rubbings with the same normal load applied to the skin. The investigations of the relationship between friction force and thickness of the SC indicates that the friction force is dependent on the thickness of the SC (see Figure 10 (V) and Figure 11 (V)). However, the normal stiffness of the skin seems not to be affected by the number of sand-paper rubbings according to the results in Figure 12.

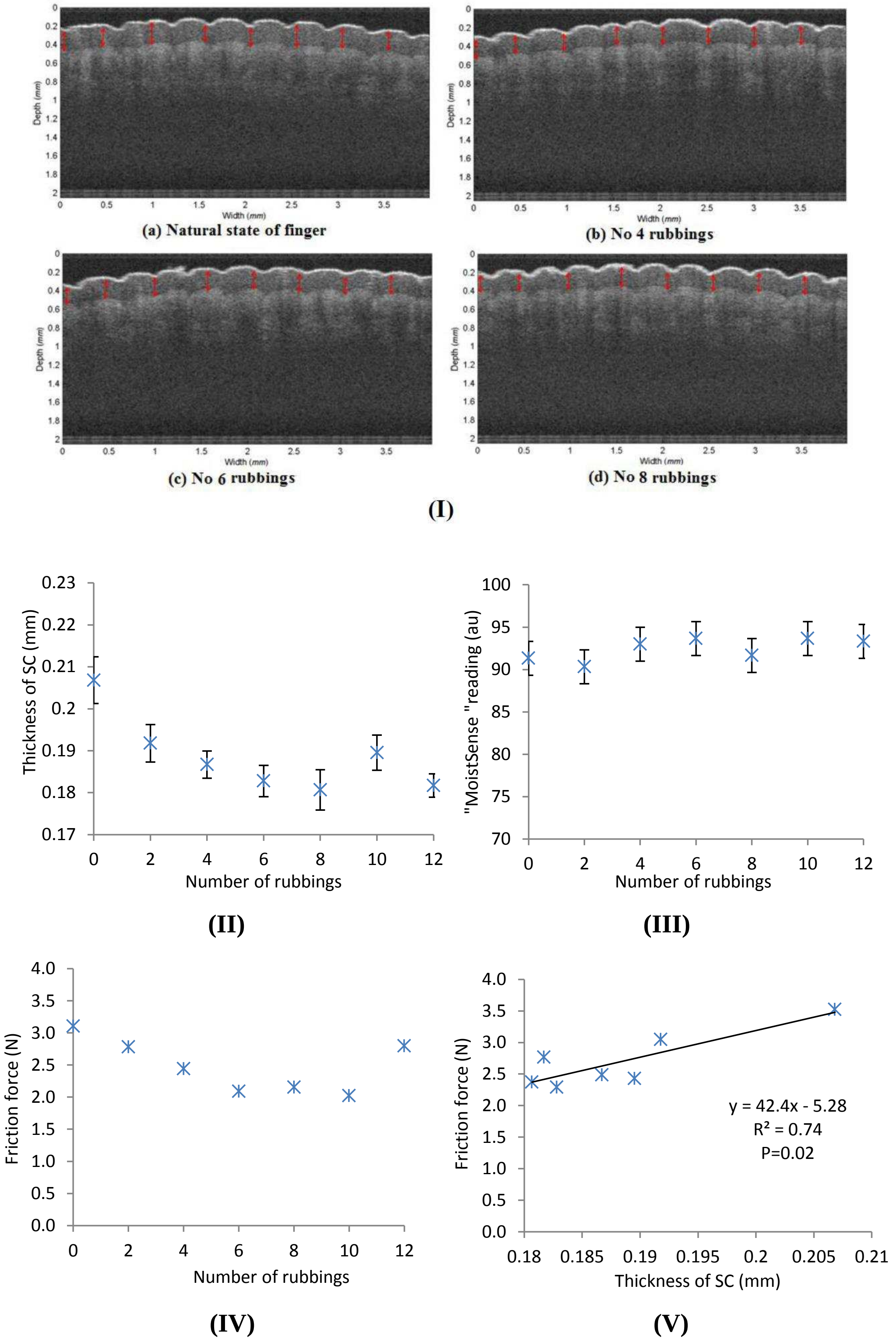


Figure 10: (I)) OCT images of the skin of the middle finger-pad of Participant 1 taken with various numbers of sand-paper rubbing; plots of the corresponding changes in the thickness of the stratum corneum (II), "MoistSense" reading (III) and friction force (IV), as well as the relationship between the friction force and the "MoistSense" reading (V).

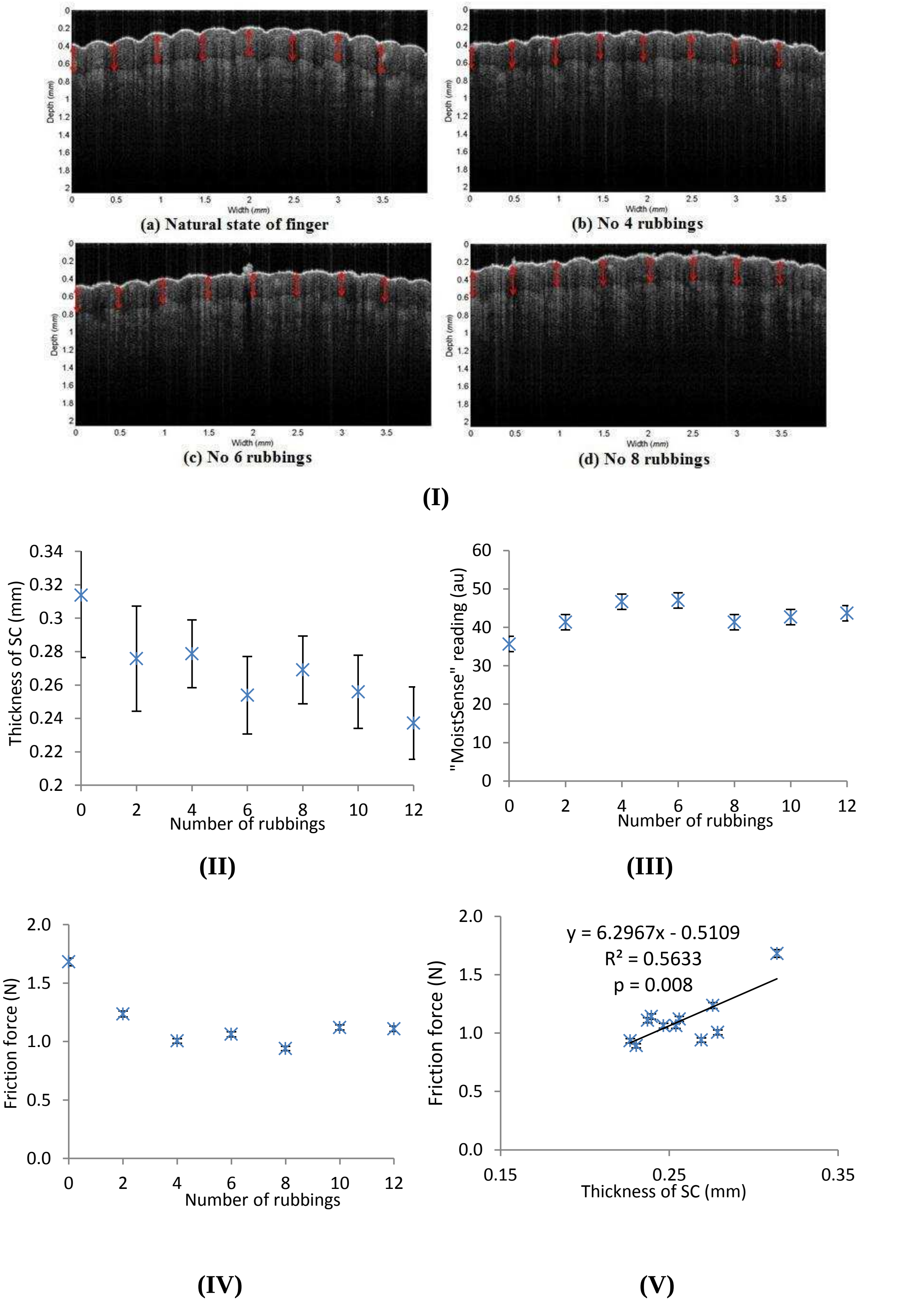


Figure 11: (I) OCT images of the skin of the middle finger-pad of Participant 2 were taken with various numbers of sand-paper rubbing; plots of the corresponding changes in the thickness of the stratun corneum (II), "MoistSense" reading (III) and friction force (IV), as well as the relationship between the friction force and the "MoistSense" reading (V). [Note: the scale of friction force is different to Figure 10].

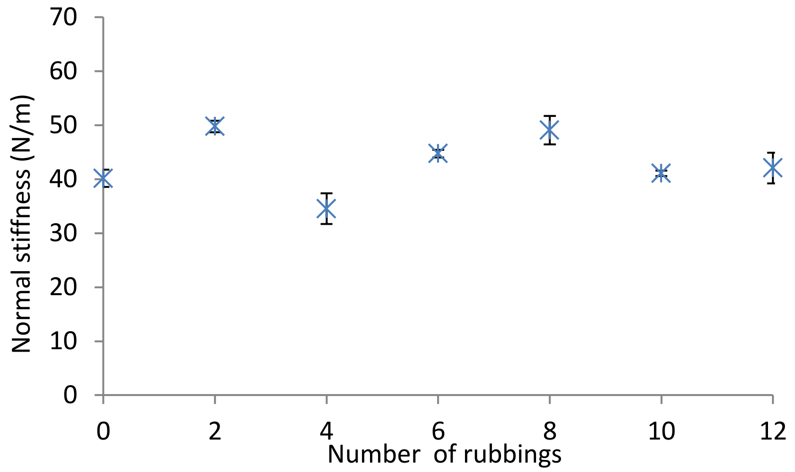


Figure 12: The change in normal stiffness of the skin at the finger of Participant 1 with rubbing.

4. DISCUSSION

As observed in previous studies, the skin friction coefficient widely varies from person to person [8, 12, 13, 17, 27], which could be attributed to various skin parameters as well as some human factors. It brings a challenge to investigate the relationships between each individual parameter (e.g. the thickness of the SC, the moisture level of skin) and skin friction. In order to avoid the influences of human factors on skin friction, such as, age, sex, etc., and mainly focus on one structural parameter, this test was designed based on the same participants.

4.1 The Effect of the Moisture Level of Skin

Scherge & Gorb [28] suggested that the impact of surface properties dominates friction forces at low force condition (< 1 N). In order to understand how skin friction alters with its surface properties, several skin parameters have been assessed in this study, including skin roughness, skin hydration and the thickness of the SC. As can be seen in Table 2, the skin friction widely varied between hand regions tested with low load, compared with that at high load condition. This could be explained by the fact that, under low load condition, skin properties make the main contributions to the friction and lead to a large variety of contact areas. However, only a few factors affect the skin friction under the higher load conditions. By analysing all parameters in Table 2, it was found that the skin hydration makes a great impact on the skin friction at both low and high load conditions. For example, by comparing the data in friction for the ring finger (high moisture) and the little finger (low moisture), it was noticed that the ring finger has a higher friction value than that of the little finger, despite both of them having similar thickness of the SC and surface roughness, therefore it can be assumed that there is a relationship between the moisture level of the skin and friction.

In both tape stripping and skin rubbing tests, the "MoistSense" readings of the skin show an initial decrease and then increase with removal of the superficial film and the skin tissue. Leveque [29] and Pailler Matteri et al. [15] reported that human skin has a gradient of material properties across different layers. A water gradient exists through skin layers, which can be attributed to the capabilities of water diffusion in internal layers and water evaporation at the skin surface. The changes that occurred in the moisture level seem to be related to the water gradient in skin layers. In the first 5 peelings of the tape stripping test, it was assumed that only the superficial film at the surface of the skin was removed, as no changes occurred on the skin structure. Skin becomes drier with the number of tape strippings, so the "MoistSense" reading obtained from the surface reduced. An increasing trend of the "MoistSense" reading was found in further stripping (ranging from 8 au to 10 au) and may be due to that the numerous extractions of the superficial layer resulting in a reduction of the thickness of the SC when the film was cleared way. As dead skin cells were removed, those cells beneath the removed cells were exposed and formed a new skin surface. Those new cells have relatively high water content because they are close to living layers, hydrated by water diffusing longer and faster compared with the outermost skin cells [30]. Therefore the "MoistSense" reading was found to increase as more skin cells were removed. This explanation also holds for the case of skin rubbing test. Finally, the "MoistSense" reading and the friction force reach a plateau in both experiments as no more skin tissue was removed.

In most previous work on moisture it has been controlled by applying water to the skin or by drying the skin. Here moisture changes resulted from "stripping" or "rubbing" of the skin. While it was shown from the "Cutometer" measurements that this did not have a big effect on the skin elasticity, the friction change may not have been entirely down the moisture change as the electric charge may also have changed on the skin surface which would also affect the "MoistSense" reading or the van der Vaal forces may have changed. This is all discussed in the following section.

4.2 Investigation of Adhesion Force between Finger-Pad Skin and Contacting Surfaces

A significant increase was found in the friction force with tape stripping, particularly in the first 10 strippings (Figure 5(IV)). As discussed earlier, the frictional behaviour of the skin involves an adhesion mechanism and deformation mechanism under low load conditions (< 2 N). The deformation mechanism refers to the deformation of asperities on the skin surface. However, no significant morphological change was found on the skin with the tape stripping except the thickness of the SC (see Figure 6(I)). Therefore, it can be assumed that the component of deformation can be neglected and the friction force is only dominated by the adhesion mechanism. According to previous research, the biological adhesion between living tissues and substrates is considered to be associated with their structures and chemical properties [31]. Marti et al. [32] and Erlanson et al. [33] indicated that the adhesion force in most cases can be expressed as a combination of electrostatic forces, van der Waals forces, capillary forces and forces due to chemical bonds or acid-base interactions. In later studies, Scherge & Gorb [28] found that there are four main contributions to the adhesion force for a silicon model in the micro-range. This observation is applicable for the study of the skin frictional behaviour, since both of them appear to behave similarly with respect to the friction. Those four contributors to the adhesion force of skin are molecular forces, electrostatic forces, capillary forces and forces due to excess charge. However, in ambient environments, it is believed that only the molecular forces (van der Waals forces) and electrostatic forces play important roles for governing the adhesion force, as well as chemical hydrogen bonds. Consequently, in this study, the total changes of the friction force can be calculated following the equation of Maksić & Thomas [34], Scherge & Gorb [35] and Butt et al. [36]:

$$\Delta F = \Delta F_{vdW} + \Delta F_{el} + \Delta F_{chem} \quad (3)$$

where ΔF_{vdW} is the change of van der Waals force, ΔF_{el} is the electrostatic force and ΔF_{chem} is the force due to chemical bonds or acid-base interactions.

4.2.1 van der Waals Force

The van der Waals force is attributed to a repulsive and/or an attractive interaction between molecules. For two flat surfaces, the van der Waals force follows the law of Butt et al. [34]:

$$\Delta F_{vdW} = \frac{\Delta G}{d} = -\frac{A_H}{6\pi d^3} \tag{4}$$

where ΔG is the van der Waals energy, d is the distance and A_H is the Hamaker constant (equal to $\pi^2 C\rho_1\rho_2 \approx 10^{-19} J$, C is the constant in the atom-atom potential, ρ_1 and ρ_2 are the numbers of atoms per unit volume). However, the van der Waals force is generally considered a relatively small force compared with other factors in most cases, because the spacing between the solids is not able to be reduced to 10 nm, because of their rough surfaces [28]. According to Equation (4), there was no significant change on the van der Waals force since the Hamaker constant and the distance were not altered with tape stripping. Therefore, it can be assumed that the influence of the van der Waals force on the adhesion force can be neglected. The electrostatic forces and the force due to chemical bond are the main contributors to the change of the adhesion force.

4.2.2 Electrostatic Forces

Landau and Lifshitz [36] have proposed a model for measuring the electrostatic energy between two different dielectrics (respective dielectric constant ε_1 for medium dielectric and ε_{skin} for skin). In accordance with this model, the electrostatic force correspond to a electronic charge Q, at a distance of D to the interface, is given by:

$$\Delta F_{el} = \frac{\Delta E_{el}}{d} = \frac{-Q^2}{4d(4\pi\varepsilon_0\varepsilon_1)D}\left(\frac{\varepsilon_{skin}-\varepsilon_1}{\varepsilon_{skin}+\varepsilon_1}\right) \tag{5}$$

where ε_0 is the dielectric constant of the air (see Figure 14). It shows that the electrostatic force is proportional to the electronic charge of the dielectrics tested.

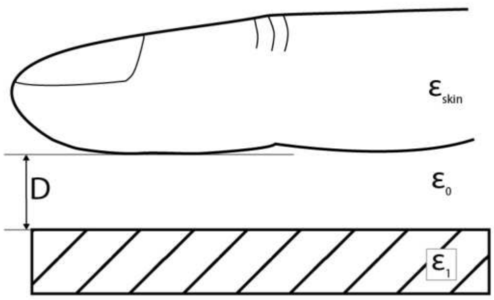


Figure 13: A modified schematic of the measurement of the electrostatic force.

The electronic charge Q on the stripped skin can be calculated with the “MoistSense” reading. The measuring principle of skin “MoistSense” reading is one of capacitance, with non-electric contact with the skin [24, 29].

$$Read\ out\ (\text{au}) = B \times C = B \times \frac{\varepsilon \times s}{d_p}(F) \tag{6}$$

where B is the arbitrary constant, C is the capacitance, ε is the difference in dielectric constant between skin and contacting dielectric $\varepsilon \approx \varepsilon_{skin}$, s is the size of sensor surface and

d_p is the distance between negative and positive poles. Since the value of B, the contact area (A) and the distance (d_p) are constant, the "$Read\ out$" highly depends on the capacitance, thus the dielectric constant of the skin. The surface electrical charge, is defined as $Q = C \times H$, where H is the potential difference (a constant).

$$Q = \frac{\varepsilon_{skin} \times s}{d_p} \times H \propto Read\ out\ \text{(au)} \tag{7}$$

By replacing the term of electronic charge Q in Equation (4), the model of the electrostatic force is given by the following equation:

$$\Delta F_{el} = \frac{-(\varepsilon_{skin} \times s \times H/d_p)^2}{4d(4\pi\varepsilon_0\varepsilon_1)D} \left(\frac{\varepsilon_{skin}-\varepsilon_1}{\varepsilon_{skin}+\varepsilon_1}\right) \propto -{\varepsilon_{skin}}^2 \left(\frac{\varepsilon_{skin}-\varepsilon_1}{\varepsilon_{skin}+\varepsilon_1}\right) \propto Read\ out\ \text{(au)} \tag{8}$$

Therefore, it can be assumed that the absolute value of the electrostatic force would increase when the electronic charge increases due to the increase of the dielectric constant of skin. This assumption was verified by the results in Figure 7 (V) and 8 (V), where the friction force shows an increasing trend as the "MoistSense" reading increased. This conclusion was also drawn by Guerret-Piécourt et al. [37], who assessed the influence of the electrical charges on the friction coefficient of insulating materials using a scanning electron microscope mirror method (SEMM). In their experiments, they found that the sapphire's ability for trapping electrons was improved after it was irradiated by UV, leading to more electrons being trapped, hence increasing the adhesion force.

In recent studies, Pailler-Mattei et al. [15] conducted similar tape stripping tests on the inner forearm. The results of their experiments show that the adhesion force rapidly increases for the first tape stripping, which is in good accordance with data presented here. They reasoned that it may be caused by the electrical phenomenon at the interface between skin and a probe. In a later study, they used a "fieldmeter" device to measure and compare the electric charge on the surface of skin before and after tape stripping [16]. Unfortunately, they did not observe any significant change on the electric charge, as well as the physico-chemical properties. This could be explained by the fact that generally the hand skin is covered with a sweat film and is more moist than the forearm. Therefore, in the current test, corresponding changes on the moisture level of the skin and the friction force with respect to the numbers of tape strippings can be directly observed. In the study of Pailler-Mattei, et al. [16], the change of the adhesion force seems to be mainly attributable to the removal of the SC since there less or no film at the surface on the forearm. In the current work, though, it is impossible to separate changes in moisture and electric charge from the "MoistSense" so it cannot be stated categorically whether both or either on their own are responsible for adhesion changes.

4.2.3 Physico-chemical Properties

According to Butt et al. [35], the force due to chemical bonds or acid-base interactions formed at the jump-off-contact can be measured by a simple model. It is assumed that the chemical bonds form randomly and have all the same value of force (F_i). The total force (ΔF_{chem}) for n chemical bonds formed is obtained as follows:

$$\Delta F_{chem} = nF_i + F_0 \tag{9}$$

where F_0 is a non-specific interaction, depending on the chemical components of the interfaces. Elkhyat et al. [38] have investigated the effect of the hydrophilic/hydrophobic balance for both slider surfaces and sliding materials on friction coefficient. The results from their tests indicated that friction coefficient for the hydrophobic/hydrophobic tribo-pair is relatively lower than those for hydrophilic/hydrophobic and hydrophilic/hydrophilic tribopairs. However, in the current study, those physico-chemical properties of the skin (hydrophilicity) and their effects on the skin friction related to the tape stripping test cannot be assessed due to limited techniques.

All analysis presented above provides a new insight into the interaction between the skin of human finger-pad and contact surfaces, but further investigations will be required to isolate the individual parameters.

4.3 Skin Mechanical Properties

In contrast to the tape stripping tests, the results of the sand-paper rubbing tests showed that the friction force is reduced significantly with rubbing, see Figure 10 (IV) and 11 (IV). This may be caused by the morphological and structural changes of the SC with rubbing. For example, in Figure 10 (I), it was found that the ridges at the surface of the skin shrink after skin rubbing, which contributes to a relative flat surface of the skin. Meanwhile, the thickness of the SC was found to gradually diminish after a few rubbings, which is validated by the experimental data in Figure 10 (II). In general, it is believed that the mechanical properties of the stratum corneum cannot influence the global mechanical properties of the skin [15, 16]. This could explain why the mechanical parameters of the skin are independent of the thickness of the SC in the "Cutometer" measurement except the distensability of the skin (see Table 1 and Figure 12). As mentioned above, the frictional interaction between human skin and contacting surfaces is complicated, and involves various mechanisms. The skin would experience two different deformations with respect to the normal load and shear force respectively when it was sliding against a flat surface. For a better understanding of the skin frictional behaviour, deformations in both vertical and horizontal directions were analysed and represented by two parameters, the normal stiffness (S_v) and the lateral stiffness (S_l). They can be used to determine the Young's modulus of skin in both directions according to the following [5, 15]:

$$\begin{cases} E_v = \frac{2\sqrt{A}}{S_v\sqrt{\pi}} & Young's\ modulus\ in\ vertical\ direction \\ E_l = \frac{2\sqrt{A}}{S_l\sqrt{\pi}} & Young's\ modulus\ in\ lateral\ direction \end{cases} \quad (10)$$

Wolfman [40] derived a relationship between the adhesion component of the friction coefficient and the Young's modulus, the equation is given as follows:

$$\mu_{ad} \propto N^{-1/3}E^{-2/3} \quad (11)$$

where N is the normal load, E is the reduced Young's modulus and μ_{ad} is the adhesion component of friction coefficient. As a consequence, the adhesion friction can be written as a function of stiffness, as

$$F_{ad} \propto {S_{v/l}}^{2/3} \quad (12)$$

However, in the current test, there was no significant change in the normal stiffness after skin rubbing, even though the thickness of the SC was reduced by 25 µm, which confirms that the change of the thickness of the SC is too small to affect the global mechanical properties of the skin (Figure 13). Due to the limitation of techniques, the lateral stiffness of the skin was not investigated here. In similar studies, Pailler-Mattei et al. [15] found that both the normal stiffness and particularly the lateral stiffness appear to decrease as a function of the SC removed. The thickness of the SC had a drop of 6 µm after 30 tape strippings, the corresponding adhesion force was observed to slightly decrease as well, except for the first tape stripping, which is in a good agreement with Equation (6). As a consequence, those observations reveal that the reduction of friction force after sand-paper rubbing may be attributed to the reduction of the lateral stiffness of the skin with respect to the removal of the SC. This is an interesting area to explore and there is much more work that could be done in future.

4.4 Skin Morphological Properties

The morphological change of the SC might be the other reason for the friction force reduction in the sand-paper rubbing tests. In this study, a new technique (OCT imaging system) has been introduced. The OCT system offered microscopic visualization of skin structure, which enable any morphological changes can be observed directly, measured, and precise predictions can be made. As can be seen in Figure 10 (I), the ridges on the surface reduce with rubbing, thus, the skin becomes more flat, and hence increases the real contact area between the finger skin and a surface. Meanwhile, it was found that the skin surface became rougher with rubbing. Under a normal condition, after the outermost layer of skin is rubbed by a piece of sand-paper, it becomes brittle and scaly, which can be directly observed by the naked eye, particularly in Participant 2 (see Figure 11 (I)). Therefore, the real contact area should decrease. Here, it is assumed that both effects are not significant, the main contributor to the change of friction force is the removal of the SC. Those influences on the friction force with respect to the physico-chemical properties of the skin should not be considered, such as chemical bonds, electronstatic forces, because it was assumed the superfacial layer was removed by hand washing prior tp the rubbing test.

5. CONCLUSIONS

When a human finger comes into contact with a surface and starts to move, there are four key factors that appear to strongly influence the frictional behaviour between the finger-pad and the contacting surfaces, including the complex interplay of materials, properties of finger-pad skin, contact conditions and environmental conditions. In this study, a commercial non-invasive imaging technique (PS-SS-OCT system) has been used along with a "Cutometer" MPA 580 device to assess the structural and mechanical properties of skin alongside moisture and friction measurements.

Initial measurements showed that the disensibility of skin is linearly dependent on the thickness of stratum corneum (taking measurements across all fingers and the palm). Linking the two sets of data from both participants it was concluded that friction increases with stratum cornuem thickness, once contact area and moisture had been accounted for, and it is therefore directly related to distensibility.

The two studies on tape stripping and sand-paper rubbing of skin gave further insights regarding the role of skin structure on friction.

In the case of the tape stripping tests, it was assumed that only the superficial layer at the skin surface was removed as no change was observed on skin structure. Friction force recorded changed with a similar trend to the moisture readings so it could be concluded that this will have led to the increase seen in friction force rather than any changes in structural properties. In fact, no changes occurred to the normal stiffness of the skin with the stripping so this could definitely be discounted as a cause. The "MoistSense" readings could indicate a change in moisture and/or a change in electric charge on the surface of the skin, both of which would cause an increase in adhesion force. Physio-chemical effects could have also played a role, but these were not measured.

In the case of the sand-paper rubbing tests, greater damage was done to the finger-pad surface, sufficient to remove part of the stratum corneum layer. The skin friction coefficient was found to have an initial decrease with repeated rubbing before a plateau is reached. This can be attributed to the fact that the thickness of the stratum corneum was reduced. While skin normal stiffness did not change it is highly likely, based on observations from previous work, that lateral stiffness will, be reduced pad skin and therefore the friction force is reduced. Here moisture did not change after the first couple of rubbings so could be discounted as a cause of friction force change.

REFERENCES

[1] Wood, E.J., Bladon, P.T., "The human skin". Studies in Biology; 162: 1985.

[2] Jones, L.A., Lederman, S.J., Human hand function. Oxford University Press, 2006, 18-21.

[3] Tortora, G.J., Derrickson, B.H., Principles of Anatomy and Physiology. 12th Edition, New York, 148-166, 2009.

[4] Sandby-Moller, J., Wulf, H.C., Poulsen, T., "Epidermal thickness at different body sites: relationship to age, gender, pigmentation, blood content, skin type and smoking habits". Acta. Derm. Venereol; 83(6): 410-3, 2003.

[5] Geerligs, M., Breemen, L.V., Peters, G., Ackermans, P., Baaijens, F. and Oomens, C., "In-vitro indentation to determine the mechanical properties of epidermis". J. Biomech; 44: 1176–1181, 2011.

[6] Peter, A.P., "Measurement of properties and function of skin", Clin. Phys. Physoil. Meas.; 12: 105-129, 1991.

[7] Hendriks, F.M., Mechanical behaviour of human epidermal and dermal layers in-vivo. PhD Thesis. Technische Universiteit, Eindhoven, 2005.

[8] Cua, A., Wileherim, K.P., and Maiback, H.I., "Frictional properties of human skin: relation to age, sex, and anatomical region, stratum corneum hydration and transepidermal water loss". Br J Dermatol; 12: 473-479, 1990.

[9] Zhang, M., Mak, A.F.T., "In vivo friction properties of human skin". Prosthetics and Orthotics International; 23: 135-141, 1999.

[10] Derler, S., Gerhardt, L.C., Lenz, A., Bertaux, E. and Hada, M., "Friction of human skin against smooth and rough glass as a function of the contact pressure". Tribology International; 42: 1565–1574, 2009.

[11] Hendriks, C.P. and Franklin, S.E., "Influence of surface roughness, material and climate conditions on the friction of human skin", Tribol Lett; 37: 361-375, 2010.

[12] Zhu, Y.H., Song, S.P., Luo, W., Elias, P.M. and 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.

[13] Veijgen, N.K., Masen, M.A. and van der Heide, E., "A novel approach to measuring the frictional behaviour of human skin in-vivo", Tribology International; 54: 38–41, 2012.

[14] Ramalho, A., Silva, C.L., Pais, A.A.C.C. and Sousa, J.J.S., "In-vivo friction study of human skin: influence of moisturizers on different anatomical sites". Wear; 263: 1044–1049, 2007.

[15] Pailler-Mattei, C., Pavan, S., Vargiolu, R., Pirot, F., Falson, F. and Zahouani, H., “Contribution of stratum corneum in determining bio-tribological properties of the human skin”. Wear; 263:1038-1043, 2007.

[16] Pailler-Mattei, C., Guerret-Piécourt, C., Zahouani, H. and Nicoli, S., “Interpretation of the human skin biotribological behaviour after tape stripping”. J R Soc. Interface; 8: 934-941, 2011.

[17] Liu, X., Lu, Z., Lewis, R., Carré, M.J. and Matcher, S.J., “Feasibility of using Optical Coherence Tomography to study the influence of skin structure on finger friction”, Tribology International: 68; 34–44, 2013.

[18] Agache, P.G, Monneur, C., Lévèque , J.L. and Rigal, J., “Mechanical properties and Young's modulus of human skin in-vivo”, Archives in Dermatological Research; 269: 221-232, 1980.

[19] Barel, A.O., Courage, W. and Clarys, P., “Suction method for measurement of skin mechanical: the Cutometer”, In: Serup, J. and Jemec, G.B.E. (eds.) Handbook of Non-Invasive Methods and the skin. Boca Raton, CRC Press; 335-340, 1995.

[20] Welzel J., “Optical Coherence Tomography in dermatology: A review”. Skin Res. Technol.; 7: 1-9, 2008.

[21] Lu, Z.H., Kasaragod, D.K. and Matcher, S.J., “Optic axis determination by fibre-based polarization-sensitive swept-source optical coherence tomography”. Phys. Med. Biol.; 56: 1105-22, 2011.

[22] Burkitt, H.G., Young, B. and Heath, J.W., Wheater's functional histology: A text and colour atlas. 3rd ed. New York: Churchill Livingstone, 1993, P. 154.

[23] http://www.moritexusa.com/products/product.php?plid=5&pcid=10&pid=17. Accessed 1/12/09

[24] Tomlinson, S.E., Understanding the friction between human finger and contacting surfaces. PhD Thesis. The University of Sheffield, 2009.

[25] Childs, T.H.C., “Human tactile perception of screen printed surfaces: self-report and contact mechanics experiments”, Proc. IMechE; 221: Part J: Journal of Engineering Tribology; 427-441, 2006.

[26] Liu, X., 2013, “”, PhD Thesis, The university of Sheffield.

[27] Cole, K.J., Rotella, D.L. and Harper, J.G., “Mechanisms for age-related changes of fingertip forces during precision gripping and lifting in adults”, The Journal of Neuroscience; 19: 3238–3247, 1999.

[28] Scherge, M., Gorb, S.S., “Biological micro- and nano-tribology: nature's solutions”. Proc. R. Soc. London. A, 2004.

[29] Fluhr, J., Eisner, P., Berardesca, E. and Maibach, H.I., Bioengineering of the skin, water and the stratum corneum. 2nd Ed. (revised), 2013.

[30] Philip, W. W and Bozenma, B. M., Bioengingeering of the skin: water and the stratum corneum, second edition; 359-368, 2005.

[31] Pailler-Mattei, C. and Zahouani, H., “Study of adhesion force and mechanical properties of human skin in-vivo”. J. Adhes. Sci. Technol; 18: 1739-1758, 2004.

[32] Martin, Y., Abraham, D.W. and Wickramasinghe, H.K., “High resolution capacitance imaging and potentiometry by force microscopy”. Appl. Phys. Lett.; 52: 1103, 1988.

[33] Erlandsson, R., Hadziioannou, G., Mate, C.M., McClelland, G.M. and Chaing, S., “Atomic scale friction between the muscovite mica cleavage plane and a tungsten tip”, J. Chem. Phys; 89: 5190, 1988.

[34] Maksic, Z.B. and Orville-Thomas, W.J., Modern modelling of the chemical bond. Elsevier: Amsterdam; 519-536, 1999.

[35] Butt, H.J., Cappella, B. and Kappl, M., “Force measurements with the atomic force microscope:Technique, interpretation and applications”. Surface Science Reports; 59: 1–152, 2005.

[36] Landau, L.D., and Lifshitz, E.M., Electrodynamics of continuous media. Pergamon Press, London; 8: 317-318, 1960.

[37] Guerret-Piécourt, C., Vallayer, J. and Tréheux, D., “Limitation induced by electrical charges effects on micromechanisms”. Wear; 254: 950–958, 2003.

[38] Elkhyat, A., Courderot-Masuyer, C., Gharbi, T. and Humbert, P., “Influence of the hydrophobic and hydrophilic characteristics of sliding and slider surfaces on friction coefficient: in vivo human skin friction comparison”. Skin Res. Technol.; 10(4): 215–221, 2004.

[39] Wolfram, L.J., “Friction of skin”, Journal of the Society of Cosmetic Chemists; 34: 465-476, 1983.