Understanding Handling Performance of Rugby Balls under Wet Conditions: Analysis of Finger-Ball Friction

Jiaojiao Liu[a], Qian Zhang[b] and Xiaoxiao Liu[b*]

[a] *The School of Sports and Physical Education, Shandong Sport University, Rizhao, Shandong, 276800, China;*

[b] *The Faculty of Engineering and Technology, Liverpool John Moores University, Byrom Street, Liverpool, L3 3AF, UK.*

[*] *Corresponding author. Tel: +44 (0)151 409 6157; email address X.Liu@ljmu.ac.uk*

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Abstract

This paper presents work with the aim of investigating the effect of moisture on the skin frictional behaviour of human finger-pads in contact with rugby balls. During sports activities, human body experiences high volumes of thermoregulatory sweating as a result of achieving body's temperature balance. Consequently, sweating alters human skin properties and contact conditions between hand skin and sports equipment, and may adversely affect exercise/sports performance. In this work, a rugby ball passing test under wet conditions was conducted to examine the influence of skin hydration on rugby ball handling performance. Then a comprehensive study was carried out to assess skin structures, frictional properties and contact areas of the interface between human finger-pads and flat surfaces at different moist conditions. It was found that the handling performance of rugby balls is strongly associated with the skin moisture level. The experimental results of the skin friction study showed that the skin friction coefficient changes with hydration time following a "bell-shape" curve. It also showed that the corresponding thickness of the stratum corneum of the examined fingers increased due to the transmission of water in skin tissues. This leads to an increase in the contact area and friction force with hydration time.

Keywords: Ball Handling Performance, Passing Tests, Hydration, Skin Friction, Skin Properties, Contact Areas

1. Introduction

Effective ball handling is one of the core skills required for players in rugby and many other ball games, in which hands contact with balls in various forms, including picking up balls, catching balls and passing balls. To achieve these, players should secure the holding of balls in a proper position that allows them to manipulate the balls in passing and catching more accurately. It is generally believed that good handling skills could contribute to a decrease in turnover, hence an increase in winning probability (Ross, 2015; Vaz, 2019). Rugby is an outdoor game that is likely to be played under various weather conditions in terms of temperature, humidity and wind, which may affect the rugby balls' frictional behaviour and travelling speed, as well as players' performances of tasks in games. For example, dropping the balls due to slippery hands was one of the most common handling mistakes faced by players in high humidity conditions at the Rugby World Cup in Japan. "The first 20 minutes the ball going to stick, and after that, it is going to be almost impossible to handle", said the South Africa coach Rassie Eramus (Woolford, 2019). Williams (2019) commented that during the tournament the humidity could go up to 75% in Japan which might bring troubles for players to use sweaty hands catching/passing damp balls. In order to cope with this scenario and minimise the possible handling errors, many rugby teams started practising with balls soaked in a variety of lubrications. For an instance, the Scotland team used shampoo to mimic the slippery handling conditions and the Wales team used baby oil for a similar purpose. The choice of the England team was dipping the balls in water (O'Sullivan, 2019). However, there is very limited research that has been undertaken to investigate effect of moisture on the handling performance of rugby balls.

Tomlinson et al. (2009) have conducted a series of passing accuracy tests along with friction measurements wherein players were asked to throw rugby balls at a target under dry and wet conditions. They observed that the balls with a higher coefficient of friction give better scores in the accuracy test. This finding could lead to a conclusion that that the accuracy of a rugby ball pass is closely associated with the dynamic frictional behaviours between human fingers and ball surfaces. In the studies of Lewis et al. (2013, 2014), they indicated regardless players' abilities and skills, the interacting surfaces of players' hands and the balls in a relative motion is considered as one of the governing factors that could influence players' performance in a game. High friction forces would be needed in catching, passing and holding the balls with the aim to improve game performance. Moreover, they found that the damp palms have the highest values of friction coefficient, followed by the dry palms and wet palms when the hands contacting with different rugby ball surfaces. They also indicated that adding various patterns of pimples on the ball surface could ease ball gripping in dry conditions, particularly the balls with dense pimple patterns because of the high friction forces between the hands and the ball surfaces could help grip. In wet conditions, the balls with less dense pimple patterns give better performance.

Skin is known as the largest organ of the human body and it exhibits heterogeneous, anisotropic and non-linear viscoelastic behaviour that bears a very close resemblance to that of rubber (Delalleau et al., 2008; Hendriks, 2005). Those unique physical-mechanical properties give skin a very complex frictional behaviour that has been investigated comprehensively in recent decades (Adams et al., 2007; Chimata & Schwarz, 2015; Derler et al., 2015; Liu et al., 2013, 2015; Pailler-Matteri et al., 2007, 2011; Tomlinson et al., 2007, 2011). In general, it is recognised that the tribology of human skin is intimately associated with the mechanisms of adhesion and hysteresis. The adhesion mechanism refers to the system where a shear force is required to break the finger skin interface with contact surfaces, and the second mechanism of hysteresis is considered to be associated with the dissipation of energy due to skin deformation. Adams et al. (2007) have proposed linear relationships to describe the friction coefficient of human skin in term of the normal load, however, those models are only subject to the skin in a pure dry state or a pure wet state. In reality, skin is exposed to different environments and interfaces with various substances as a protector in daily activities all the time, which make it difficult to keep the skin clean and dry. For instance, during sports activities, massive heat generated within human body cells needs to be regulated in order to maintain a heat balance without interrupting organisms. Thermoregulatory sweating is the primary mechanism of cooling body by allowing heat to be consumed with the evaporation of sweat at skin surface. Consequently, sweating could alter human skin properties and adversely affect exercise/sports performance.

The moisture effect is one of the key concepts attracting more attention in this research field. Previous related published works have shown that skin friction varies with different moisture levels of skin (Adams et al., 2007; André et al., 2009; Cua et al., 1990; Dinc et al., 1991; Gerhardt et al., 2008; Hendriks & Franklin, 2010; Johnson et al., 1993; Sivamani et al., 2003). Two different relationships (i.e. a linear and a bell-curved relationship) have been suggested for explaining the hydration dependence of the skin friction coefficient. For example, Cua et al. (1990) reported that there was a significant linear relationship between skin hydration and coefficient of skin friction for both young and old groups. Sivamani et al. (2003) observed that the coefficient of dynamic friction for the hydrated abdomen skin gradually decreased from 0.35 to 0.2 (pre-hydration value) after water exposure. In the studies of Adams et al. (2007) and Tomlinson et al. (2011), they found a "bell curve" relationship in the coefficient of friction with respect to various contacting materials and hydrated fingers. Their experimental results showed there was an initial increase in the coefficient of friction when the examined fingers were soaked in water for approximately 30 seconds, and then the coefficient of friction decreased after the skin reaches its maximum hydration balance. After several detailed investigations of the curve response, it was concluded that the changes in the coefficient of friction could be attributed to three mechanisms: water absorption of skin, viscous shearing action between liquid bridges and capillary adhesion between skin and the contacting surface (Dinc et al., 1991; Tomlinson et al., 2007). Furthermore, Tomlinson et al. (2011) carried out a series of tests in order to investigate the influence of skin hydration on the skin friction with respect to each mechanism and suggested that the mechanism of water absorption was the key contributor to the increase of the skin friction. However, very little detail was given in term of this mechanism; therefore, a thorough study is yet to be carried out.

This study aims to investigate in detail the influence of moisture on the skin frictional behaviour of human finger-pads in contact with rugby balls via the studies of skin properties related to skin hydration. Therefore, in this work, three series of experiments were designed and carried out, including a rugby ball passing test and measurements of the stratum corneum (SC) thickness along with skin friction tests. Finally, a further analysis was performed to assess how the contact area of finger-pads in contact with objects is altered with skin hydration.

2. Experimental Materials and Methods

2.1 Rugby Ball Passing Test under Different Moisture Conditions

2.1.1 Experimental Details

In order to assess the effect of skin hydration on the rugby game performance, eight male rugby players, aged between 18 and 20 years, from Shandong Sports University were invited participate in this study. Those players have developed similar skills in rugby through their regular training. In this study, the participants conducted the test with pimpled balls under four different conditions: a natural state, a medium hydration state, a high hydration state and an addition of water, to examine how the accuracy of ball pass changes with different moisture of skin. For the natural-state test, the examined hands of participants were cleaned and dried using paper towels, prior to the test. A "*Moist Sense*" device was used to record the moisture readings of participants' thumb and middle fingers in their right hand (for details see Liu et al., 2015).

As shown in Figures 1, the net was placed at a position seven metres away from the zone AB. During the tests, participants were guided to pick a rugby ball from position E at a distance of 4 m to zone AB, then run to the zone AB and throw the ball to a net simultaneously. After completing the shot, the participants ran toward position F to get the ball and then returned to zone AB to perform another shot. Regarding the middle hydration test, the participants were asked to conduct ten-minute regular warm-up activities and repeat the passing test. The third test was done in a relative high hydration state where the participants were asked to conduct twenty-minute warm-up activities to increase their skin moisture content. The last test was done by soaking rugby balls in tap water for about one minute to ensure ball surfaces are covered with water. For each test, the participants were asked to complete four successful shots with respect to different moisture conditions. The time taken to complete all shots was recorded and used to determine the performance score. A scheme was employed as a guide for awarding marks in this study, as shown in Table 1. This scheme was derived from a revision of the China national sports college entrance examination and marking standard (China national sports college entrance examination and marking standard, 2018).

<**Figure 1** The illustration showing how players conduct the ball passing test.>

<**Table 1** The marking scheme used for rugby target passing test (China national sports college entrance examination and marking standard, 2018).>

2.1.2 Statistical Analysis

The collected data from the test were entered into a spreadsheet (Microsoft Excel) and then exported into statistical software SPSS version 26 for further analysis. Both descriptive and inferential statistical analysis methods were used in this study. Firstly, a descriptive analysis of the data was performed for moisture readings (average data and standard deviations). Because of the varieties of the moisture level of players' finger-pads, the data of moisture readings for every player were normalised to the range of 0.0 to 1.0. In order to determine whether there is a significant difference in the moisture level for different hydration groups, a nonparametric method: Freidman test was used. Finally, correlation analyses were conducted to investigate the relationship between the normalised skin moisture reading and the target score. A Pearson correlation coefficient R was calculated to assess the correlation between the real measured data and a model's predicted values. In the statistical analysis, the significance was set with a p value ≤ 0.05.

2.2 Measurements of the SC Thickness and the coefficient of Skin Friction

The SC thickness was measured by a non-invasive technique – an optical coherence tomography system (OCT) (Michelson Diagnostic Ltd) as shown in Figure 2. It is an imaging technique based on the principle that those three tissue layers of human skin present different light reflectance and transmittance properties. This system employs a coherence light source with a centre wavelength of 1300 nm and a bandwidth of 110 nm FWHM (Santec Limited) to capture cross-section images of biological issues. The infrared light in the system is divided into two arms: a sample arm and a reference arm. For the sample arm, the relative long wavelength light is set to focus on the examined sample, in which the light scatters in different depths of skin tissue. The infrared light in the reference arm is reflected by a mirror at a fixed delay at the end of the arm. The combination of these two reflected lights from the examined sample and reference mirror enables a two dimensional image to be viewed where various tissues are displayed as bright and dark regions (Welzel, 2008). The SC and other epidermis layers can be identified according to their light refractance properties, therefore the SC thickness can be measured by calculating the distance between the skin surface and the epidermis layer (Liu et al., 2013). The current set-up of the OCT system allows the visualization of the internal structure of skin to the depth of images obtained with a resolution of 10 µm (axis) x 15 µm (lateral). Despite that, this equipment is also advantageous in producing real time multiple images in a second, permitting for three dimensional image reconstructions of the examined tissue. The space between slides is 0.04 mm (Lu et al., 2011).

For the measurement of skin friction, a low load miniature force platform system (Mode: HE6X6, Advanced Mechanical Technology, Inc) was employed. As shown in Figure 3, this test set-up is mainly consisted of a 152 x 152 mm ^{2}force plate, a PC and a PJB-101 interface box. It works on the principle of strain gauge flexibility technique that enables force measurement in X-, Y- and Z-axes. The capacity of the force plate is 22 N in X- and Y-axes and 44 N in Z-axis with an accuracy of 1%. During measurements of a finger sliding against the plate surface, the force acting in the Z-axis is considered as a normal load/force, the corresponding forces in *X*-axis and *Y*-axis are friction forces. Thus, the friction coefficient can be obtained by the calculation of the ratio between the normal force (*Z*-axis) and the friction force (*X*- axis or *Y*-axis).

In this series of tests, participants were invited and requested to clean and dry their hands before the test. A variety of moisture levels in skin were achieved by soaking participants' middle fingers on right hands in tap water for a range of times (up to a maximum of 400 s). Excess water was then removed by a paper towel. During measurements, the examined finger-pads were held to face to the lens of the OCT (see Figure 2) as instructed. In order to obtain more accurate and reliable results, the examined fingers were fixed in a position to guarantee all images were collected from the same regions of the finger-pads. In order to avoid the impact of water evaporating to experiment, all participants were guided to complete the friction measurements immediately following the measurements of the SC thickness. The time delay for friction measurements were controlled within 30 s after hydration. The friction experiments were done on participants' middle fingers sliding on a 5 mm wide acetal strip (approximate roughness *Ra* of 0.5 μm) with a normal load of 1.5 $\pm$0.2 N. The moisture level of skin with respect to different periods of hydration was also recorded using the "*Moist Sense*" device. To achieve reliable measurement, each test was repeated at least three times on the tested region.

< **Figure 2** The set-up of optical coherence tomography for measuring stratum corneum thickness (Liu et al., 2013).>

2.3 Measurements of Contact Area

In addition to the measurement of the SC thickness, the OCT system also provides an alternative approach for quantifying the change in the real area of contact between the examined fingers and a contacting surface in relation to water hydration. With the current setup of the OCT system it is impossible to monitor the whole contact area. Therefore, a small area of contact region (3.2 mm^2) on the finger-pad was selected to be an example that represents the general situation about the contact area. This series of tests were done by the same middle fingers of participants where the finger-pads were introduced to contact a glass window of the multi-axis force plate with a constant load (shown in Figure 4). Regard the set-up of the system and image analysis, a full description can be found in previous work (Liu et al., 2015, 2018). The measurements of the contact area were taken by pressing dried and soaked fingers (400 s soaking time) against the glass window of the multi-axis force plate with an angle between 25 ° and 40 °. The applied normal load acting on the glass window was about 1 ± 0.1 N. In addition, the examined fingers were held stationary with intention of examining the same region of the finger-pad to ensure repeatability (at least three times).

<**Figure 3** The multi-component force platform system (Liu et al., 2015).>

<**Figure 4** The set-up of optical coherence tomography for measuring contact areas (Liu et al., 2018).>

3. Results

3.1 Rugby Ball Passing Test under Different Moisture Conditions

The results from the ball passing test are shown in Table 2. The moisture readings of the examined fingers were found to increase significantly from the "natural" state to the "hydrated" state when the participants were taking part in a warm-up activity for various length of time. The Freidman test showed that the warm-up activity has a significant impact on the moisture level of the skin ($p < 0.001$). The hydration level of the fingers rose to around 99 au after the participants doing the warm-up for 20 min. It was also observed that the hydration of the fingers reached the maximum moisture reading in the case of adding additional water to rugby balls, where the fingers seemed to become saturated and were supposed not to absorb any more water. In addition, it shows that the target score was improved with moisture changing from the natural state to the medium hydrated state, then decreased as the moisture reading increased to around 99 au. There was a further decrease of the target score in most participants when the saturated fingers with a small amount of additional water applied on the balls. Based on the analysis, it can be concluded that the target score (y) is associated with the skin moisture level (x) with a parabolic relationship, which could be described by a quadratic polynomial model: $y = ax^2 + bx + c$ ($R > 0.9$, $p <$ < 0.03) (see Figure 5).

< **Table 2** Summary of results of the target passing test. >

< **Figure 5** Effect of moisture on the ball passing test >

< **Figure 6** Optical coherence tomography images collected from the middle finger of a participant after being soaked in water for: (a) dry skin, (b) 20 s, (c) 80 s and (d) 400 s. >

3.2 Measurements of the SC Thickness and the coefficient of Skin Friction

Figure 6 shows four OCT images of finger-pad skin that were collected from a participant corresponding to various periods of hydration time (i.e. dry, 20 s, 80 s and 400 s). In the images, the SC layer is determined by red vertical arrows that enable the change of the SC thickness to be observed. These changes in the SC thickness of the finger with respect to hydration time were quantified and plotted in Figure 7(a). It can be observed that the SC thickness is increased by 20% with soaking (up to 400 s). In the natural state, the SC thickness was found to be 0.2 mm and raised to 0.24 mm after being soaked for 400 s. It is expected the skin becomes saturated between 80 and 120 s of hydration as no noticeable change was observed in the SC thickness. Furthermore, there is no significant change was observed on the surface ridges, which means that the surface texture on the skin seems unlikely to be affected by the absorption of water (see Figure 6).

Figure 7(b) displays the plot of the moisture reading as a function of hydration time, in which two non-linear relationships are observed. In the “natural” skin conditions, the moisture level of skin is 53 $\pm$0.6 au and it is increased by 55% after 80 s of hydration. Overall, the result shows there is a significant increase in the moisture reading at the beginning, and then the moisture reading levels off at about 82 au with hydration time. This could be due to the fact that the keratinocytes in the upper layer of skin (SC) reach a hydration-balance and cannot take in more water, thereby the moisture reading remains constant between 80 s and 120 s. After that, the skin may become over-hydrated and begin to reduce the capacity of water-binding, which will cause the moisture level to slightly drop and reach a plateau. There is a variation in the coefficient of skin friction for the soaked fingers, as shown in Figure 7(c). It is noticed that the figure is very similar to that of the skin moisture (Figure 7(b)), i.e. the coefficient of friction shows an initial rapid decline, which corresponds to these starting points in Figure 7(b). After then, the coefficient of friction starts to increase and then decrease and reaches a plateau related to the moisture level of skin. Moreover, it was noted that there is approximate 25% increase when the tested fingers were saturated, which indicates that the frictional properties of the finger-pad skin appear to be more easily influenced by water.

< **Figure** 7 Relationships between (a) the stratum corneum thickness and the hydration time, (b) the moisture reading and the hydration time, and (c) the coefficient of skin friction and the hydration time.>

3.3 Measurements of Contact Area

Figure 8 shows four OCT skin images relating to the finger-pad in contact with a glass window (1 N load applied) with respect to different periods of hydration time. In each image, the top superimposed line (red line) denotes the ridge boundary at skin surface, and the bottom one (blue line) within the living epidermis is the papillary layer. When increasing the hydration time, more and more skin tissue will be expected to be involved in contact against the glass window, which will result in an increase in the contact area. This assumption is proved true by the results of experiments in this study. As shown in Figure 9, the ratio of the real contact area to the nominal contact area is around 0.40 for the natural fingers. In the case of soaking the finger in water, the corresponding ratio was found to increase to 0.52 for 20 s hydration, 0.57 for 80 s and 0.64 for 400 s hydration, respectively. The ratio of the real to the apparent contact area between the finger and the glass surface is increased by about 60% with hydration time, particularly in the first 80 s.

< **Figure 8** Optical coherence tomography skin images for a dried and hydrated finger in contact against a glass window (1 N load applied) with respect to various hydration time: (a) dry skin, (b) 20 s, (c) 80 s and (d) 400 s.>

< Figure 9 The ratio of real contact area against nominal contact area vs. hydration time. >

4. Discussion

4.1 Rugby Ball Passing Test under Different Moisture Conditions

Table 2 shows that the moisture level of fingers is altered with various activities. There is a rapid increase in the skin moisture reading when the participants are exercising for a short of period. For an instance, the moisture level is found to rise from 69 au to 96 au, 56 au to 99 au for participant 1 and participant 2 after taking part in 20 min of exercise. This change was also observed by Tomlinson et al. (2011), and they indicated that the finger hydration would rise when volunteers were participating in various activates. The results of their moisture survey showed the moisture reading ranged from 50 au (in resting) to 90 au (in exercise), which is consistent with the findings of this study. This is due to the participants' bodies experience sweating in exercise, which results in a change in the skin moisture.

Regarding the ball passing test, the results show a bell curve of the target score where an initial increase is found, followed by a gradual drop when the moisture reading increases beyond a threshold, as displayed in Figure 5. This bell-curve behaviour in ball passing test agrees with the work of Tomlinson et al. (2009), who carried out passing accuracy tests on various rugby ball textures in both dry and wet conditions. They also found that the coefficient of friction and the target score follow a linear relationship. The balls with higher coefficient of frictions presented better scores in passing test. The coefficient of frictions of the dry balls was found greater than that of the wet balls. Based on these findings, it could be concluded that a hand/ball with a very high moisture level will give a low friction coefficient and therefore a bad target score. It is very similar to what is observed in this study and showed that the target score is closely associated with the moisture level. However, they did not study the passing accuracy test related to damp conditions, which has been further investigated in our research. In some other studies, Lewis et al. (2013, 2014) stated that an appropriate increase of moisture in finger-pads could change the mechanical or physico-chemical properties of skin (i.e. Young's Modulus), and consequently, causes an increase in the skin friction and the passing accuracy. This conclusion could be used to explain why the target score is improved with 10-minute warm-up exercise in our study. In the case of high hydration, the decrease in the target score could be attributed to the excessive sweeting/water on ball surfaces. As can be seen in Table 2, the moisture reading measured in the finger-pads reaches its saturated status for most participants after 20 min exercise. In this case, it is unlikely for the skin surface to remain dry due to there is still some sweat remaining unevaporated. The additional water/sweat may act as a lubrication between the hand and the balls' surface and possibly leads to a lower friction force, hence a lower target score. This assumption is also evidenced by the observation of a further decrease of the pass score when additional water was added on the surface of the balls.

4.2 The Effect of Skin Hydration on the Skin Friction

The results of the friction measurements showe that a curved response would be better for describing the relationship between the coefficient of skin friction and the hydration time (see Figure 7(c)) and this agrees with the work of Tomlinson et al. (2011). In their studies, the coefficient of friction was found to vary with moisture conditions. It showed an initial increase in the friction coefficient with a small amount of water and then a decrease when water was continuously added to the hands. The curved relationship observed between the coefficient of friction and the hydration time in this study is also found to be in accordance with the "bell-shape" distribution reported by Adams et al. (2007) who investigated the skin frictional behaviour for a polypropylene probe sliding against human forearms. They pointed out that coefficient of friction increases from 0.2 μ to 4.2 μ when demineralised water is added to the forearm, and then returns to the value for dried skin as water is removed from the skin. This phenomenon could be attributed the fact that as adding water directly to the examined skin surface during sliding movement, it is expected that the skin would become softer due to a part of the water being absorbed by human skin, and thereby contributing to an overall rise in the contact area and the coefficient of skin friction. With respect to the water that has not permeated into the skin, it forms "liquid bridges" between the finger ridges and the contacting surface, which may act as a contributor to the increase of the friction coefficient due to the viscous shear stress being increased. The contact area, in this case, might increase and cause the increase of the capillary adhesion as well. However, no details are given on how the contact region varies with the moisture level in their studies. This has been addressed in this study.

Consequently, several different physical mechanisms have been assumed to contribute to the changes in the coefficient of friction, and the high similarity of results obtained from these different experiments reveals the hypothesis that water absorption has a large impact on the skin friction is true (Adams et al., 2007; Lewis et al., 2013, 2014; Tomlinson et al., 2009, 2011). In our study, the skin friction measurements were designed based on the assumption that water absorption is the only possible cause for the increase in the skin friction due to the fact that water on the examined skin surface was removed by a paper towel prior to tests.

Owing to the plasticizing effect of water, the human skin surface is expected to become smoother under water treatment, thereby generating a larger contact area and skin friction. As displayed in Figure 6, there is no significant change observed in the skin surface texture as expected, but the thickness of the SC presents an increase with the hydration level. A possible explanation of this phenomenon could be that these surface ridges, as they are known, form corresponding to the pattern of the papillary layer (Wood & Bladon, 1985). However, due to the fact that the time scale of water hydration was not sufficient, it is believed that there was no (or less) water transmitted into the layers of living epidermis and/or dermis that could result in a change in the appearance of the skin surface.

4.3 Measurements of Contact Area

In previous studies, many researchers indicated that the increase of skin friction is ascribed to the growth of the contact area between skin and contacting surfaces due to skin's Young's modulus reducing with water hydration (Adams et al., 2007; Andre ´et al., 2008; Gegardr et al., 2008; Hendriks& Franklin, 2010; Johnson et al., 1993; Tomlinson et al., 2011; Pasumarty et al., 2011). In this study, it is noted that both the real area of contact and the SC thickness experience a same trend, which reveals that the increase of the contact area could be ascribed to the decrease in the skin stiffness due to skin swell. Since the experiments are designed based on the mechanism of water absorption and the skin friction is believed to be dominated by adhesion force, it would be assumed that the coefficient of skin friction is strongly dependent on the contact area. Unexpectedly, the correlation between the friction coefficient and the hydration time in Figure 7(c) presents a different tendency compared to that of the contact area, as shown in Figure 9, which reveals that there are other mechanisms enhancing the skin friction in addition to the water absorption. Masen (2011) has conducted a similar study and indicated that the increase in the coefficient of skin friction due to water hydration may be associated with the increase of adhesion and deformation. When hydrating skin by water, water softens skin and brings more skin into contact with sample surfaces, resulting in an increase in the real area of contact, hence an increase in the adhesion force. In the meantime, skin might also experiences a corresponding increase in the deformation in the interface between the examined skin and the contacting surfaces attributing to the increase of real area of contact associated with the adhesion.

5. Conclusion

In the present paper, the influence of hydration of skin on rugby players' performance has been investigated using a ball passing test. It was found that the relationship between the skin moisture and the passing accuracy can be described using a quadratic polynomial function. It was observed that players achieved better scores in passing when increasing the moisture level of skin to a certain level. After the skin on the examined finger-pads was saturated, it took longer for players to complete the pass, therefore, resulting in lower target scores. A full analysis suggested that the potential cause of this phenomenon could be the corresponding change in skin friction due to hydration. This paper then presents the work on exploring the effect of skin hydration on the coefficient of skin friction based on the mechanism of water absorption. The findings from the friction measurements show that the coefficient of skin friction varies with hydration time (up to 400 s) following a “bell-shape” curve. This may be attributed to the changes of the contact areas between the skin and the surfaces due to water treatment. An appropriate amount of water adding to the skin will change the skin properties hence increase the contact areas and the coefficient of friction. When an excessive amount of water is added to the skin, the coefficient of friction will decrease due to the decrease of the contact areas. In the measurement of contact areas, it indicates that the increase in the ratio of the real to the apparent contact area is likely due to the swelling of skin. The above findings provide important information to understand the frictional behaviour of skin between human hands and the sport equipment in response to various levels of skin hydration.

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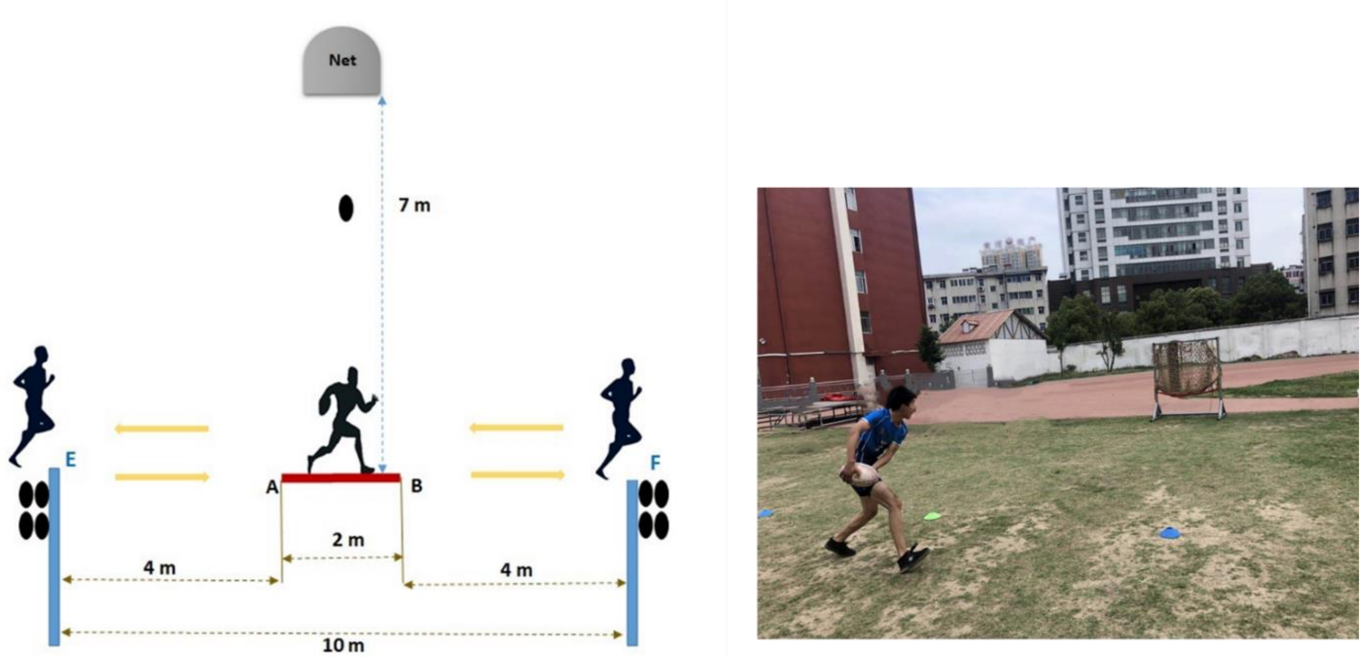
Table 1 The marking scheme used for rugby target passing test (China national sports college entrance examination and marking standard, 2018).

Score	Time Taken (s)
10	< 13.08
9	13.09 - 13.15
8	13.16 – 13.22
7	13.23 – 13.29
6	13.30 – 13.36
5	13.37 – 13.43
4	13.44 – 13.50
3	13.51 -13.57
2	13.58 - 13.64
1	13.65 - 13.71
0	>13.71

Table 2 Summary of results of the target passing test.

Participant		Moisture conditions			
		Natural	Hydrated 1	Hydrated 2	Extra Water
1	MMR ± SD (au)	71.3 ±1.8	73.0 ±1.8	96.0 ±2.8	99.0 ±0.0
	Target Score	6	9	6	5
2	MMR ± SD (au)	56.3 ±1.3	72.3 ±1.0	99.0 ±0.0	99.0 ±0.0
	Target Score	5	7	5	4
3	MMR ± SD (au)	51.3 ±2.8	69.7 ±1.8	86.7 ±6.9	99.0 ±0.0
	Target Score	7	8	8	5
4	MMR ± SD (au)	56.0 ±4.4	77.0 ±3.6	99.0 ±0.0	99.0 ±0.0
	Target Score	7	9	7	7
5	MMR ± SD (au)	67.0 ±1.6	75.0 ±2.8	99.0 ±0.0	99.0 ±0.0
	Target Score	6	8	6	6
6	MMR ± SD (au)	68.0 ±1.7	72.0 ±0.0	99.0 ±0.0	99.0 ±0.0
	Target Score	7	8	5	4
7	MMR ± SD (au))	62.7 ±4.3	71.3 ±0.8	93.3 ±3.9	99.0 ±0.0
	Target Score	5	7	8	5
8	MMR ± SD (au)	66.7 ±0.8	78.0 ±0.4	99.0 ±0.0	99.0 ±0.0
	Target Score	7	9	6	6

Note: MMR represents a mean moisture reading, Hydrated 1 represents a medium hydration state and Hydrated 2 represents a high hydration state.



(a) Sketch of a ball test

(b) Image of passing a ball to the net

Figure 1 The illustrations showing how players conduct the ball passing test.

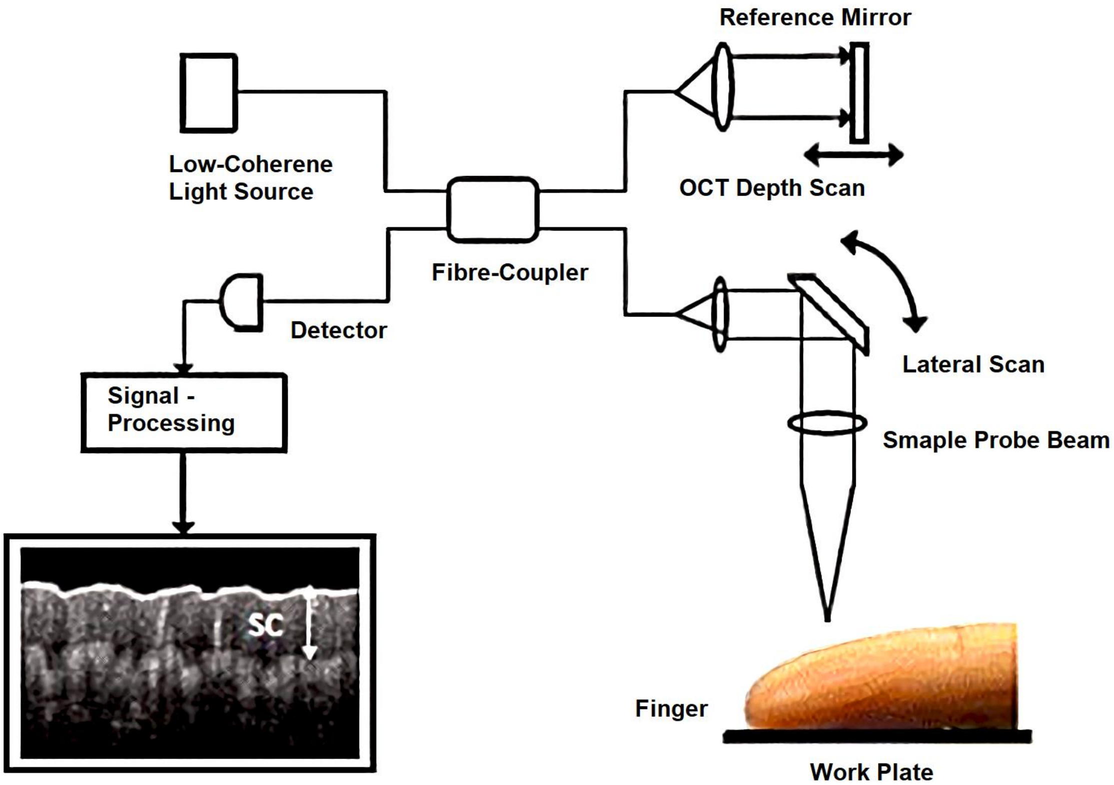


Figure 2 The set-up of optical coherence tomography for measuring stratum corneum thickness (Liu et al., 2013).

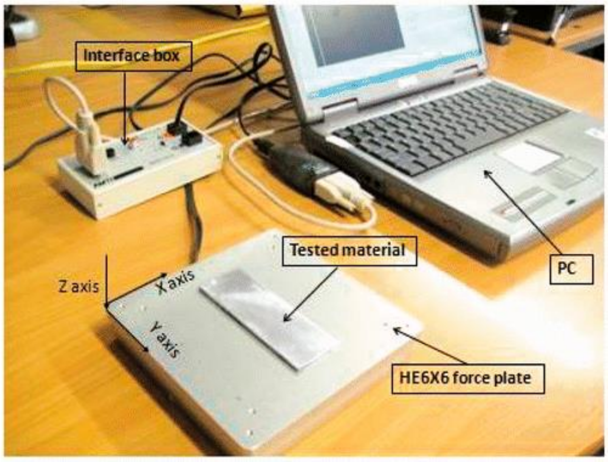


Figure 3 The multi-component force platform system (Liu et al., 2015).

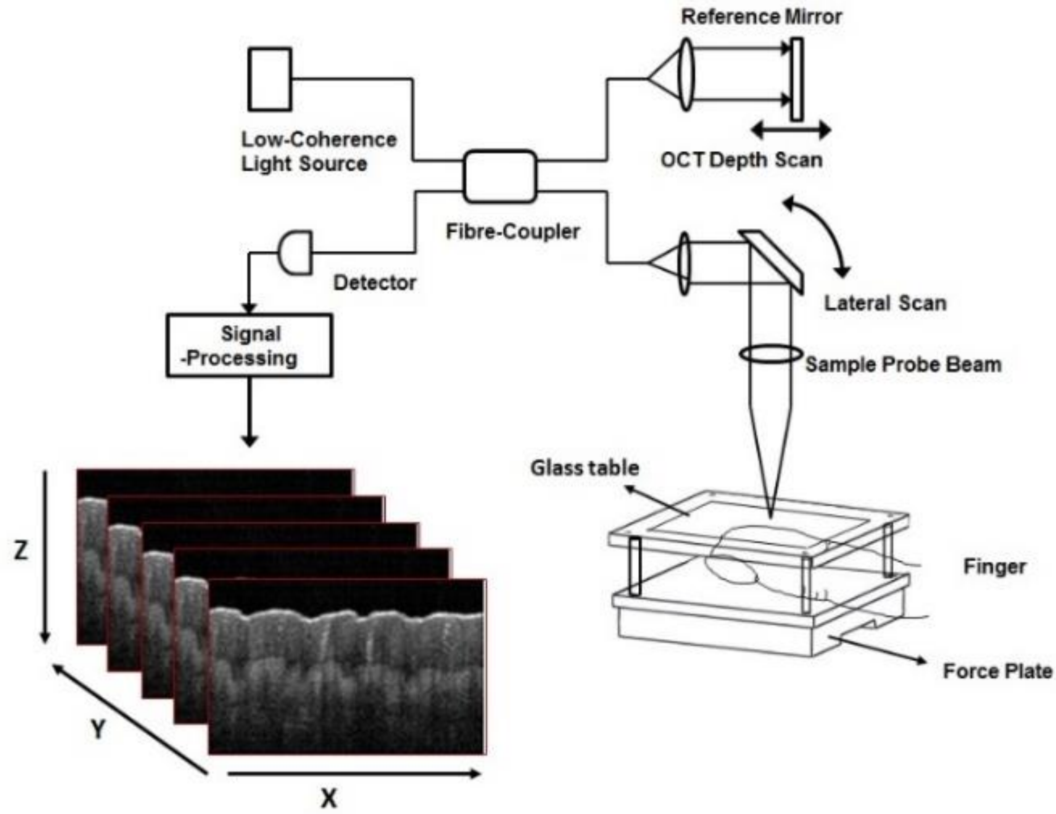


Figure 4 The set-up of optical coherence tomography for measuring contact areas (Liu et al., 2018).

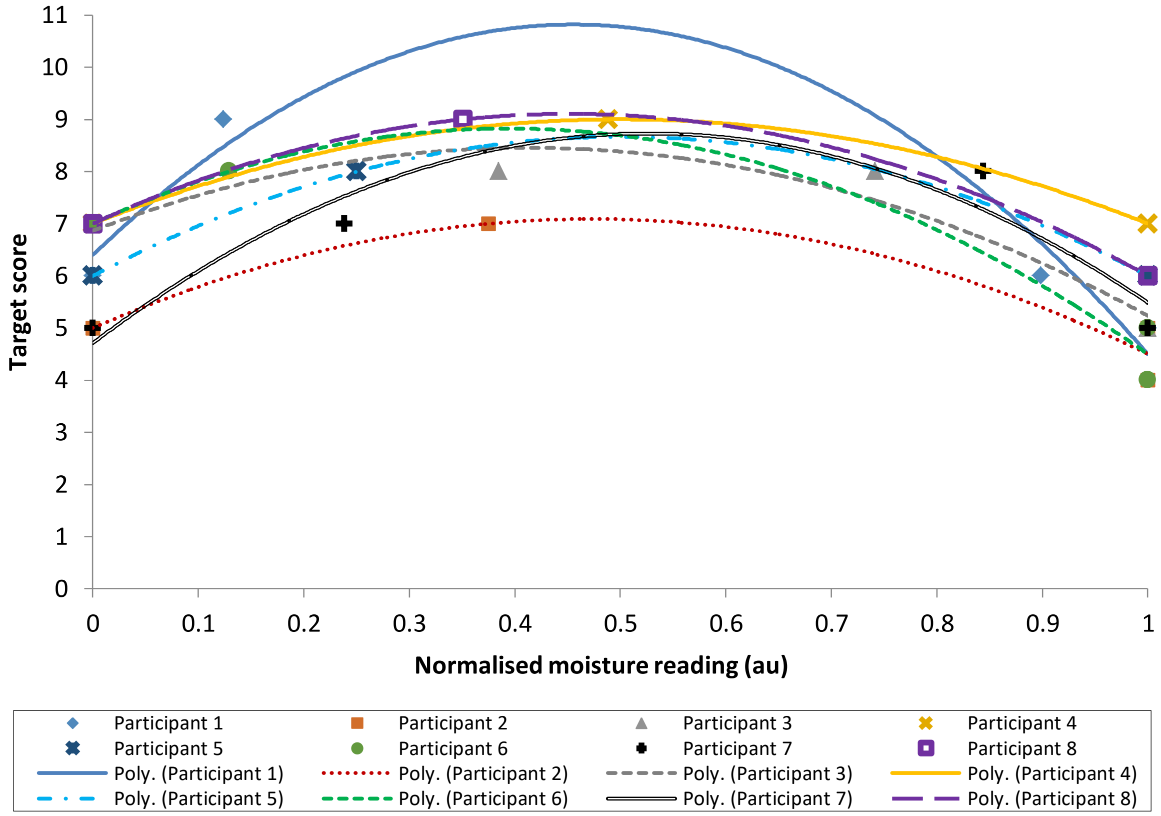


Figure 5 Effect of moisture on the ball passing test.

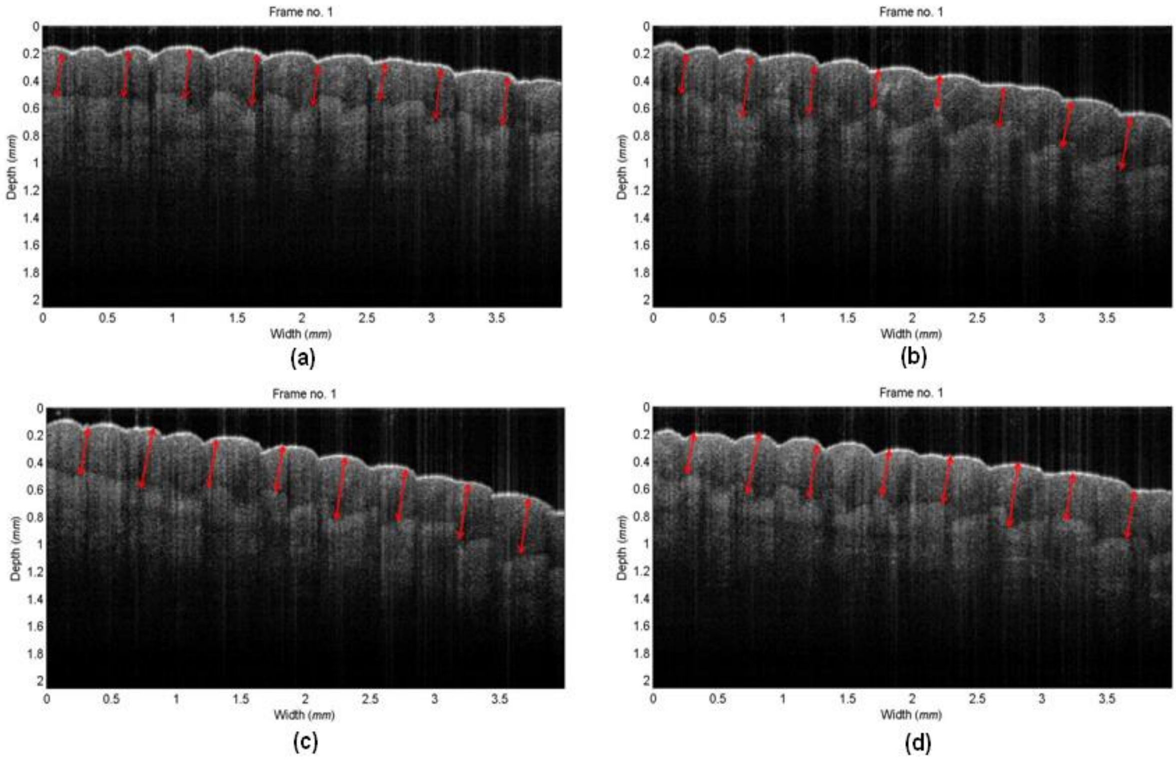


Figure 6 Optical coherence tomography images collected from the middle finger of a participant after being soaked in water for: (a) dry skin, (b) 20 s, (c) 80 s and (d) 400 s.

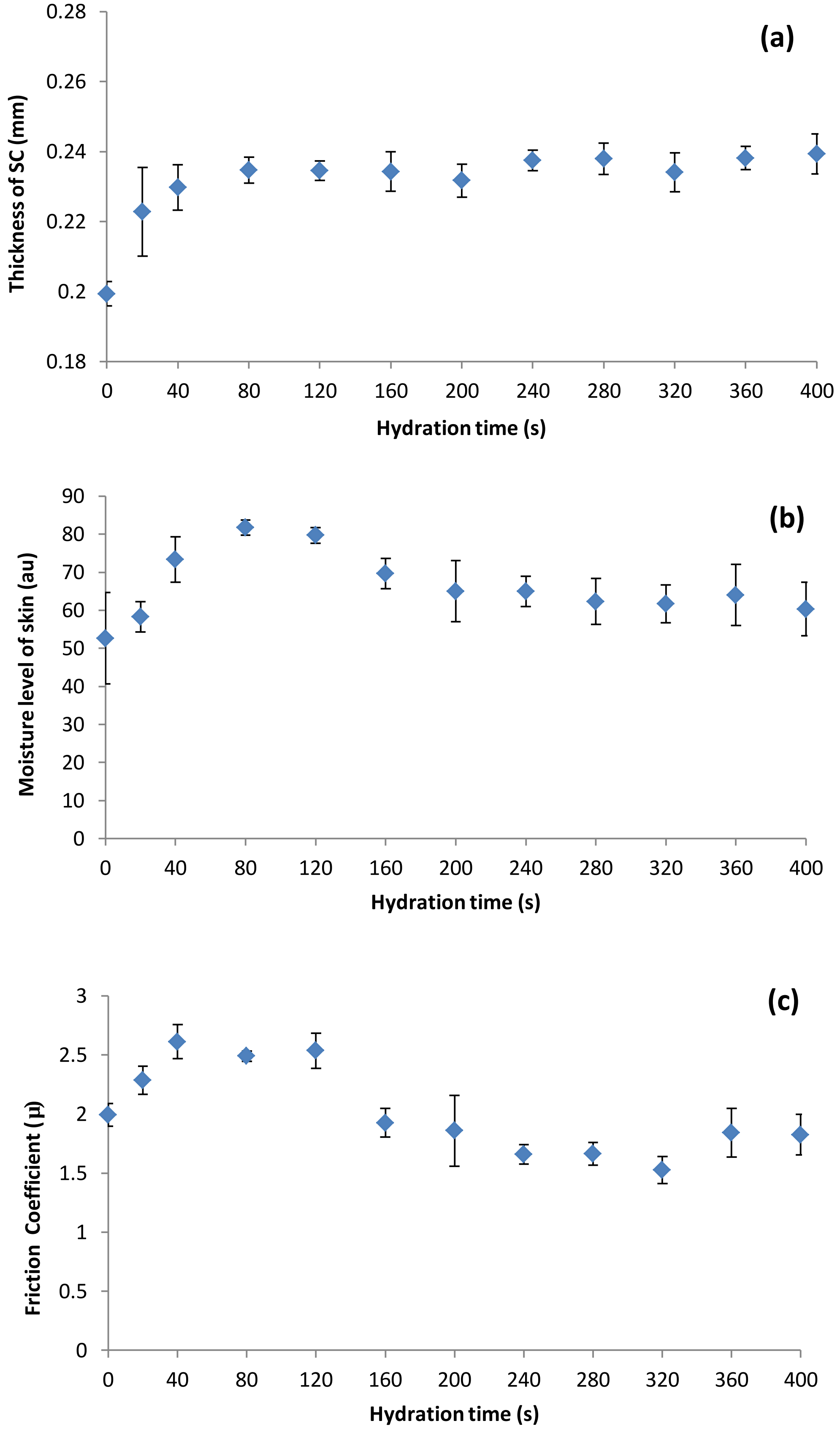


Figure 7 Relationships between (a) the stratum corneum thickness and the hydration time, (b) the moisture reading and the hydration time and (c) the coefficient of skin friction and the hydration time.

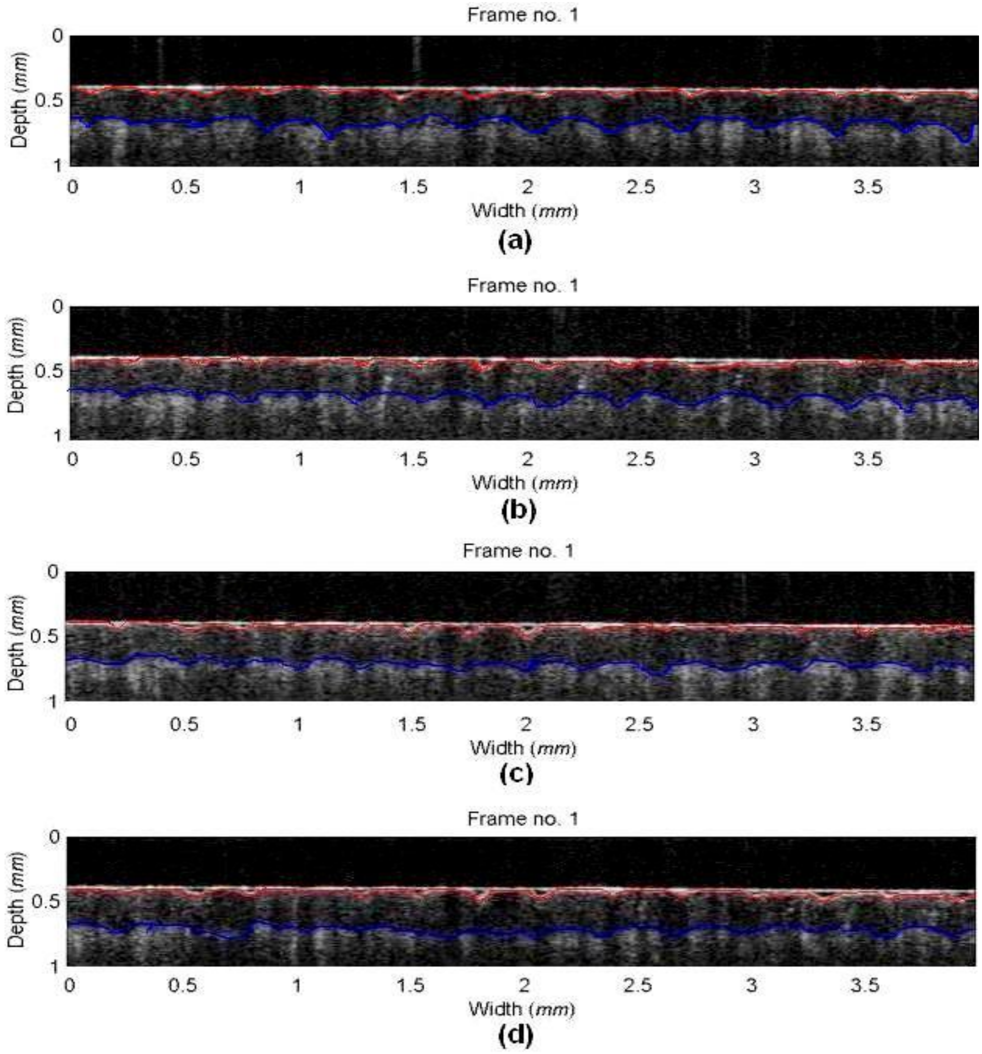


Figure 8 Optical coherence tomography skin images for a dried and hydrated finger in contact against a glass window (1 N load applied) with respect to various hydration time: (a) dry skin, (b) 20 s, (c) 80 s and (d) 400 s.

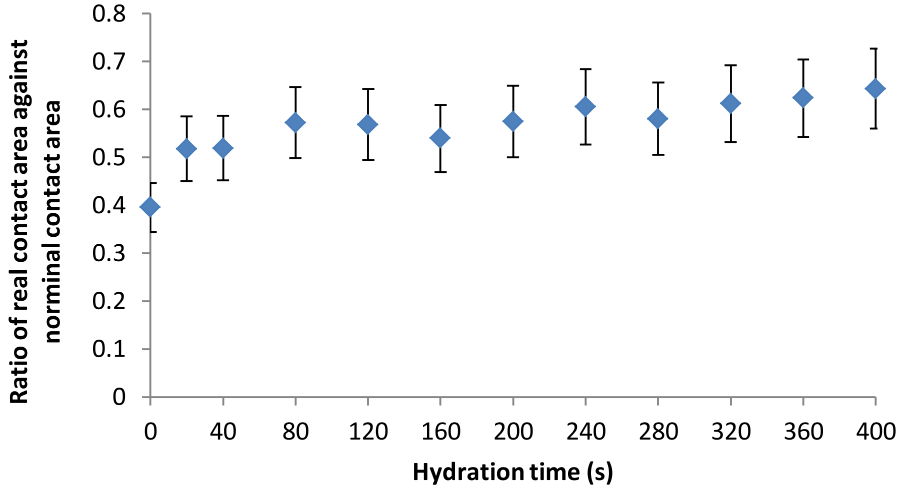


Figure 9 The ratio of real contact area against nominal contact area vs. hydration time.

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