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Instrumental Evaluation of Stickiness of Textiles Under Wet Skin Surface

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ABSTRACT People sweat due to metabolism, exercise, or being in hot environment. The presence of moisture within textile-skin interface will increase the adhesion of water to textile causing sensorial discomfort. Pressure and friction in combination with moisture can lead to skin irritations, abrasions, or even skin contact injuries. This paper describes the design and construction of textile stickiness measurement system which can measure the stickiness of textiles under wet skin surface. Synthetic leather was used to simulate the skin layer while predetermined amount of water was sprayed evenly on it. One edge of the testing sample was mounted on the sample holder while the remaining portion was laid flat. Testing sample connecting to the force gauge was moved across the wet simulated skin surface at a constant speed and the drag force against the dragging distance was measured. The uniqueness of this instrument is that the degree of skin wetness is adjustable and water supplied to the sample increases gradually with dragging distance, simulating from mild to profuse sweating condition. Besides, the way to mount the sample is novel (mounting only one edge of the sample and without external pressure applied) and this is closer to the actual wearing condition. Also, various fabrics can be tested with high accuracy and repeatability. Attempts have been made to correlate the measured stickiness property with the perceived feeling of stickiness and a relatively high correlation was found. This instrument is useful for product selection, especially, for sportswear, hygiene products, or medical textiles.

INDEX TERMS Comfort, drag force, friction, stickiness, textiles.

I. INTRODUCTION

Human skin is practically in extended contact with textiles and the tactile sensation of textiles is closely related to its surface properties [1]. When textile is wet, the attractive force at the interfaces of textile-water and water-skin rises, and the textile may cling to any surface it touches. Stickiness, in term of friction and surface tension of liquid, at the skin-textile interface is often associated with clingy or clammy sensation. This is considered by many researchers to be a major source of textile-evoked discomfort. Besides, friction on skin is a critical factor for skin injuries like irritations, abrasions and blisters. These are caused by cyclic mechanical loads if contact pressures and shear forces are high or if these last for long period of time. Elevated skin moisture level macerates the skin, which can result in greater susceptibility to skin injury or higher risk of infection [2]. Also, textile-skin friction may cause severe skin disease, decubitus or affect wound healing. This is a problematic issue for sensitive, aged, and injured skin. Derler and Gerhardt [3] found that in the case of moist or wet skin, friction coefficient is significantly higher than on dry skin surface. The friction properties of textiles are also relevant in the medical application. People who have urinary incontinence used absorbent hygiene products regularly and prolonged contact with textiles of high friction can lead to abrasion [4] or even dermatitis [5].

Stickiness of textiles determines its adhesion to other surface, which occur quite frequently during practical use of fabrics and clothing. The optimum performance depends on its specific application. For sportswear or hygiene products, textiles with low stickiness against skin seems to be appropriate. So far, product development has mainly focused on other comfort-related properties, like water absorbency, water vapor permeability, and air permeability, whereas stickiness of textiles against moist or wet skin surface were seldom investigated.

In order to investigate the stickiness of textiles, researchers have conducted human subjective tests [6], [7] or in vivo study [1], [4], [8], [9]. However, many uncontrollable errors do exist in subjective tests, for example, differences in skin hydration level and variations in lipid content of skin surface [1]. Additionally, a large sample size should be tested in order to reduce error by some extremities and this would be a time-consuming and costly task. This hinders the use of subjective test to evaluate fabric stickiness and instrumental measurements are an effective alternative, providing objective and more repeatable results.

In the last century, numerous instruments have been developed to study friction or stickiness of textiles (as exemplified in Appendix A). Testing instruments differ primarily in the type of relative motion (linear [10]–[15] or rotational [16] movements), the way to measure drag force, and the material of the sliding partners [17]. However, majority of the conventional testing methods have limited implications about clothing comfort. Arbitrary materials such as steel [16], [18] and piano wire [19] were used as the counterpart in contact with textiles. The surface and frictional properties of these materials may differ from human skin remarkably. Some studies investigated friction in fabric-to-fabric contact [12], [16]. However, this might have limited implication about clothing comfort as well. Second, inadequate information (i.e. frictional property under dry condition only) was obtained by the conventional methods. In tribological studies, the relationship between skin moisture level and frictional property has been investigated recently. Linear [20], power-law [21], exponential [22], and bell-shaped [23], [24] relationships were reported. However, there is no definite conclusion about the type of relationship observed; hence, a dry friction value cannot be used to predict its frictional behavior during wet state. On the other hand, in terms of stickiness/frictional properties of textiles, only dry state of the fabrics was investigated in most of the studies [16], [19], [25], [26] whereas the stickiness/frictional properties of textiles under different wetness levels have not been studied systematically. Van Amber *et al.* [11] have investigated the frictional properties of textiles in damp condition against the simulated skin (Lorica®Soft). They used a Wascator with different wetting cycles and wetting duration to prepare for damp fabrics with varying wetness. Ke *et al.* [27] have also investigated the frictional property of textiles under wet condition. The sample was first immersed in water for one minute and excess water was then removed with tissue paper before measurement. However, no effort was made to standardize the exact volume of water held in the specimens. Gerhardt *et al.* [20] did a vivo study on friction measurement between hydrated human skin and wetted hospital fabrics. Same to Van Amber *et al.*'s [11] work, the amount of moisture applied is not standardized, thus the repeatability of the result is questionable. Third, special equipment is required for the conventional machineries and so their cost are rather high.

With regard to the above research background, the aim of this study is to fill this research gap to develop a novel testing method that is easy to use, precise and available at an acceptable cost. This instrument would facilitate the product development process for sportswear, intimate apparel, health care product, incontinence product, and possibly medical textiles. In this article, the design and principle of TSMS is firstly mentioned, followed by introducing sample details and examining the uses of TSMS. In addition, an informative mapping technique which describes four meaningful stickiness properties is introduced. This could help to select the most comfortable fabric efficiently. Apart from that, investigation on accuracy and repeatability of TSMS is provided. The validity of the instrument is also studied by examining the correlation between TSMS measurement results and the subjective stickiness rating. Besides, regression analysis is performed to find out the factors that contribute to stickiness sensation.

II. METHOD

A. PRINCIPLE OF TSMS

The simulated skin was first wetted to predetermined wetness level by spraying water throughout the whole dragging path. Sample attached to the sample holder was connected to the force gauge and was dragged against the stationary simulated skin plane (Lorica®Soft) at a constant speed. During dragging, the amount of water supplied to the test sample increased gradually at a constant rate. At the beginning of the experiment, it simulates mild sweating condition. As long as dragging continues, much more water was supplied to the test sample and this corresponds to the profuse sweating condition. The resulting drag force against dragging time (or dragging distance) was measured. Unlike previous studies [11], [27], water supplied to sample is controlled and is not fabric dependent. Instead, variable amount of water can be sprayed onto the simulated skin and this corresponds to product end-uses.

TSMS result is affected by the adhesion between simulated skin and sample. This is in fact varied by the difference in textile parameters such as fiber materials, yarn design, morphology, surface structure, fabric construction, and finishing.

B. HARDWARE CONFIRGURATION AND MECHANISM

TSMS can measure the stickiness of fabrics automatically. Its setup can be broadly divided into four parts: (i) accessory for water supply, (ii) measurement part, (iii) sample stage, and (iv) computer system. The schematic drawing of TSMS is depicted in Fig. 1.

Regarding the accessory for water supply (see Fig. 2), it includes a balance, a water masking box, and a sprayer. Before the test, the simulated skin (1), Lorica®Soft, was placed onto the balance and covered with the water masking box. This box helps to ensure that predetermined amount of water was sprayed evenly within the testing area.

For the measurement part, a force gauge (Chatillon DFS II) (10) with capacity of 2 lbf and accuracy of ± 0.1% of full scale was utilized. It was mounted on a translation stage (11) and its movement was driven by the motor (13).

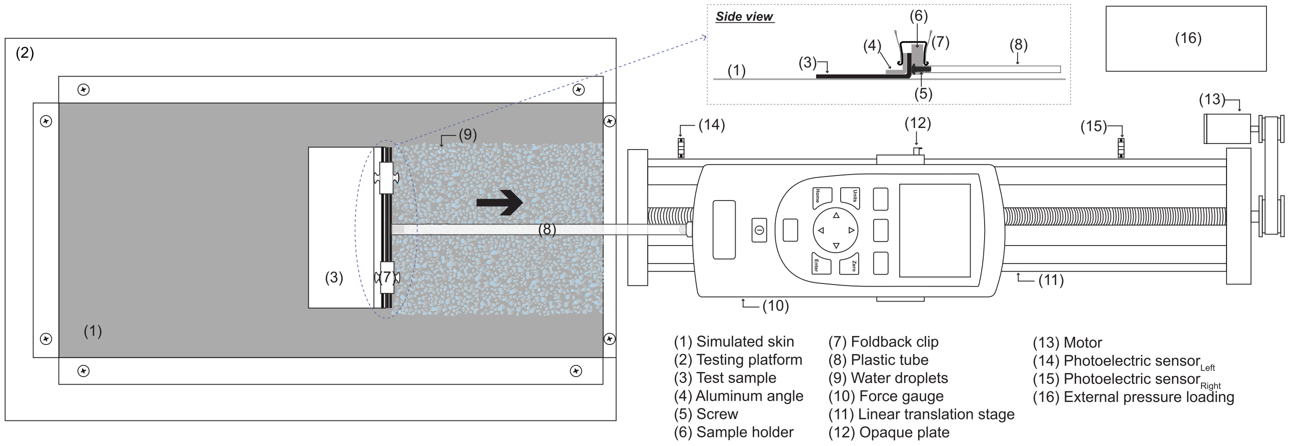


FIGURE 1. **Schematic drawing showing the main components of the textile stickiness measurement system (TSMS).**

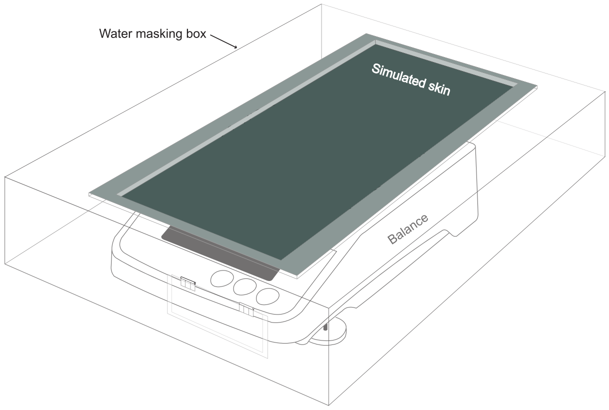


FIGURE 2. **Schematic drawing showing setup for spraying water to the simulated skin.**

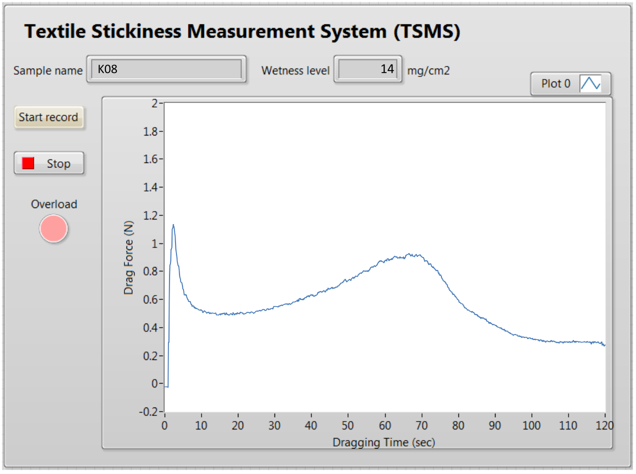
The drag speed was set at 2 mm/s whereas the drag displacement was set at 24 cm. To control the dragging distance and to terminate the dragging motion, two photoelectric sensors (EE-SX 671, ORMON) were used. The sensor was activated when the opaque plate (12) mounted onto the moving stage passed through its slot. Photoelectric sensor$_{\text{Right}}$ (15) was used to control the end point of dragging whereas photoelectric sensor$_{\text{Left}}$ (14) was used to fix the starting point of each experiment.

A piece of simulated skin (Lorica®Soft) (1) was used as the contacting material. It was glued onto the plastic plate and was held firmly onto the testing platform (2). The test sample (3), mounted on the sample holder (6), was placed onto the simulated skin (1) during test. The way to mount the sample (3) onto the sample holder (6) is illustrated in the side view of Fig. 1. In brief, a small portion of sample was bent perpendicular to the sample plane and a 12 cm long aluminum angle (4) was put on top of the sample (3). The small portion of fabric (1 cm × 12 cm) was mounted in between the sample holder (6) and the aluminum angle (4) under tension by two foldback clips (7). The sample (3) as well as its holder (6) was connected to the force gauge (10) with a 25.5 cm long plastic tube (8). Before the test, an external normal load (2 g/cm^2) (16) was applied to the sample for 5 s which helps to ensure even contact between the sample and the simulated skin.

The force required to drag the sample against the simulated skin (1) was measured. The displacement distance and its corresponding drag force were recorded by the connected computer system.

C. CONTROL PROGRAMMING

LabVIEW programming was used to develop an interface for recording the drag force against dragging time. Fig. 3 shows the control interface for TSMS. When the dragging force excess 80% of the capacity of the force gauge, the overload indicator will be lighten which helps to protect the force gauge.


Textile Stickiness Measurement System (TSMS)

Sample name K08

Wetness level 14 mg/cm2

FIGURE 3. **TSMS control interface.**

D. EXPERIMENTAL SETTING

1) TYPE AND MORPHOLOGY OF CONTACTING MATERIALS

The simulated skin used in this study is synthetic leather, Lorica®Soft, a combination of polyurethane and polyamide microfibers with surface topography similar to that of human skin. The morphology of Lorica®Soft and skin of a lady's back is shown in Fig. 4. It shows that there are furrows and ridges on both surfaces. Apart from morphology, the hydrophilicity of Lorica®Soft is of similar range as human skin. The contact angle of Lorica®Soft is 89.6° whereas the contact angle of the untreated forearm is around 84° to 88° [28], [29].

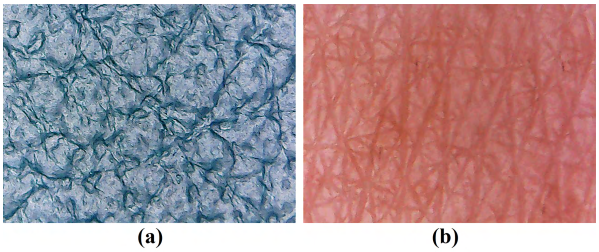

(a) (b)

FIGURE 4. Microscopic images of (a) face side of Loric®Soft; and (b) skin of a 40's lady.

In the area of skin research, in vivo investigation found that the coefficients of friction (COF) for dry skin ranges from 0.12 to 0.65 whereas the COF for wet skin is higher (ranges from 0.7 to 1.4 [30]–[36]) due to softening of the top layer of the skin [37]. The dry COF of the Lorica®Soft used in this study is 0.16 which is close to the COF of human skin.

The surface roughness (Ra) of Lorica®Soft is 14.93 μm [1] whereas the surface roughness (Ra) is 12-15 μm in forehead, 12-13 μm in volar forearm and 11-15 μm in cheek [3]. Therefore, it suggests that the surface roughness of Lorica®Soft is very close to human skin.

2) MAGNITUDE OF NORMAL FORCE AND DESIGN OF SAMPLE HOLDER

The normal force applied onto the sample should depend on product end-use. Its magnitude might affect testing repeatability. In Xu *et al.*'s [38] study, they mentioned that tension should be applied to ensure effective contact for friction measurement. Small tension resulted in friction instability whereas high tension severely stretched and distorted the skin layer. Carr *et al.* [12] found that the COF between fabrics decreased as the pressure applied onto the fabrics increased. It suggests that pressure may affect the frictional property and it should be studied carefully.

Sample holder which fully covers the fabric gives even pressure to the sample. This may simulate the wearing condition of sock or hygiene products where the textile was worn under pressure. However, when the sample was pressed onto moist skin surface, the amount of water absorbed in the sample was affected by its compressibility apart from its water absorbency. Air will be replaced with water and bubbles will be formed within the interfaces. This will vary the contact area possibly and so affecting the repeatability of the testing result.

In this study, in order to study the stickiness of apparel fabrics under wet condition, no external pressure loading was applied onto the sample during dragging. Instead, only one edge of the sample was mounted on the sample holder and water acts as adhesive which brings sufficient connection between fabric and simulated skin. The sample may be elongated by the drag force (from sample holder) and adhesion force (of water). The degree of elongation depends on fabric's properties and fabric-simulated skin interaction. This sample holding technique is closer to actual wearing condition of clothing.

3) DRAGGING VELOCITY OF SAMPLE HOLDER

When dragging velocity is too low, stick-slip phenomenon often occurs which leads to signal fluctuation. In contrast, when the dragging velocity is too high, some of the microscopic surface friction information will be ignored [39] and the tester itself will vibrate which influences the stability of friction signal [38], [40]. In Sabrina's [4] work, she mentioned that the sliding speed is generally agreed to have a negligible effect on coefficient of friction. Studies by Ajayi [25], Wang *et al.* [40], and Virto and Naik [41] also found that the sliding speed has a limited influence on the frictional properties. With the consideration of testing stability and efficiency, the dragging velocity was set at 2 mm/s in this study.

4) EFFECT OF ENVIRONMENTAL CONDITION

Kenins [9] found that increasing environmental humidity from 10 to 90% results in a rise in forearm skin friction of about 20 to 50%. It suggested that the testing environment should be controlled properly. With reference to the conventional testing condition, testing was performed in standard climatic condition (20±1 °C, 65±5% RH).

5) DETERMINATION OF WETNESS OF SIMULATED SKIN

Preliminary study found that drag force has a bell-shape relationship with wetness level of simulated skin, implying that a peak drag force will be observed under specific water level. In order to find out the peak of the bell-shape drag force curve, the amount of water supplied to the sample should be chosen carefully and preliminary study found that this is approximate to the water absorption capacity of fabric. In general, the amount of water sprayed onto the simulated skin can be chosen with reference to Fig. 5. Fig. 5 points out the range of water supply of five recommended wetness conditions. The number shown on the left of each bar is the minimum amount of water supply whereas the right one denotes its maximum value. When a group of fabrics is to be compared, it is recommended to select the wetness level where its water supply range can cover the water absorption capacity of all samples investigated.

In this study, the 22 fabrics investigated can be broadly divided into two groups based on their water absorption capacity and product end-uses. All fabrics were dragged against the simulated skin sprayed with a relatively low water content (6 mg/cm^2). And for Group A's fabrics, their water absorption capacity ranging from 24.56 mg/cm^2 to 70.99 mg/cm^2 is much higher than the water supply amount

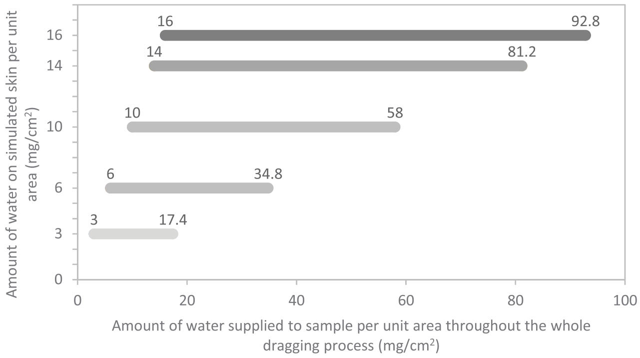
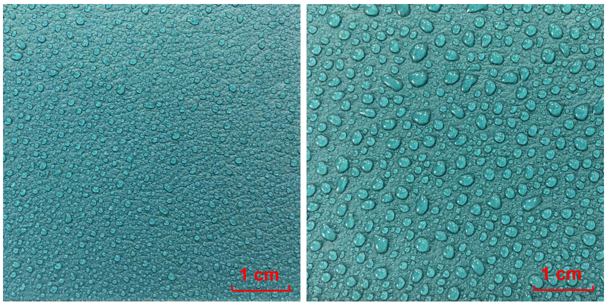


FIGURE 5. **Examples of some recommended wetting conditions (Dragging distance=24 cm).**

given by the 6 mg/cm^2 condition. Hence, according to Fig. 5, the 14 mg/cm^2 wetness condition was additionally performed on group A's fabrics. The images of Lorica®Soft sprayed with 6 mg/cm^2 and 14 mg/cm^2 water are shown in Fig. 6(a) and 6(b), respectively.



(a) (b)

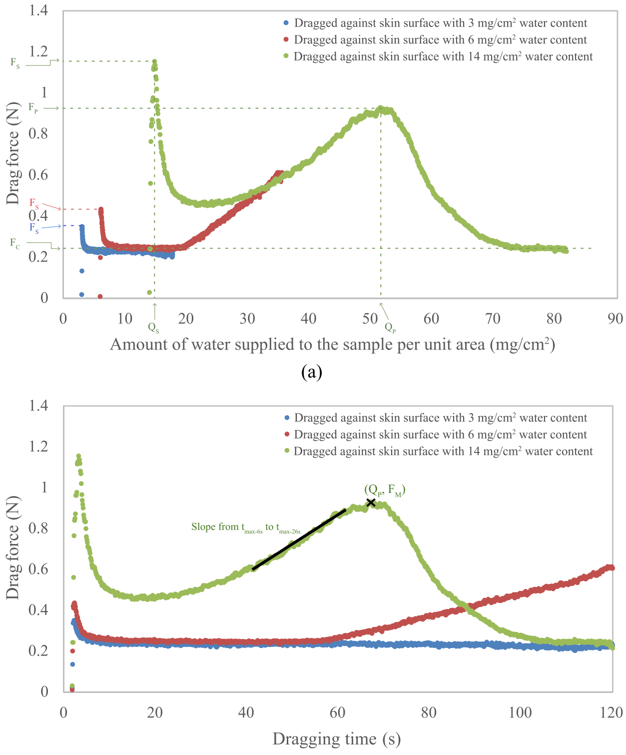
FIGURE 6. **Simulated skin under different wetness levels. (a) 6 mg/cm^2; and (b) 14 mg/cm^2.**

E. MEASUREMENT PARAMETERS

Frictional characteristic often denoted by coefficient of friction (COF), is defined as the ratio of the frictional force parallel to the surface to the normal force pressing on the surface. However, this study aims to investigate the actual wearing condition of apparel fabric. During wear, there is no normal force applied to the fabric usually and so the actual force was assessed instead of COF. Also, water film was formed in-between the fabric-water and water-skin interfaces when the fabric is saturated with water. Since then, the fabric may not have direct contact with the simulated skin and so the force required to drag against the simulated skin is termed as drag force instead of frictional force. In this study, a series of parameters are defined to describe the stickiness of fabrics.

1) STATIC DRAG FORCE (F_S)

Static drag is defined as the force required to initiate the movement. In the plot of drag force versus dragging time (Fig. 7(a)), the first peak corresponds to the static drag. At this point, it is the threshold of motion, the adhesion junctions are broken. In terms of the real situation, F_S represents how much



(a)

(b)

FIGURE 7. **The drag force curves for a typical fabric, K08, under different wetness levels of skin surface. (a) Drag force as a function of amount of water supplied to the sample per unit area; and (b) drag force as a function of dragging time.**

force required to move a fabric from skin laterally. Due to the contribution of surface tension of water, Fs in wet contact is larger than in dry contact.

2) PEAK DRAG FORCE (F_P)

Literatures showed that drag force of sample is not linearly related to wetness level of skin. In fact, it increases with water content of the sample before saturated and then reaching a peak value. Further increasing the water content of the sample will reduce the drag force. From the plot of drag force versus amount of water supplied to the sample, a bell-shape relationship is observed. Peak drag force (F_P) is defined as the peak value of the bell-shape curve (e.g. the peak value of the green curve shown in Fig. 7(a)). The difference between F_P and F_S is that F_P refers to the kinetic force required to keep sample moving on a wet surface (i.e. the 2nd peak) whereas F_S represents the force required to initiate the movement (i.e. the 1st peak).

3) AMOUNT OF WATER SUPPLIED TO SAMPLE AT F_P(Q_P)

It is related to the amount of water supplied to the sample while F_P is achieved. It is expressed as mg/cm^2.

4) WATER CONTENT OF SAMPLE AT F_P (W_P)

Given Q_P is known, the water content of the sample at that particular moment can be calculated according to (1).

This indicates the degree of wetness in terms of geometrical volume of the sample when F_P is achieved. Higher W_P implies that majority of the space within the sample is occupied with water.

$$W_P = \frac{Q_P(g/cm^2)}{\text{Thickness (cm)} \times \text{Porosity}(\varepsilon)} \times 100\% \qquad (1)$$

5) SATURATION LEVEL OF SAMPLE WHEN ACHIEVING $F_P(S_P)$

Given Q_P is known, the saturation level of the sample at that particular moment can be calculated according to (2). This indicates the degree of saturation in terms of water absorption capacity of the sample when F_P is achieved. When Q_P is higher than its water absorption capacity, S_P is higher than 1.

$$S_P = \frac{Q_P}{\text{Water absorption capacity of sample (mg/cm}^2\text{)}} \qquad (2)$$

6) SLOPE OF DRAG FORCE CURVE BEFORE ACHIEVING $F_P(SL_P)$

This parameter denotes the effect of water on drag force. Sample with higher slope has a greater increment on drag force under the same amount of water supplied, implying that it is more sensitive to the change in skin moisture level. Preliminary study found that slope is almost constant from 26 s before achieving F_P to 6 s before achieving F_P and so these 20 second data were used for calculation. Fig. 7(b) shows the portion of the curve that the slope should be calculated from.

7) DRAG FORCE AT SPECIFIC WATER LEVEL (F_X)

The specific water level X is expressed as milligram of water per unit area (mg/cm^2). The drag force at water level X can be simply estimated from the plot of drag force versus the amount of water supplied to the sample per unit area.

8) DRAG FORCE AT COMPLETELY SATURATED CONDITION (F_C)

When the sample is excessively wet, its drag force starts decreasing. The drag force curve tends to be stable when there is a thick water layer within the interfaces. The drag force at that stable level is termed as F_C (see Fig. 7(a)).

F. OPERATIONAL TESTING PROCEDURES

The operational testing procedures are listed below:

- Test the water absorption capacity of the samples. This can be done by immersing the sample into a water tank for 5 minutes and then taking it out with tweezers and hanging it onto a rod vertically. When there is no water dip from the fabric within 30 s, water gain in fabric is measured and it is expressed as mass of water gain per unit area of fabric. This value can be used to determine the wetness level of the simulated skin.
- Check the position of the sample holder and make sure it is located at the starting point of the test
- Mount the fabric properly to the sample holder
- Place the simulated skin onto the balance and covered it with water masking box
- Wet the simulated skin with predetermined amount of water by spraying method
- Slightly pull up the sample and insert the simulated skin onto the testing platform
- Release the sample onto the simulated skin and then slightly adjust its position to ensure the force shown in the force gauge is approximate to zero.
- Apply an external pressure (2 g/cm^2) onto the sample for 5 s to ensure the sample has sufficient contact with the simulated skin
- Press the 'start and record' button in TSMS control interface
- Switch on the motor to enable automatic sample dragging for 24 cm at a speed of 2 mm/s
- Once the sample has travelled for 24 cm, it stopped moving automatically
- Press the 'Stop' button in TSMS control interface
- Unmount the sample from the sample holder and switch on the motor with backward motion to bring the sample holder to the starting position.
- Take away the simulated skin and use soft tissue paper to dry it gently
- The apparatus is now ready for next set of specimen
- Replace the stimulated skin after 30 measurements

G. CALIBRATION

The evenness of water spray on the simulated skin should be calibrated according to the following procedures. This depends on the manipulation of the experimenters. Each of them should be well-trained before actual testing. For the training, experimenter should spray water to the simulated skin as even as they can. After that three pieces of filter paper (3 cm×3 cm) were put on different spots of the simulated skin. If the water gain from the filter papers is within 3% of the predetermined amount and if they can do this repeatedly, the experimenter can be regarded as reliable.

Besides, the movement speed of the force gauge should be recorded periodically. The experimenter should ensure that the dragging time should be 120±1 s.

The calibration of the whole setup can be done by dragging a standard sample (e.g. bleached plain cotton fabric) at a constant speed and the force required to drag the sample against the simulated skin was measured. The coefficient of variance (CV%) is to show the repeatability of the test. For the standard material, if F_P and Q_P is within 3% CV, we could conclude that the setting is well-calibrated.

III. SAMPLE SPECIFICATIONS

Twenty two types of fabrics investigated were conditioned in standard atmosphere (20 ± 1 °C and 65±5% RH) for at least 24 hours prior to testing. They were cut 12 cm in weft direction and 6 cm in warp direction. No specimen was tested more than once. The specifications of these fabrics are

TABLE 1. Details and specifications of various fabrics.

Group	Fabric code	Fabric Type	Fabric structure	Fiber content	Yarn count	Fabric sett		Weight (g/m^2)	Thickness (mm)	Porosity	Water absorption time (s)[a]	Water absorption capacity (mg/cm^2)	Surface friction (MIU)[b]	Surface roughness (SMD)[b]
						epi	ppi							
A	K01	Knitted	Single jersey	40 % cotton, 60 % polyester	32s	[c]	[c]	144.6	0.56	0.8224	15.5	37.17	0.191	1.68
	K02	Knitted	Single jersey	95 % rayon, 5 % spandex	32s	[c]	[c]	259.0	0.86	0.8022	0.7	61.54	0.211	2.26
	K03	Knitted	1x1 rib	Cotton	32s	[c]	[c]	231.2	1.08	0.8615	0.6	70.99	0.191	3.81
	K04	Knitted	Single jersey	Cotton	32s	[c]	[c]	126.8	0.64	0.8713	6.2	41.19	0.190	1.81
	K06	Knitted	Pique	95 % polyester, 5 % spandex	[c]	[c]	[c]	182.1	0.89	0.8507	13.1	24.56	0.246	7.39
	K07	Knitted	Pique	DuPoint Coolmax	[c]	[c]	[c]	140.6	0.67	0.8475	4.6	45.60	0.175	1.15
	K08	Knitted	Pique	Polyester Bamboo Charcoal	[c]	[c]	[c]	152.2	0.56	0.8016	58.2	41.45	0.224	5.72
	PINK	Knitted	Double jersey mesh	Polyester	[c]	34	56	228.1	0.97	0.8312	0.5	55.85	0.262	4.35
	Orange	Knitted	Single jersey mesh	Polyester, Lycra	[c]	41	131	202.6	0.60	0.7545	6.3	36.52	0.282	4.66
	BMesh	Knitted	Double jersey mesh	Polyester	[c]	45	58	173.9	0.80	0.8444	1.7	56.44	0.267	4.19
	Purple	Knitted	Double jersey interlock	Polyester	[c]	26	43	245.0	0.94	0.8117	3.5	57.75	0.264	8.40
	W08	Woven	Plain	Cotton	21s x 21s	60	60	157.0	0.66	0.8464	1.5	30.79	0.196	5.68
B	W01	Woven	Plain	Cotton	80s x 80s	90	88	56.6	0.37	0.9002	31.8	14.62	0.177	3.44
	W02	Woven	Plain	Cotton	60s x 60s	90	88	78.6	0.40	0.8736	9.2	17.13	0.162	2.98
	W03	Woven	Plain	Cotton	40s x 40s	133	100	156.9	0.42	0.7598	13.0	18.26	0.181	2.89
	W05	Woven	Plain	Cotton	40s x 40s	133	72	135.9	0.48	0.8147	3.6	22.59	0.187	4.11
	W06	Woven	Twill	Cotton	40s x 40s	133	72	132.4	0.56	0.8465	2.2	25.99	0.183	2.54
	W07	Woven	Plain	Cotton	40s x 40s	120	60	114.8	0.48	0.8459	2.9	22.16	0.179	3.62
	WMJ	Woven	Micro jacquard	Polyester	[c]	[c]	[c]	97.5	0.31	0.7735	180.0	13.43	0.174	12.13
	W3M	Woven	Plain	96 % polyester, 4 % spandex	[c]	[c]	[c]	89.1	0.28	0.7685	87.5	16.46	0.210	2.36
	SIL	Woven	Plain	Silk	[c]	163	108	68.1	0.20	0.7460	180.0	12.38	0.193	3.20
	PET	Woven	5/1 twill	Polyester	[c]	169	75	156.2	0.38	0.7043	40.9	9.21	0.154	2.74

[a] Water absorption time was assessed by wettability test (AATCC 79).

[b] Measured by Kawabata Evaluation System for Fabrics (KES-F4). Samples were conditioned in standard chamber (20±1°C and 65±5%RH) for 24 hours before testing.

[c] Undefined

summarized in Table 1 and the image of these fabrics is shown in Appendix B.

Group A is mainly knitted fabrics which is thicker and have higher water absorption capacity. It includes various types of moisture management fabrics with different surface feature. Some are knitted with mesh pattern and some are with pique pattern. Group B contains woven fabrics which are thinner and their water absorbency are lower. It includes a group of fabrics made of same material (cotton) but vary in fabric sett, yarn count and fabric structure. Additionally, it includes woven fabrics which is made of polyester and silk.

The porosity of the fabric is calculated according to (3) with reference to Hsieh's work [42].

$$\text{Fabric porosity} = 1 - \frac{\text{Fabric weight}\ (g/cm^2)/\text{Fabric thickness}\ (cm)}{\text{Bulk density of fibre}\ (g/cm^3)} \tag{3}$$

IV. RESULTS AND DISCUSSION

A. TYPICAL DRAG FORCE CURVE

Fig. 7 shows drag force curves of a typical fabric, K08, obtained by TSMS. There are two ways to illustrate the dragging phenomenon. First is the drag force against the amount of water supplied to the sample per unit area (see Fig. 7(a)). Second is the drag force against dragging time (see Fig. 7(b)). Drag force increases from approximate 0 at time 0 to a peak value within several seconds of testing. The first peak denotes the force required to initiate the movement and is defined as static drag force. Later on, drag force quickly breaks through the peak value and declines rapidly once that motion is in progress and this relates to the kinetic drag state.

Fabric K08 was dragged against the skin surface with different wetness levels (3 mg/cm^2, 6 mg/cm^2, and 14 mg/cm^2) and the results are illustrated in blue, red, and green, respectively, as shown in Fig. 7. For the skin surface with 3 mg/cm^2 water content, fabric K08 is still relatively dry after dragging for 24 cm and so the drag force curve remains steady after breaking through the static drag force (i.e. the blue curve). This is because the maximum amount of water supplied to the sample is just 17.4 mg/cm^2 which is far below its water absorption capacity (41.45 mg/cm^2).

When dragging against skin surface with 6 mg/cm^2 water content, it can be observed that the drag force curve is in U-shape (i.e. the red curve). Continuously increasing the wetness would increase the real contact area by capillary adhesion, suppress the movement of the sample, and thus increasing the drag force. However, the maximum amount of water supplied to the sample is just 34.8 mg/cm^2 which is also lower than its water absorption capacity (41.45 mg/cm^2) and so no F_P is observed.

As for the skin surface with 14 mg/cm^2 water content (i.e. the green curve), the maximum amount of water supplied to the sample is 81.2 mg/cm^2 which is much higher than its water absorption capacity (41.45 mg/cm^2) and so F_P can be found. Excessive water on skin would form a lubricant film on the contact surface, which contributes to reducing drag force. As shown in Fig. 7(a), when Q_P is above 51.8 mg/cm^2, the drag force starts decreasing. Similar finding was also found in others' work [24]. Du and Yu [43] mentioned that decreasing slope reflects the slipping of sample on surface.

B. SUMMARY OF MEASUREMENT RESULT

Fig. 8(a) and Fig. 8(b) show the measurement results for Group A's fabrics whereas Fig. 8(c) summaries the results for Group B's fabrics. Fig. 8(a) shows that the drag force curves for Group A's fabrics are not in bell shape under 6 mg/cm^2 water supply and no F_P is observed. This is because the amount of water supplied to fabric is far below its water absorption capacity. Hence, these fabrics were additionally tested under wetter skin surface (14 mg/cm^2) and the results are shown in Fig. 8(b). It shows that fabric K07 has the highest F_P whereas fabric PINK has the lowest F_P. On the other hand, fabric PINK has the highest Q_P whereas fabric K06 has the lowest Q_P. For Group B's fabrics, F_P can be found under drier skin surface (6 mg/cm^2). It shows that fabric W3M has the highest F_P whereas fabric W03 has the lowest F_P. On the other hand, fabric W07 has the highest Q_P whereas fabric SIL has the lowest Q_P. Explanation about the testing results is provided in the following section.

In Fig 8(b) and 8(c), it shows that F_C can only be found in some samples, for example, fabric K04 (F_C = 0.26N), K06 (F_C = 0.23N), K08 (F_C = 0.24N), Orange (F_C = 0.25N), W08 (F_C = 0.2N), SIL (F_C = 0.21N) and PET (F_C = 0.23N). The between-fabric difference is low for these fabrics. It suggested that when water film was formed between interfaces (i.e. profuse sweating condition), the force required to drag the sample is of similar level. Besides, it suggested that the dragging distance should be longer in order to show the F_C for all samples.

From these dragging curves, a series of parameters were extracted and are shown from Fig. 9.

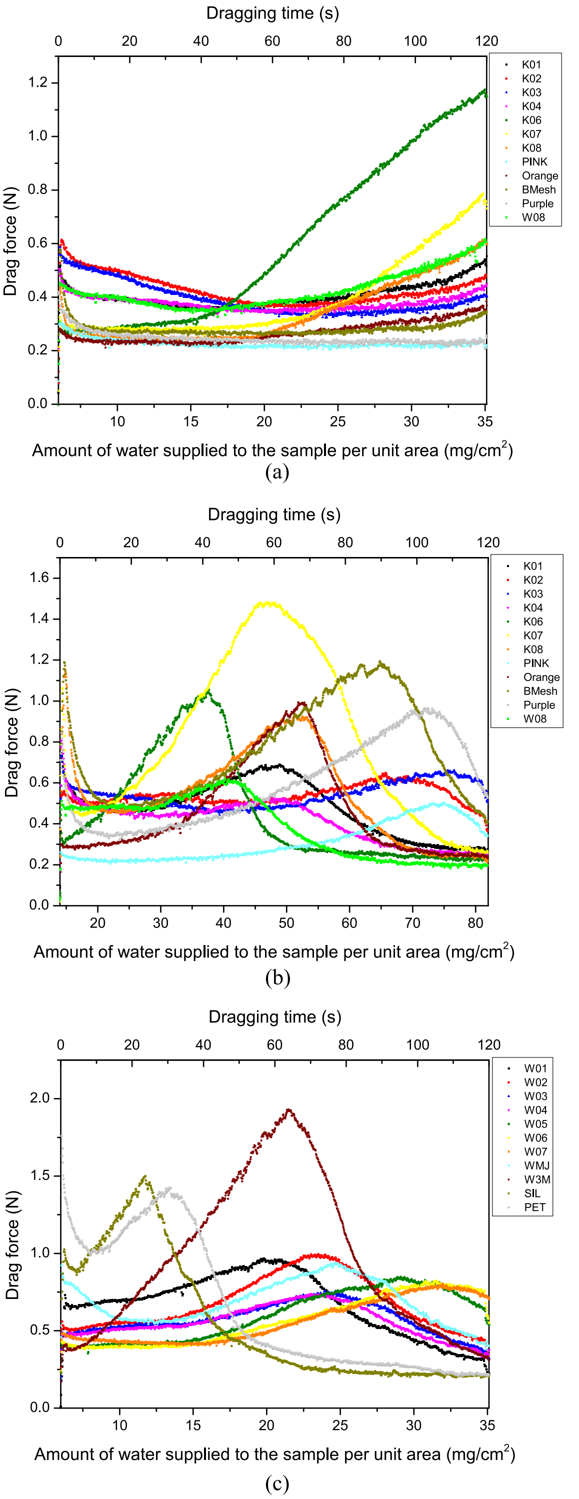
C. INVESTIGATING THE USAGE OF TSMS

In order to investigate whether TSMS is capable of differentiating the stickiness of various fabrics, one-way between-subject ANOVA test was performed on both Group A's and Group B's fabrics separately. The significance level of the statistical analysis conducted in this study was set at 0.05. The statistical analysis shows that there are significant differences in all cases ($p<0.05$), implying that TSMS is versatile.

1) EFFECT OF FABRIC CONSTRUCTIONAL PARAMETERS ON STICKINESS

To further investigate the effect of fabric constructional parameters on stickiness, independent t-test was performed and the results are summarized in Table 2.

First, fabric K03 and K04 were compared to study the effect of fabric structure on stickiness. These two fabrics are made of same material (32s cotton). Fabric K03 is in 1×1 rib structure whereas fabric K04 is in single jersey structure. Independent t-test shows that these two samples have significant differences in terms of F_P, Q_P, W_P, S_P, and SL_P ($p<0.05$). Fabric K03 is heavier, thicker with higher water absorption capacity implying that much water is required to saturate the fabric and so its Q_P is significantly larger. Fabric weight as well as Q_P is higher for fabric K03, so higher force is required to drag the fabric contributing to higher F_P.



(a)

(b)

(c)

FIGURE 8. Drag force as a function of amount of water supplied to the sample per unit area and dragging time. (a) Group A's fabrics dragged across simulated skin with 6 mg/cm^2 water content; (b) Group A's fabrics dragged across simulated skin with 14 mg/cm^2 water content; and (c) Group B's fabrics dragged across simulated skin with 6 mg/cm^2 water content.

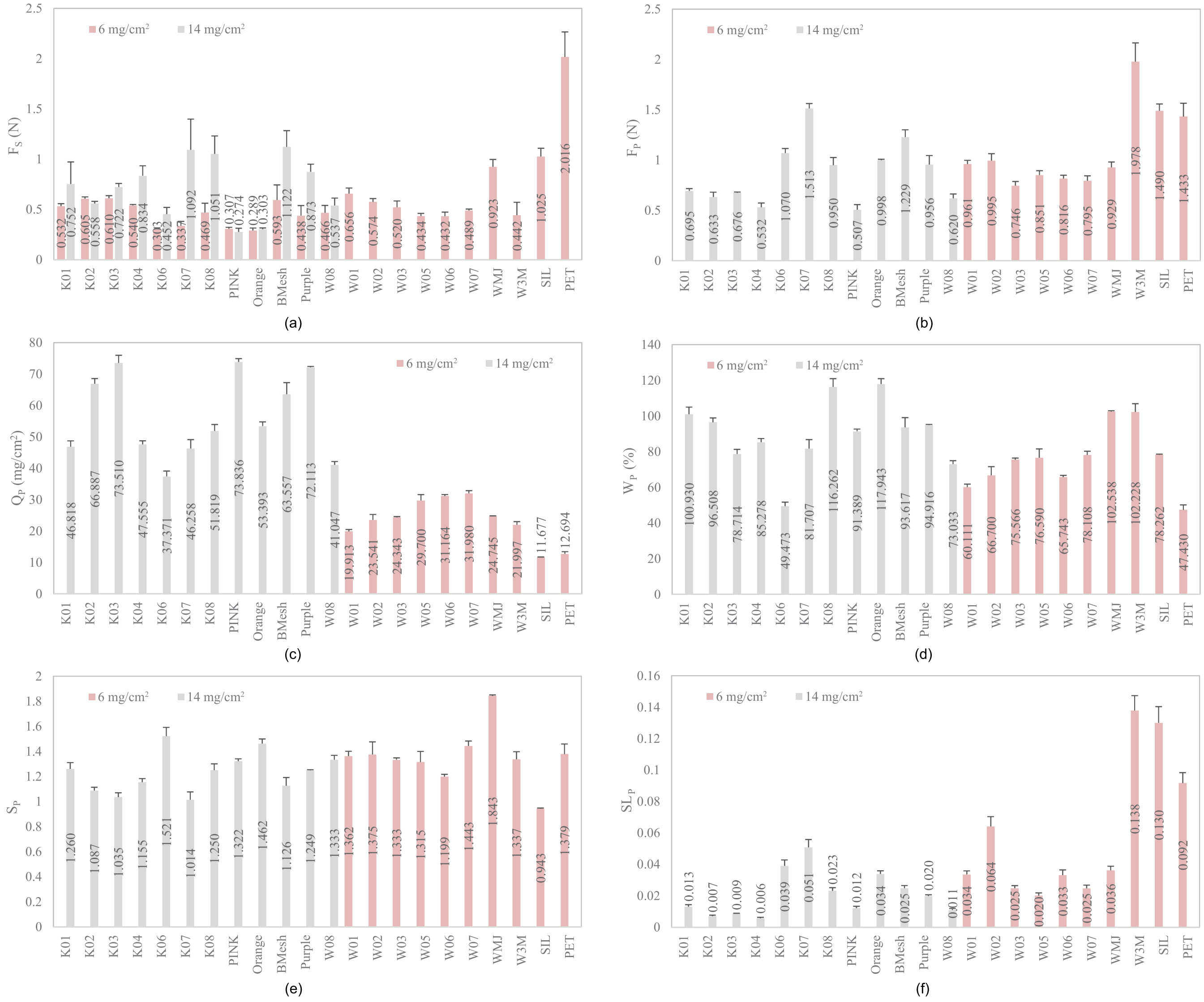


FIGURE 9. TSMS results under different wetness levels of skin. (a) Static drag force (F_S), (b) Peak drag force (F_P), (c) Amount of water supplied to the sample at F_P (Q_P), (d) Water content of sample at F_P (W_P), (e) Saturation level of sample when achieving F_P (S_P), and (f) Slope of drag force curve before achieving F_P (SL_P).

TABLE 2. p-value from independent t-test.

Pairs	Reasons for comparison	F_S	F_P	Q_P	W_P	S_P	SL_P
K03-K04	Study the effect of fabric structure on knitted fabric	0.141	0.024^a	0.000^a	0.028^a	0.010^a	0.001^a
W05-W06	Study the effect of fabric structure on woven fabric	0.886	0.289	0.191	0.007^a	0.232	0.001^a
W01-W02	Study the effect of yarn count	0.059	0.483	0.019^a	0.082	0.847	0.001^a
W03-W05	Study the effect of fabric density	0.093	0.040^a	0.009^a	0.742	0.734	0.027^a
W03-W07		0.452	0.255	0.000^a	0.130	0.011^a	0.945
W05-W07		0.031^a	0.215	0.135	0.651	0.076	0.043^a

^{a} Significant at 0.05 level

Besides, W_P for fabric K03 is significantly lower than fabric K04. It is because fabric K03 is much thicker and it is lined up with grooves on its surface (see Appendix B). The yarns goes up and down repeatedly which inhibit in-plane and transplanar wicking. Therefore, for fabric K03, F_P is achieved under lower water content. For fabric K04, due to the nature of single jersey structure (i.e. unbalance structure between fabric face and back) and its thickness, it rolls up from its edge easily when getting wet. This will greatly reduce the contact area with wet skin surface and so the increase in skin wetness level only brings considerable increase in drag force (i.e. resulting in lower SL_P).

Another pair (fabric W05 and W06) which is woven with the same material (40s cotton) and has the same fabric sett (epi: 133 and ppi: 72) was compared to study the effect of fabric structure. Fabric W05 is a plain weave fabric whereas fabric W06 is a twill fabric. Independent t-test indicates that there are significant differences in W_P and SL_P ($p<0.05$). W_P of fabric W05 is significantly higher than that for fabric W06 ($p<0.05$) whereas SL_P of W05 is significantly lower than that for fabric W06 ($p<0.05$). This is because fabric W05 has rougher surface (as suggested by the SMD value measured by KES-F, see Table 1) which reduces the contact points with wet skin surface. Hence, it can occupy with higher percentage of water when F_P is achieved (i.e. higher W_P) and it is not as sensitive as fabric W06 with the change in skin wetness (i.e. lower SL_P).

Third, fabric W01 and W02 were compared to study the effect of yarn count. They are plain weave cotton fabrics with the same fabric sett (epi: 90 and ppi: 88). Fabric W01 is woven with finer yarn (80s cotton) whereas fabric W02 is woven with coarser yarn (60s cotton). Independent t-test shows that these two samples have significant differences in terms of Q_P and SL_P ($p<0.05$). Fig. 9(f) shows that SL_P for fabric W01 is much lower. This is because its porosity is very high (0.9002) and it is very thin (0.37 mm). Its cover factor is very low as shown in Appendix B. Also, due to its lower water absorption capacity, its Q_P is lower and much water was left on the simulated skin after dragging and so the effect of water on it is less (i.e. lower SL_P). Fig. 10 proves that the correlation between Q_P and water absorption capacity is strong ($R^2 = 0.94$).

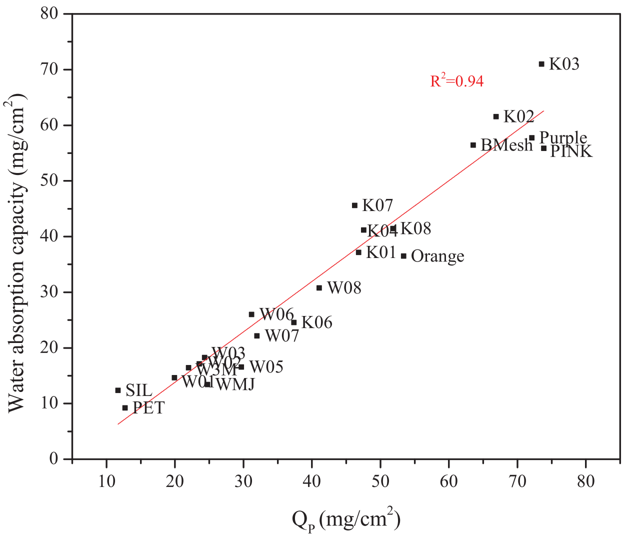


FIGURE 10. **Correlation between Q_P and water absorption capacity.**

Fourth, fabric W03, W05, and W07 were compared to study the effect of fabric sett. They are plain weave fabrics woven with 40s cotton yarn. Fabric W03 is the densest fabric, followed by fabric W05 and W07. F_P for the densest fabric (i.e. W03) is the lowest. Independent t-test shows that it is significantly lower than fabric W05 ($p<0.05$). The dense fabric provides less room for the fiber to swell and for water to bond, so the adhesion of water to fabric is less, contributing to lower F_P. The results also indicate that Q_P for fabric W03 is significantly lower than fabric W05 and W07 ($p<0.05$). This is because its water absorption time is significantly longer (W03: 13s; W05: 3.6s, W07: 2.9s).

These examples demonstrates that TSMS is capable of differentiating stickiness among fabrics even though they share similar constructional parameters.

Among the 22 fabrics, F_P is the lowest for fabric PINK. Its back side is very rough with big caves which reduces the contact with skin (See Appendix B). Gwosdow *et al.* [6] also suggested that clothing is judged comfortable when the number of contact points between fabric and skin surface is small, and the skin surface is dry.

2) EFFECT OF FIBER ON STICKINESS

Table 1 shows that in dry condition, the surface friction (MIU) of fabric PET (i.e. polyester fabric) and SIL (i.e. silk fabric) is of similar level as other woven fabrics (i.e. cotton fabrics). However, when they are wet, their F_P are significantly higher than the others. It agrees with other researchers that the effect of fiber type became much more pronounced with the presence of water [11].

Under wet skin surface, the chemical composition of the fiber may affect the amount and speed of water absorption. Absorbency may be lower for fabrics made of synthetic fiber (e.g. nylon and polyester) but higher for most natural fibers (e.g. wool and cotton) [9]. With increasing wetness, water may condense on the pores and cracks of the fiber surface. Some fibers like cotton may swell and liquid water will penetrate the fiber mass. Stickiness of material is generally dependent on the wettability of the fiber surface.

D. MAPPING THE STICKINESS PROPERTIES OF SAMPLES

This section provides a mapping technique for describing the stickiness properties of samples under wet skin surface. Four important parameters are plotted in one graph as shown in Fig. 11. This is useful for comparing large group of samples. The x-axis is Q_P whereas the y-axis is F_P. In general, a comfortable fabric should have low drag force when dragging against wet surface (i.e. F_P is low) and large Q_P which

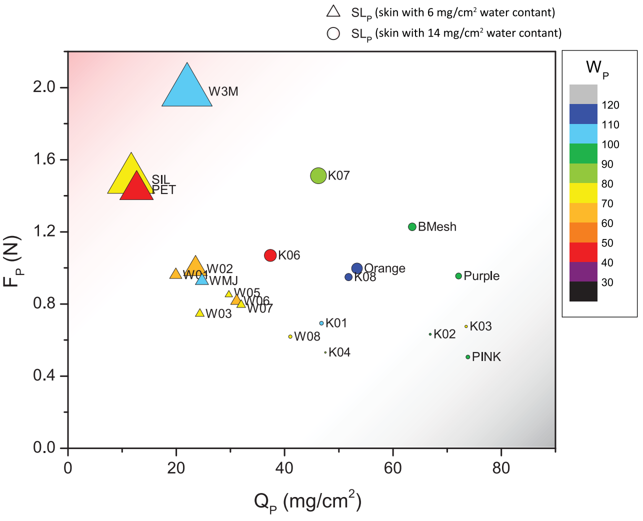


FIGURE 11. **Fingerprint of stickiness parameters including F_P, Q_P, W_P and SL_P.**

TABLE 3. Coefficient of variation (CV%) of different measurement parameters under different wetness levels of Lorica® Soft.

Fabric code	Static drag force (F_S)		Peak drag force (F_P)		Amount of water supplied to the sample at F_P (Q_P)		Water content of sample at F_P (W_P)		Saturation level of sample when achieving F_P (S_P)		Slope of drag force curve before achieving F_P (SL_P)	
	6 mg/cm^2	14 mg/cm^2	6 mg/cm^2	14 mg/cm^2	6 mg/cm^2	14 mg/cm^2	6 mg/cm^2	14 mg/cm^2	6 mg/cm^2	14 mg/cm^2	6 mg/cm^2	14 mg/cm^2
K01	4.6	29.3	-	3.3	-	4.0	-	4.0	-	4.0	-	10.4
K02	3.1	3.8	-	7.6	-	2.5	-	2.5	-	2.5	-	9.1
K03	4.4	4.9	-	1.1	-	3.3	-	3.3	-	3.3	-	1.4
K04	1.7	11.9	-	7.8	-	2.5	-	2.5	-	2.5	-	11.1
K06	4.3	14.7	-	4.3	-	4.6	-	4.6	-	4.6	-	9.6
K07	12.9	28.1	-	3.3	-	6.2	-	6.2	-	6.2	-	9.8
K08	19.6	17.1	-	8.0	-	4.0	-	4.0	-	4.0	-	8.7
PINK	4.8	13.7	-	10.0	-	1.4	-	1.4	-	1.4	-	10.4
Orange	8.7	4.2	-	1.1	-	2.5	-	2.5	-	2.5	-	6.1
BMesh	25.3	14.4	-	5.9	-	5.8	-	5.8	-	5.8	-	7.1
Purple	22.7	8.8	-	9.4	-	0.4	-	0.4	-	0.4	-	4.3
W08	15.9	14.0	-	7.0	-	2.7	-	2.7	-	2.7	-	7.9
W01	8.6	-	3.9	-	2.9	-	2.9	-	2.9	-	6.9	-
W02	5.7	-	7.0	-	7.4	-	7.4	-	7.4	-	9.8	-
W03	12.2	-	5.6	-	1.1	-	1.1	-	1.1	-	6.7	-
W05	5.9	-	5.2	-	6.5	-	6.5	-	6.5	-	8.5	-
W06	9.4	-	4.1	-	1.5	-	1.5	-	1.5	-	9.9	-
W07	2.9	-	6.1	-	2.8	-	2.8	-	2.8	-	8.6	-
WMJ	8.0	-	5.7	-	0.4	-	0.4	-	0.4	-	7.3	-
W3M	29.0	-	9.5	-	4.6	-	4.6	-	4.6	-	6.9	-
SIL	8.1	-	4.6	-	0.5	-	0.5	-	0.5	-	8.0	-
PET	12.4	-	9.2	-	5.8	-	5.8	-	5.8	-	7.2	-
AVERAGE	10.46	13.74	6.09	5.73	3.34	3.33	3.34	3.33	3.34	3.33	7.97	7.99

can withstand much water before achieving F_P. For those samples located at left top corner (i.e. orange zone), it gives the poorest wear comfort in terms of stickiness sensation. Take fabric W3M as an example, it can be regarded as very discomfort since its F_P is large and Q_P is relatively low. On the other hand, comfortable sample is located at the right bottom corner (i.e. grey zone). Fabric PINK situated in the grey zone is comfortable since its Q_P is high whereas its F_P is low.

Apart from F_P and Q_P, two additional parameters can be obtained from Fig. 11. That is SL_P and W_P. The size of each point relates to and is proportional to SL_P. If the size of the data point is comparatively large (i.e. large SL_P), it implies that the sample is very sensitive to water in terms of drag force (i.e. a constant increment in skin wetness might arouse a larger increment in drag force). For fabrics which have relatively poor wettability and low water absorption capacity (e.g. fabric W3M, SIL, and PET), their SL_P is comparatively high. This is because their water absorption capacity is low and water cannot penetrate into the fabric easily. Instead, water adheres to its surface which increases the contact points between fabric and skin dramatically. Fabric WMJ, however, is an exceptional case. Although its wettability and water absorption capacity is poor, its SL_P is exceptionally low (i.e. the size of the data point is rather small as shown in Fig. 11). This is because there are many protruding tunnels on its surface as shown in Appendix B. These tunnels greatly and successfully reduce the contact area.

Another important information obtained from Fig. 11 is W_P and this is denoted by the color of each data point. The implication of each color is shown in the figure legend. Fabric Orange, K08, K01, W3M, WMJ is in blue color, implying that their W_P is relatively high. On the other hand, fabric K06 and PET is in red color, suggesting that their W_P is relatively low. The wettability of fabric PET is rather poor and its floating yarns in 5/1 twill structure increases the contact points with wet skin surface, so its W_P is low. Fabric K06 is a kind of mesh fabric (as shown in Appendix B). The size of the pores is rather large which does not facilitate transplanar wicking. Therefore, when W_P is as low as 50%, F_P is achieved.

E. SYSTEM ACCURACY OF TSMS

All measurements are subject to some uncertainties [44]. System accuracy was assessed in terms of accuracy of different parts of the setup. In the market, there is no commercial method for testing the stickiness property of samples under wet condition and so we cannot compare this with other test methods in terms of accuracy.

In summary, the accuracy of force gauge and balance is 0.1% and 0.0005%, respectively.

F. REPEATABILITY OF TSMS

To ensure testing repeatability, it is necessary to handle the sample in a repeatable manner and maintain the instrument in a constant condition. Different parts of the instrument such as the motor, the force gauge, the simulated skin, the external pressure loading and the sprayer should be calibrated properly. The evenness of water sprayed on simulated skin, the homogeneity of the simulated skin, the surface feature of the simulated skin after repeated use, the movement speed of the force gauge, the pressure applied onto the sample, the height difference between the sample platform and the force gauge from level and sprayer efficiency may contribute to the variability of the result and a constant setup should be maintained.

The CV% of various measured parameters by the TSMS is summarized in Table 3. Except F_S, the CV% of the remaining parameters is relatively low. The average CV% for

F_P, Q_P, W_P, S_P, SL_P ranges from 3% to 8% as shown in the last row of Table 3. Regarding F_S, the average CV % is 10.46% for 6 mg/cm^2 wetness condition and 13.74 % for 14 mg/cm^2 wetness condition, which is comparatively high. For the static drag, it is likely to be affected by the placement of the sample before test. Also, since there is only little water absorbed into the sample by that time and a slight deviation in it would cause a large variation in static drag force.

G. VALIDITY OF TSMS

In order to examine the validity of the instrument, the correlation between TSMS results against the subjective stickiness sensation assessed by Tang *et al.*'s [45] method was examined. In their study, constant amount of water was sprayed onto the test sample directly. Depending on its water absorption capacity, the amount of water absorbed by the sample (A_W) varied and was additionally recorded. Same procedure was applied onto the reference fabric. During test, these two fabrics (i.e. sample & reference fabric) were rubbed onto their volar forearms automatically and simultaneously. Subjective rating of the test sample was assessed using the magnitude estimation technique. The rating of the reference sample is defined as 100. If the test sample is one time stickier than the reference sample, a rating of 200 should be given. The stickier the sample, the higher the rating is and vice versa.

Based on A_W, the drag force at that specific water level (F_X) can be calculated from the results measured by TSMS. The correlation between F_X and subjective stickiness rating is shown in Fig. 12. A relatively high correlation between TSMS result and subjective stickiness sensation ($R^2 = 0.58$) indicates that TSMS can realistically simulate the actual wear condition.

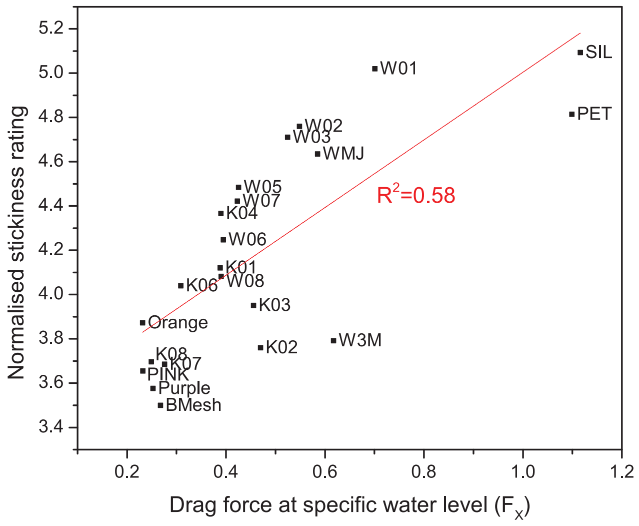


FIGURE 12. Scatter plot showing the correlation between F_X measured by TSMS and subjective assessment on stickiness sensation.

Based on the subjective sensory response, the important parameters affecting stickiness sensation were figured out using the multiple linear regression technique. The input dependent variable is subjective stickiness sensation whereas the independent variables include: F_S, F_P, Q_P, W_P, S_P, and SL_P. Stepwise regression was performed on two groups of fabrics separately and the results, as shown in Table 4, indicate that Q_P and F_P are important parameters affecting stickiness sensation in both groups. For group A's fabrics, 74.7% of the variance in stickiness can be predicted from Q_P and F_P. For group B's fabrics, 83.4% of the variance in stickiness can be predicted from Q_P and F_P.

TABLE 4. Results for regression analysis.

	Model		Unstandardized Coefficients	Standardized Coefficients	Sig.	R	R^2
			B	Beta			
Group A	1^a	(Constant)	86.033		0.000	0.60	0.36
		Q_P	-0.522	-0.603	0.038		
	2^b	(Constant)	113.920		0.000	0.86	0.75
		Q_P	-0.655	-0.758	0.002		
		F_P	-23.571	-0.638	0.005		
Group B	1^a	(Constant)	204.565		0.000	0.69	0.48
		Q_P	-3.958	-0.690	0.027		
	2^b	(Constant)	352.433		0.000	0.91	0.83
		Q_P	-6.704	-1.168	0.001		
		F_P	-76.617	-0.766	0.006		

^{a} Excluded variables: F_S, F_P, W_P, S_P, SL_P
^{b} Excluded variables: F_S, W_P, S_P, SL_P

V. CONCLUSIONS

An instrument for measuring stickiness of fabrics under wet skin surface was developed. Constant amount of water was sprayed evenly onto the synthetic leather to simulate wet skin surface. The mechanism of TSMS is that the textile sample was dragged across the wet simulated skin at a constant speed while the amount of water supplied to the sample increases gradually, simulating from mild to profuse sweating condition. The resulting drag force was measured by the force gauge. The measurement results reveal that with sufficient water supply to the sample, the relationship between drag force and wetness level of sample is in bell-shape and the peak drag force (F_P) was found to have strong correlation with its water absorption capacity ($R^2 = 0.94$). Hence, in order to obtain the bell-shape drag force curve and to find out the F_P, the amount of water supplied to the simulated skin should be chosen carefully and it should be higher than its water absorption capacity. If the amount of water supply is too low, F_P cannot be found.

In the initial stage of dragging, drag force increases gradually with dragging distance. The increment of drag force can attribute to surface tension of water which increases the contact points between fabric and skin. Further wetting the sample might create a lubricating layer within the interfaces and so the drag force starts decreasing. In this experimental setup, when excessive water is applied, the drag force tends to be stable, which is around 0.23 N.

TABLE 5. **Conventional test methods for measuring frictional properties and stickiness of textiles.**

Study	Type	Principle	Material of sliding partner	"Skin" condition	Comments
Gupta *et al.* (2008) [17]	Inclined plane method	The bottom of the block and the platform is covered with the test material. One end of the platform, which is initially horizontal, is slowly raised until the block resting on it starts to slide. The angle causing slippage reflects the frictional behavior.	Fabric	Dry	- Only static friction can be known - May have limited implication in clothing comfort
Carr *et al.* (1988) [12]	Dragging type fabric-to-fabric test	The test samples are attached to the aluminium platform and the mating fabric is mounted on a Plexiglas sled using water soluble glue. The sled is connected to a thread passed through a low friction pulley to Instron tensile tester.	Fabric	Dry	- Mounting the sample to the sample holder with glue which takes time for drying - May not hold the sample properly - Expensive machinery (Tensile Tester)
Ajayi (1992) [25]	Dragging type fabric-to-fabric test	The frictional property of a fabric is measured by mounting a rectangular specimen on a horizontal platform over which a sled covered with an identical fabric is dragged.	Identical fabric, rubber, perspex	Dry	- Expensive machinery required (Elongation Tester)
Van Amber *et al.* (2015) [11]	Dragging type fabric-to-Simulated skin test	The frictional property of a fabric is measured by mounting a rectangular specimen on a horizontal platform over which a sled covered with a piece of simulated skin is dragged.	Lorica®Soft	Dry and moist	- Use Wascator to wet the fabric cannot standardize the volume of water held in the specimen - Expensive machinery required (Tensile Tester)
Hermann *et al.* (2004)[26]	Dragging type	The test sample is attached to the aluminium platform using double-sided tape. The PMMA sled is connected to a thread passed through a low friction pulley to the tensile tester.	PMMA sled	Dry	- Expensive machinery required (Tensile Tester)
Ramkumar *et al.* (2003) [46]	Dragging type	The artificial finger sledge is attached to a weight on the free end. When the weight is higher than the dragging force, the movement of the sledge can be reversed and frictional behavior over a number of cycles of reciprocating traverse can be examined.	Polyvinylsiloxane	Dry	- Expensive machinery required (Tensile Tester)
Hohenstein institute [47]	-	Water is supplied to a porous, sintered glass plate using a calibrated motorized burette simulates perspiring skin. The sample is fastened to a cylinder and pulled across the plate. The force required to do this is called the cling index.	porous, sintered glass plate	Wet	-
Kawabata (1975) [19]	Sliding type	The sample is laid flat and the probe is pressed onto the fabric. The coefficient of friction given by the ratio of force registered in the transducer, attached to the friction probe, to the normal force, is plotted as a function of the transverse distance.	piano wires	Dry	- Simulate the condition when the fabric is picked and stroked between fingers. - Piano steel do not have similar frictional property as human skin - This instrument is intended for shirting material only and it is not suitable for knitted fabrics or elastic fabrics since fabric will be stretched or distorted during measurement - Expensive machinery required (KES-F)
Chen *et al.* (2015) [48]	Sliding type	A commercial artificial finger mounted on a tribometer at the angle of 30 degrees from the horizontal is used to scan fabric samples along their warp direction.	Commercial artificial finger	Dry	-
Bertaux *et al.* (2007) [49]	Sliding type	The fabric sample is placed on top of the skin. The fabric remains stationary while the skin model is submitted to a reciprocating movement (650 cycles). The frictional force between the skin model and a fabric sample is measured by a quartz force sensor combined with a charge amplifier.	Lorica®Soft	-	-
Lima *et al.* (2005) [16]	Rotary type	The principle is based on the dry clutch, where an annular shaped flat upper body rubs against a lower flat surface, which rotates around a vertical axis at a constant angular velocity. Friction coefficient between the two surfaces, measured by a precision reaction torque sensor, is proportional to the level of the dragging torque.	Steel	Dry	- Steel do not have similar frictional property as human skin
Kenins (1994) [9]	Dragging type in vivo study	The subject's forearm or hand is placed in the support and a strip of fabric is dragged across the skin. One end of fabric is suspended with a dead weight while another end is attached to a strain gauge.	Human skin	Dry and wet skin	- It is not easy to keep human forearm in a static position.
Wang *et al.* (2009) [40], (2012) [24]	Dragging type in vivo study	Forearm or simulated forearm is mounted onto the armrest. Both end of the fabric is mounted with clamp. The fabric is then pulled across the forearm and the roller. The friction equipment pulls forearm up and down and the relative dragging friction between fabric and skin is measured.	Skin	Dry, Wet	The way to wet the fabric may not be reproducible (i.e. soaked in water, kneaded gently and hung for a predetermined duration.)
Gerhardt *et al.* (2008) [20]	In vivo sliding type study	Frictional measurement is carried out using a triaxial quartz force plate. The volunteers rubbed their inner forearm against the textiles on the force plate in a reciprocating and uniform motion and the force required is measured.	Inner forearm	Dry and wet	- The force applied by the participant is subject to quite large variation.

From the drag force curve, a series of parameters can be extracted, including: (i) static drag force, (ii) peak drag force, (iii) amount of water supplied to the sample at F_P, (iv) water content of sample at F_P, (v) saturation level of sample when achieving F_P, (vi) slope of drag force curve before achieving F_P, (vii) drag force at a specific water level, and (viii) drag

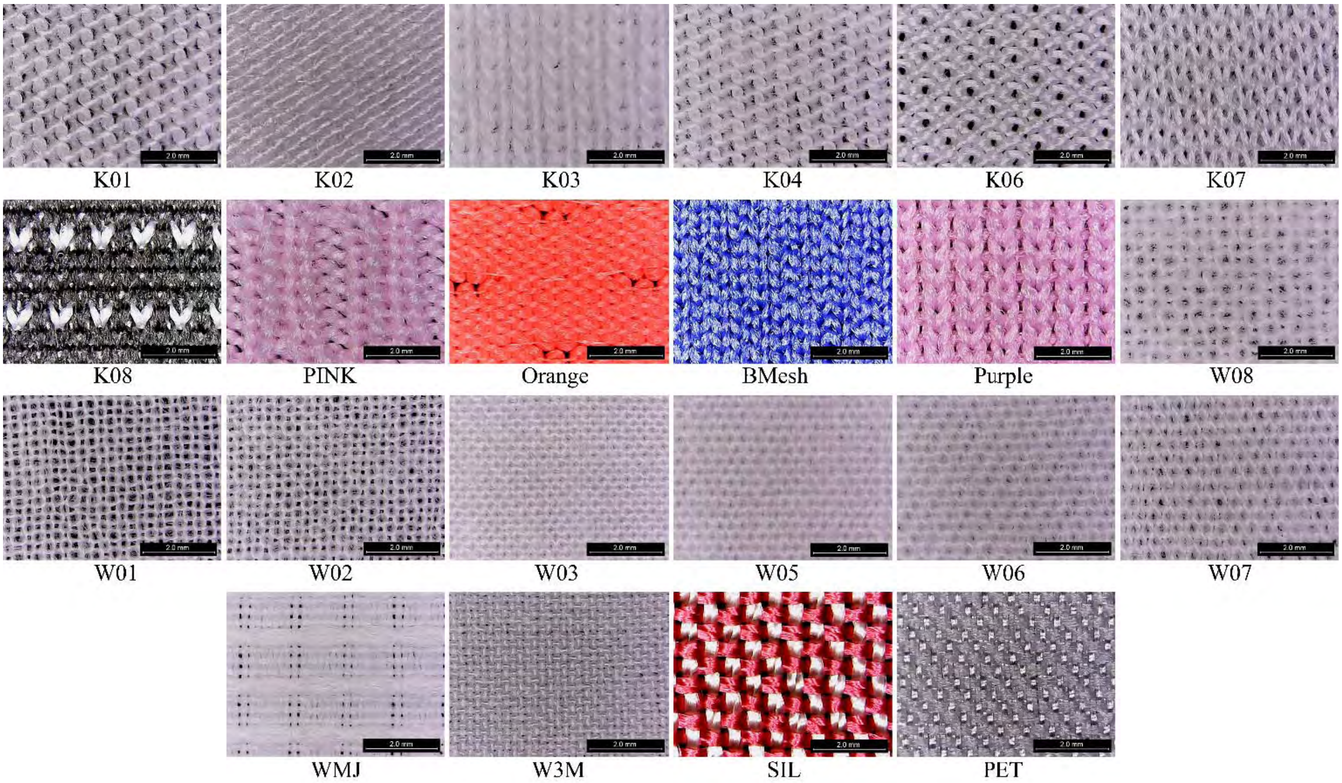


FIGURE 13. Images of the 22 fabrics investigated. (back side of the sample).

force of sample at completely saturated condition. These parameters were adopted to differentiate fabrics made by differing fabric constructional parameters and fiber content. For those fabrics which have less contact area with wet skin surface, they tend to give better performance in terms of stickiness. Experimental results also found that the effect of fiber type became much more pronounced with the presence of water within the interfaces. Additionally, an informative mapping technique which describes four meaningful stickiness properties was introduced. This could help to visualize the performance of a group of fabrics. Besides, regression analysis found that F_P and Q_P were significant factors contributing to stickiness sensation.

The uniqueness and advantages of TSMS include:

- capable of measuring stickiness properties under different moisture levels
- versatile in terms of the type of fabrics tested (including knitted and elastic fabrics)
- comprehensive description on stickiness properties of samples against skin
- simple setup with high system accuracy
- short testing and fabric preparation time
- affordable cost
- the way to mount the sample to the sample holder enables fabric elongation freely during dragging which simulates actual wear condition of clothing

Compared with conventional instrument, like Kawabata Evaluation System for Fabric, TSMS is simple, versatile, and closer to wear condition at an acceptable cost which make it suitable for routine testing of fabrics. With this instrument, fabrics can be characterized efficiently which helps to develop comfortable product.

APPENDIX A

See Table 5.

APPENDIX B

See Fig. 13.

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