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Research Article

Tactile perception of textile fabrics based on friction and brain activation

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Abstract: Tactile perception plays a critical role in the interaction of humans and environment. It begins with the mechanical stimulation induced by friction and is processed in the somatosensory cortex. To quantify the tactile perceptions of textile fabrics, the mechanical properties of fabrics and the features extracted from the friction and vibration signals were correlated with the subjective sensation rated by questionnaires. Meanwhile, the technique of functional magnetic resonance imaging (fMRI) was used to identify the brain areas responsible for the tactile perception of textile fabrics. The results showed that during the tactile perception of textile fabrics, the coefficient of friction increased with the increasing normal load, indicating that the deformation mechanism of skin was relevant to the friction of skin against fabrics. The features of spectral centroid (SC), coefficient of friction, and diameter and critical buckling force of fiber had a strong correlation with the perceived fineness, slipperiness, and prickliness of fabrics, respectively. The postcentral *gyrus*, supramarginal *gyrus*, and precentral *gyrus*, with the corresponding functional regions of the primary somatosensory cortex (SI), secondary somatosensory cortex (SII), primary motor cortex (MI), and secondary motor cortex (MII), were involved with the perceptions of fabric textures. The fiber properties and fabric surface structures that caused the multidimensional feelings tended to induce the large area, intensity, and percent signal change (PSC) of brain activity. This study is meaning for evaluating the tactile stimulation of textile fabrics and understanding the cognitive mechanism in the tactile perception of textile fabrics.

Keywords: tactile perception; friction; brain activation; characteristic features; textile fabric

1 Introduction

Even humans cannot see objects, they can still perceive and recognize them through the sense of touch. Tactile perception plays a critical role in the interaction of humans and environment. When perceiving the surface textures, the fingers usually slide over the surface, and then the friction-induced vibrations stimulate the cutaneous mechanoreceptors. Tactile information travels from cutaneous mechanoreceptors to the cerebral cortex through the sensory pathways [1], and finally is processed in the somatosensory cortices [2, 3]. The related research of tactile perception involves tribology, physiology, and psychology, which can be widely applied in the innovation of electronic skin, surface texture design of reliable grip products, and quality evaluation of textile comfort and cosmetic feelings.

The evaluation of tactile perception is of great interest to the manufacturers and designers of textile products since it plays a critical role in the assessment of their quality. Questionnaires are common methods used in tactile sensing evaluations of fabrics [4, 5]. However, these questionnaires require hundreds of subjects and are expensive. The results were also influenced by the cognition, physiology, psychology,

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and social background of individuals, who showed large subjective biases [6, 7]. Therefore, in the textile industry, the mechanical properties of fabrics, such as bending, compression, surface roughness, and friction, are usually measured with a Fabric Touch Tester instrument to quantitatively characterize and evaluate the fabric [8, 9]. However, the quantitative measurement of the physical properties of textile fabrics cannot reflect the interaction of fingers and fabrics during tactile perception. Thus, an efficient, accurate, and objective method is necessary for conducting tactile sensing evaluations of fabrics.

Moreover, the friction and vibration between the felt surfaces and skin have received great attention when studying and quantifying tactile perception. The vibration and friction signals generated when human fingers or artificial fingers touch different surfaces were analyzed and related to the surface and mechanical properties of a surface [10–14]. For example, Fagiani et al. [15] investigated the vibration spectrum obtained by finger scanning textiles and highlighted the changes of the vibration spectrum as a function of contact parameters. Zhou et al. [16] focused on the mechanism of how sliding speed affects tactile perception by analyzing the dynamical and tribological signals obtained from the movement of fingers. To investigate the influence of surface roughness on tactile perception, Zahouani et al. [17] analyzed the vibrational features of the human finger during different friction conditions.

It should be noted that the friction between surface textures and skin provides vibratory stimuli on the skin surface during tactile perception, which in turn activates the somatosensory cortex. It is hard to evaluate the tactile perception according to only the mechanical properties of fabrics and the friction behavior of skin. Until now, the cognitive mechanisms of brain associated with the tactile perception are not well understood. According to the literatures, the functional magnetic resonance imaging (fMRI) and electroencephalograph (EEG) are the feasible technologies to investigate the brain activity during tactile perception.

fMRI technology measures brain activity by detecting changes of blood flow associated with tactile perception with a high spatial resolution [18]. fMRI technology has been used to investigate the brain functional response to the cutaneous prickling of fiber [19] and the surface roughness of fabric [20], the primary brain regions related to the fabric hand [21], and the fabric comfort perception [22]. The previous studies have proved that fMRI is a remarkable tool to study the cognitive mechanism of the brain on the mechanical stimulation of fabric on human skin.

Due to the high temporal resolution, ease of use, and low cost, EEG has been widely used to explore the brain activities associated with the tactile perception of textured and rough surfaces [23–25]. Previous studies of perceptual processing have reported the earlier somatosensory evoked potential (SEP) components and P300 component [26, 27], which were extracted from the event-related potential (ERP). Recently, the coefficients of friction between textile fabrics and human fingers and the induced vibrations have been correlated with brain ERP results [28, 29].

Friction is an important stimulating factor of tactile perception when touching textile fabrics and brain activities in response to a fabric stimulus is critical in understanding the cognitive mechanism of tactile perception. This investigation systematically studied the tactile perception of fabrics based on subjective evaluation, fiber features, surface friction and vibration, and neurophysiological response of the brain. To quantify the tactile perceptions of textile fabrics, the mechanical properties of fabrics and features extracted from the friction and vibration signal were correlated with the subjective sensation rated by questionnaires. Meanwhile, to identify the brain regions responsible for the tactile perception of the textile fabric and to find the neural activity related to the feeling of prickliness, fineness, and slipperiness, fMRI was used to measure the cerebral blood flow of subjects when they felt different textile fabrics. This study provided the evaluation method of tactile perception of products that contact with skin directly (e.g., the textile products and skin care products). Furthermore, it contributes to the understanding of the cognitive mechanism of tactile sensation.

2 Experimental details

2.1 Samples

Five fabric samples were chosen for the tactile stimulus samples. Figure 1 shows the microscopic images of the surfaces of the five fabric samples, and Table 1 shows their structures, components, warp–weft densities, and surface roughnesses. The surface roughnesses of fabrics were measured using a digital microscope (DSX 1000, Olympus, Tokyo, Japan). The sampling area was 270 μm × 270 μm, and the sampling number was 4.

2.2 Participants

Twenty healthy, 20–25 y of age (mean±standard deviation = 22.7±1.9 y), and right-handed males took part in the test. All subjects have given their written informed consent before the test. This study was conducted in accordance with the International Ethical Standards and was approved by the Ethics Committee of Xuzhou Central Hospital (No. XZXY-LJ-20210513-054, Xuzhou, China).

2.3 Friction measurement

A reciprocating motion tribometer was designed for the friction test during tactile perception, as shown in Fig. 2. In the test, the index finger contacted the fabric sample through the elliptic hole in the touching platform. The fabrics were cut into 50 mm × 50 mm samples and fixed on the stage of a triaxial force sensor (JDS-12, Bengbu Sensor System Engineering Co. Ltd., Bengbu, China). The triaxial force sensor could measure the applied normal load and friction force directly. The force ranges of the sensor are 0–10 N for z direction and 0–5 N for x and y directions with the resolutions of 0.2 and 0.1 N, respectively. To avoid the body movement during touching, the fabric samples were rubbed against the surface of the fingers, which were kept still during the test. The movement of the triaxial force sensor was controlled

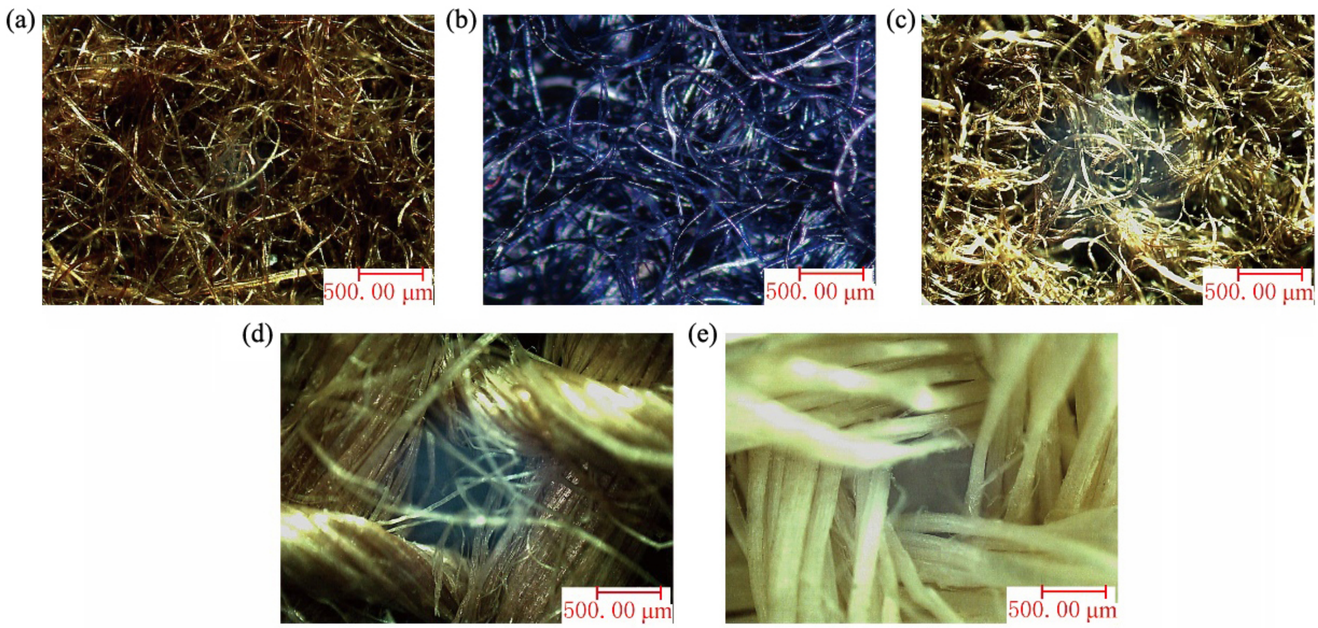

Fig. 1 Surface microscopy images of fabric samples: (a) #1, (b) #2, (c) #3, (d) #4, and (e) #5.

Table 1 Structures, components, warp–weft densities, and surface roughnesses of fabric samples.

Sample	#1	#2	#3	#4	#5
Structure	Plain	Plain	Plain	Plain	Plain
Component	W 60%/P 40%	W 50%/P 50%	W 15%/P 85%	Linen 100%	Ramie 100%
Warp–weft density (per 10 cm)	410 × 330	289 × 230	280 × 225	71 × 62	45 × 35
Diameter of yarn (μm)	450±39	476±22	481±33	815±28	1,483±132
Surface roughness, R_a (μm)	0.354	0.587	0.789	7.51	10.21

Note: W means wool, and P means polyester.

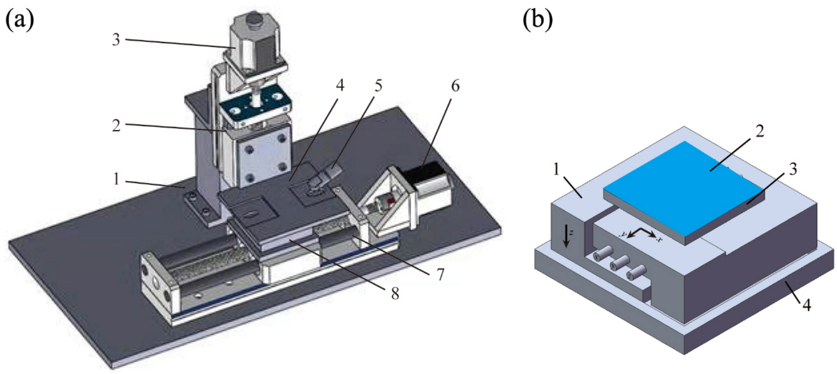

Fig. 2 Schematic diagrams of (a) friction tester and (b) triaxial force sensor.

by the ball screw, which was driven by the stepping motor. The triaxial force sensor measured the vibration and friction between them.

Different touching loads (0.5, 1.0, 1.5, 2.0, 2.5, 3.0, and 3.5 N) were applied by subjects and were monitored by the signal acquisition system. The touching distance and velocity were 40 mm and 15 mm/s, respectively. After one touching test, the subject lifted his finger and waited for approximately 1.5 s for the next touch. Each trial was repeated twice.

2.4 Processing of vibration signals

Since the noise from the device and environment will also induced vibration, the vibration signals of finger should be denoised. Here we took #5 fabric sample as an example to show the denoising process. The original vibration signals were collected when the finger moved across #5 fabric sample, and the frequency spectrum of signal was obtained by using the fast Fourier transform (FFT), as shown in Fig. 3(a). The no-load vibration signal derived from the device and environment was collected under the non-contact condition, and the frequency spectrum of the signal was obtained by the FFT, as shown in Fig. 3(b). The results show that the dominant frequency of the no-load signal is mainly around 164 Hz, which is similar to the dominant frequency of the original signal. A Butterworth filter is used to remove the noise of 164 Hz from the original vibration signal directly, and the filtered signal is shown in Fig. 3(c). For other samples, the vibration signals were processed by using the same method.

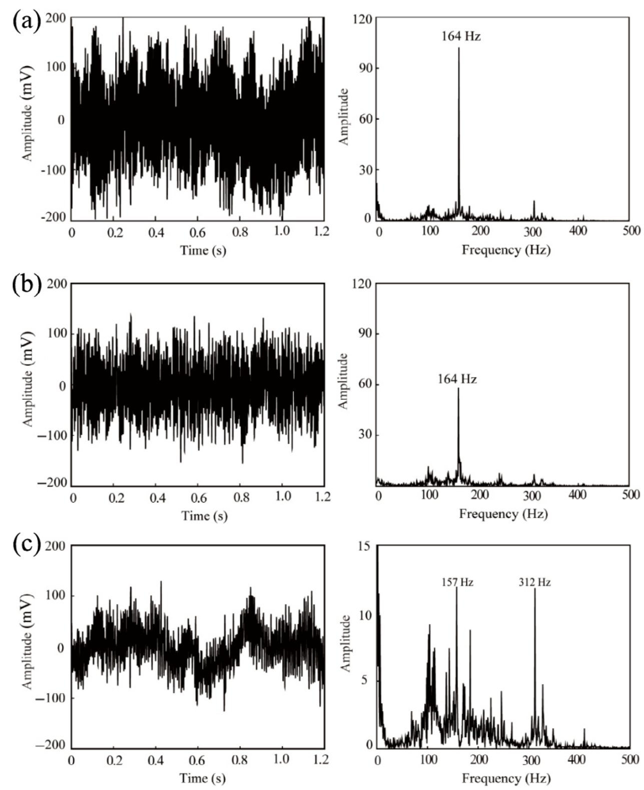

Fig. 3 Typical time-domain signals and frequency spectra of (a) original vibration signal, (b) no-load vibration signal, and (c) filtered vibration signal. All signals were collected under a velocity of 15 mm/s and a normal load of 1.0 N for sample #5.

2.5 Characteristic features

The tactile perception of fine textures is mediated by skin vibrations generated as the finger slides across the surface, which is the horizontal resolution of tactile perception on surface [30]. It has been observed that the finer textures produce higher-frequency vibrations, while the coarser textures produce lower-frequency vibrations [31]. The spectral centroid (SC) can determine the weighted frequency power of the vibrations and is a common parameter for the tactile fineness [30–32]. To obtain the relationship between fineness feeling and skin vibrations, the SC was chosen and calculated by using Eq. (1):

$$\mathrm{SC}=\frac{\sum_i\left(\mathrm{fft}\left(y_i\right)^2 f_i\right)}{\sum_i \mathrm{fft}\left(y_i\right)^2} \tag{1}$$

where y_i is the amplitude of the vibration signals, i is the index of the sample number in the time domain, and f_i is the frequency. fft(y_i) indicates that the signal is analyzed based on the FFT. A finer surface has a higher texture space density and usually corresponds to a high vibration frequency. According to Eq. (1), a large SC value indicates a fine texture, and a small value indicates a relatively coarse texture.

The coefficient of friction is commonly used to characterize the slipperiness feeling [15]. It is the ratio between the friction force and normal load. According to Ref. [33], the lower the values of the coefficient of friction, the slipperier the surface is felt.

2.6 fMRI data acquisition and processing

The fMRI data were collected with an MRI system (GE Discovery MR750w 3.0T, General Electric company, Boston, USA) at Xuzhou Central Hospital, China. During the test, the assistant rubbed the fabric samples against the right index finger of subject with a velocity of approximately 0.33 Hz and a sliding distance of 40 mm. The subjects were told to keep as still as possible and to focus on feeling the stimulus.

A block design was used in the test, as shown in Fig. 4. Each run was composed of nine stimulus blocks of 30 s and eight rest blocks of 30 s. One fabric sample was presented in three blocks for one run. The duration of each run was 8.5 min.

The data were analyzed by using a software package (SPM12, Wellcome Department of Imaging Neuroscience, London, UK). Activated voxels in statistical maps of interest were visualized with the xjView Toolbox for SPM (https://www.alivelearn.net/xjview/) for anatomical labeling and volume quantification. Preprocessing of the data included slice scan time correction, motion correction, spatial normalization, and spatial smoothing.

According to the common brain activity area during tactile perceiving the three textile fabrics, the primary somatosensory cortex (SI), secondary somatosensory cortex (SII), primary motor cortex (MI), and secondary motor cortex (MII) were chosen as the regions of interest (ROIs). The percent signal change (PSC) is usually calculated using a baseline of the mean of the time series on a voxel. It can represent the influence of tactile stimulation on the ROIs. In this study, the mean PSC within each ROI was calculated by using MarsBaR toolbox (http://marsbar.sourceforge.net).

2.7 Subjective evaluation

In the subjective evaluation, the feelings of the fabric were divided into fineness, prickliness, and slipperiness. Training was given to all subjects before the test. In training, a silk sample was initially presented to subjects as reference stimulus. The subjects (eyes covered and hands free) took the fabric using the left hand and rubbed the silk surface over the forearm skin of the right hand for 10 s. It was informed that evaluation scores for fineness, prickliness, and slipperiness were 5, 0, and 5 for reference stimulus, respectively. In each trial, subjects perceived the fabric and orally reported the feelings of the given fabric according to the reference stimulus. Finally, the scores (ranging from 0 to 5) were averaged for each subject. Each fabric was presented twice per participant. Rest time was 1 min between each trial.

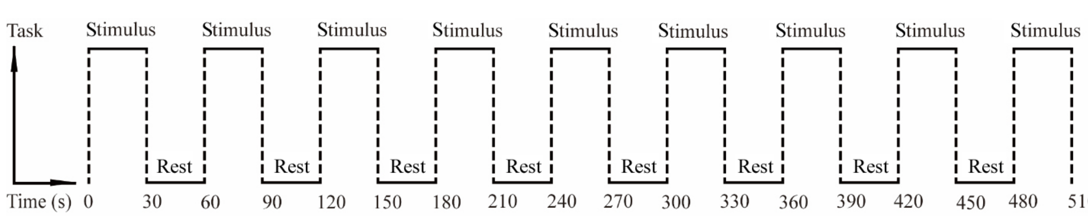

Fig. 4 Schematic of the block paradigm.

Higher human evaluation scores for sensations of fineness, prickliness, and slipperiness correspond to finer feeling, pricklier feeling, and slipperier feeling, respectively.

3 Results and discussion

3.1 Friction analysis between skin and fabrics

It is usually to describe the coefficient of friction of skin by Eqs. (2) and (3) [34, 35]:

$$F = kW^n \tag{2}$$

$$\mu = kW^{n-1} \tag{3}$$

where F is the friction force, W is the normal load, μ is coefficient of friction k is a load-dependent coefficient of friction, , and n is the load index.

Because of the viscoelastic properties, the friction of human skin depends on the normal load, effective contact area, and elastic modulus. The friction force comes from the adhesive friction F_{adh} and deformation friction F_{def} between the skin and material surface [34, 36].

$$F = F_{\text{adh}} + F_{\text{def}} \tag{4}$$

$$F_{\text{adh}} = \tau A_{\text{r}} = \pi \tau_0 \left(\frac{3R}{4E}\right)^{2/3} W^{2/3} + \alpha W \tag{5}$$

$$F_{\text{def}} = \beta \left(\frac{9}{128R}\right)^{2/3} \left(\frac{1-\nu^2}{E}\right)^{1/3} W^{4/3} \tag{6}$$

where τ is the interfacial shear strength; A_{r} is the real contact area; τ_0 is the intrinsic interfacial shear strength; R is the radius of the sphere; E and ν are the Young's modulus and Poisson's ratio of the deformable countersurface, respectively; α is the pressure coefficient; and β is the viscoelastic hysteresis loss fraction. It may be seen that Eqs. (5) and (6) are in the form of Eq. (2) with $n = 2/3$ and $4/3$, respectively.

In this study, μ as a function of W of all samples are plotted in Fig. 5. The experimental data were fitted to Eq. (3), and the corresponding values of k and n were shown in Table 2. It showed that the value range of n was between 1.28 and 1.33, which was confirmed to the load index of deformation friction.

According to Wolfram [37], adhesive friction is related to the interfacial shear resistance caused by

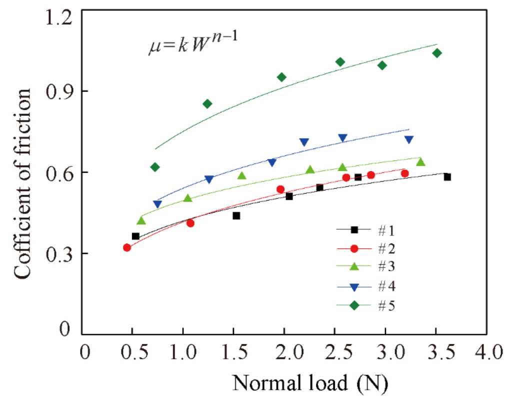

Fig. 5 Coefficient of friction as a function of applied load of five fabric samples

Table 2 Experimental and derived data of five samples.

Sample	#1	#2	#3	#4	#5
k	0.42	0.42	0.49	0.54	0.75
n	1.28	1.33	1.23	1.29	1.29

the formation and breaking of inter-atomic junctions between the SC and the fabric. Adhesive friction is proportional to A_{r}, and μ increases with the decreasing normal load [38, 39]. The deformation friction is related to the work expended to deform the skin and the sub-surface tissue and to the viscoelastic hysteresis or ploughing of the skin when the skin slides over the fabric. A contribution due to deformation is expected to increase the coefficient of friction with the increasing normal load [40, 41].

The common view in the literatures is that adhesion is the primary component of skin friction, and the deformation component is small compared to adhesion [37]. However, in some cases, the deformation was also assumed to play a role in the friction between human skin and textiles. Sanders et al. [42] studied the friction between prosthetics, orthotics, and sock fabric and the skin. For all materials, the coefficient of friction increased with the applied normal load, indicating that deformation was involved in friction. The studies of Derler et al. [14] and Gerhardt et al. [39] also found the evidence that skin deformation mechanisms were related with the friction of skin and textiles. As shown in Fig. 5, for all fabric samples, μ increased with the increasing W, indicating that the skin deformation mechanisms are relevant for the friction of skin against fabrics. Our results also confirm with the related studies.

Here, as shown in Fig. 6, because the fibers existed in the contact interface of the surfaces, direct contact between the fabric and skin surfaces was separated by these fibers, and the formation of inter-atomic junctions between the SC and the fabric was broken off. Friction force mainly comes from deformation friction between the skin and fabric surfaces, and the adhesion friction was relatively small. Meanwhile given by the hairiness and weave construction of fabric, fiber friction also influenced the friction.

3.2 Characteristic features of the fineness and slipperiness sensations caused by fabric

To quantify the fineness and slipperiness feeling of fabric, the subjective evaluation scores were correlated with SC and coefficient of friction of a finger when touching different surface roughness fabrics, as shown in Fig. 7. Pearson correlation analyses were performed to evaluate the correlation of the surface roughness, characteristic features, and tactile sensation using the SPSS data analysis software.

The results showed that SC and fineness were negatively correlated to the surface roughnesses with $r = -0.936$ and -0.977, respectively, where SC and perceived fineness decreased with the increasing surface roughness of fabrics. μ was positively correlated to surface roughness ($r = 0.918$), and the perceived slipperiness was negatively correlated to surface roughness ($r = -0.939$), where μ of the finger increased, and the perceived slipperiness decreased with the surface roughness of fabrics increased. References [33, 43] also suggested that the perceived slipperiness was influenced by the surface roughness, and materials with higher surface roughness were perceived as less slippery.

As shown in Table 1, surface roughness increased, and warp–weft density decreased from #1 to #5. When fingers touched and slid on the fabric surface, with increasing surface roughness and decreasing warp–weft density, indentation of the fabric asperities into the skin became large, and deformation friction derived from the viscoelastic hysteresis of skin and mechanical

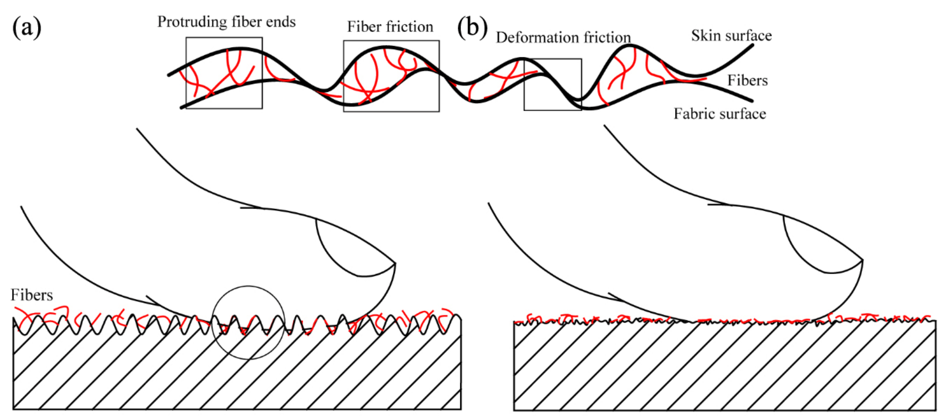

Fig. 6 Schematic diagram of finger touching: (a) rough and (b) smooth fabric surface.

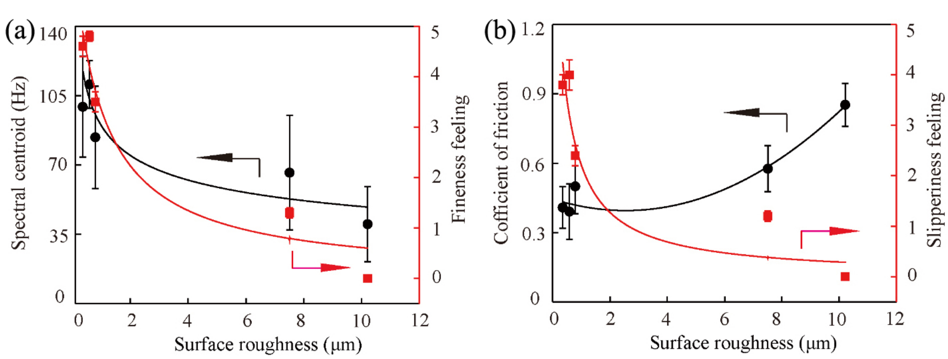

Fig. 7 Relationship between (a) SC and fineness feeling and (b) coefficient of friction and slipperiness feeling when a finger touches different surface roughness fabrics.

interlocking of asperities increased. Therefore, the increasing surface roughness led to the large deformation friction and coefficient of friction, and a low sensation of slipperiness. From #1 to #5, the space of the fabric texture increased, and the density of the fabric texture decreased as warp–weft density decreased. When fingers slide on a rough fabric surface, their vibration frequency decreases, resulting in a decreasing SC and low sensation of fineness.

The results also showed that a fine and slippery perception of fabric was in accordance with a large value of SC and a small value of μ. Significant correlations were observed between characteristic features and tactile sensation. SC was positively correlated to fineness ($r = 0.935$, $p < 0.05$), where group data show that perceived fineness increased with increasing SC. The coefficient of friction was negatively correlated to slipperiness ($r = -0.885$, $p < 0.05$), where group data show that perceived slipperiness decreased with the increasing coefficient of friction. It suggested that the characteristic features of the SC and coefficient of friction were influenced by the surface roughness, and they have a strong correlation with the perceived fineness and slipperiness of fabrics, respectively.

3.3 Characteristic features of the prickling sensation caused by fabric

The fibers presented various forms of contact with the skin surfaces that affected the tactile perception of fabric, especially the prickling feeling. When the contact between the protruding fiber ends and skin is point contact, the small contact area and large contact stress will induce a strong prickly feeling. Namely, a fabric-evoked prickly feeling is caused by protruding fiber ends, applying a force to the skin, as shown in Fig. 6.

The critical buckling forces of fiber ends are commonly recognized as an objective indicator of prickliness when human skin contacts short, and coarse fiber ends protrude from fabric surfaces. According to the stability theory of a slender rod, the critical buckling force of single fibers P_{cr} is

$$P_{cr} = \frac{\pi^3 E_f r_f^4}{C' L_f^2} \tag{7}$$

where E_f is the Young's modulus of the fiber, L_f is the length of the fiber ends protruding above the fabric surface, r_f is the radius of the cross-section of the fiber, and C' is a constant depending on the boundary conditions of fiber end. Here, the fiber end held in fabric is assumed to be fixed, and the fiber end against human skin is assumed to be hinged. A fixed-hinged end restraint was chosen as the boundary conditions of fiber end, hence $C' = 1.999$ [44].

Fiber diameter is also one of the important factors causing sensations of prickliness [45, 46]. Previous studies suggested that 30 μm [47, 48] and 0.75 mN [48, 49] were the critical fiber diameter and critical buckling force for prickle discomfort, respectively. In this study, the fabric was folded and clamped between two slides. The image of the protruding fiber was taken by the microscope. The length and diameter of the fibers were measured by the image measurement software. The average values were based on ten measurements. The critical buckling force was calculated according to Eq. (7), which is shown in Table 3. It should mention that because the measured diameter and L_f were the approximate values, the calculated critical buckling force was also the approximate values, but it can still reflect the distinction. The relationship between critical buckling force and sensation of prickliness and that between diameter of fiber and sensation of prickliness are shown in Fig. 8. The results showed that the diameter and critical buckling force were positively correlated to the prickliness with $r = 0.83$ and 0.84, respectively, where the feeling of prickliness increased with the diameter, and the critical buckling force increased. It

Table 3 Average diameters, lengths, and critical buckling forces of fibers.

Sample	#1	#2	#3	#4	#5
Diameter (μm)	19.9±3.8	23.5±7.1	31.2±6.9	61.7±24.8	122.6±72.3
Length (mm)	1.0±0.2	1.1±0.2	1.2±0.3	4.5±0.6	6.4±0.9
Critical buckling force (mN)	0.49	0.92	2.95	7.53	17.18

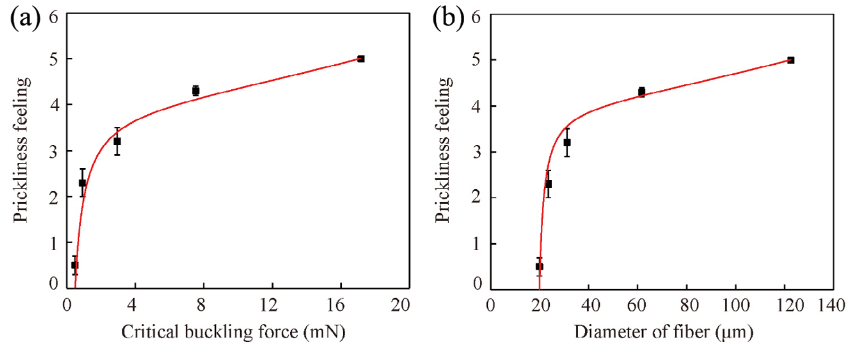

Fig. 8 Relationship between (a) critical buckling force and sensation of prickliness and that between (b) diameter of fiber and sensation of prickliness when fingers touch different fabrics.

suggested that the characteristic features of the diameter and critical buckling force of fiber have a strong correlation with the perceived prickliness.

As shown in Table 3, the critical buckling force and average diameter of sample #1 were lower than the critical values of 0.75 mN and 30 μm, respectively, which caused prickling discomfort, so sample #1 rarely caused a sensation of prickliness. As the critical buckling force and average diameter increased, the contact stress applied by the fibers increased, which induced a strong sensation of prickliness.

The mechanoreceptors in skin are the main receptors of tactile perception, and the somatosensory cortex is the cognitive region for tactile perception. It is necessary to discuss brain activity when humans feel different fabrics.

3.4 Brain activation caused by fabric

Subjective evaluation of humans can reflect the sensitivity of the brain in response to tactile sensation. Comparing the evaluation scores of the three feelings, #1 and #2 were close, and #4 and #5 were close, suggesting that the brain's response to tactile perception was similar. Therefore, #1, #3, and #5 were supposed to show more differences in brain activities and were chosen as the fMRI test samples.

Figure 9 displays the brain activation related with the tactile perception of the three fabrics. The brain activity information for each fabric is shown in Table 4. To compare the brain activity of three fabrics, the activation areas and PSCs in the main functional regions of the brain are extracted and shown in Fig. 10.

The results indicated that the anatomical locations of the postcentral *gyrus*, supramarginal *gyrus*, and precentral *gyrus*, with the corresponding functional regions of the SI, SII, MI, and MII, were mainly activated and involved in the perception of fabric. The PSC and cluster size of the SI were higher than those of other brain areas. In Wang et al.'s study [19], the significant activations in the somatosensory areas (SI and SII) and motor areas (MI, and MII) responding to cutaneous prickling stimulation were also be observed.

According to Refs. [3, 50, 51], somatosensory systems composed of SI and SII play a critical role in the texture discrimination. The SI formed by Brodmann areas (BAs) 1, 2, and 3 is crucial for the processing and encoding of the sensory inputs received through receptors located within the skin [3, 50]. Recent work has suggested that only BA3 should be referred to as SI, since it receives the bulk of the thalamocortical projections from the sensory input fields [52]. Table 4 shows that the voxels in BA3 and BA2 of SI were mainly activated, which indicated that the tactile information of the fabric texture was received by BA3, and then inputted to BA2. Since SII is part of a higher-order association center for tactile object recognition, the further tactile discrimination of fabric texture may involve SII (BA40) and SSA (BA5 and BA7) [51, 53].

Figure 10 and Table 4 also show that sample #3 stimulated the largest brain activity area, intensity (t-value in Table 4), and PSC. Sample #5 stimulated the smallest brain activity area, intensity (t-value in Table 4), and PSC. According to the fiber properties and fabric surface structures of the three fabric samples, sample #5 mainly induced a sensation of prickliness due to the largest critical buckling force and diameter of the fiber. Sample #1 mainly induced

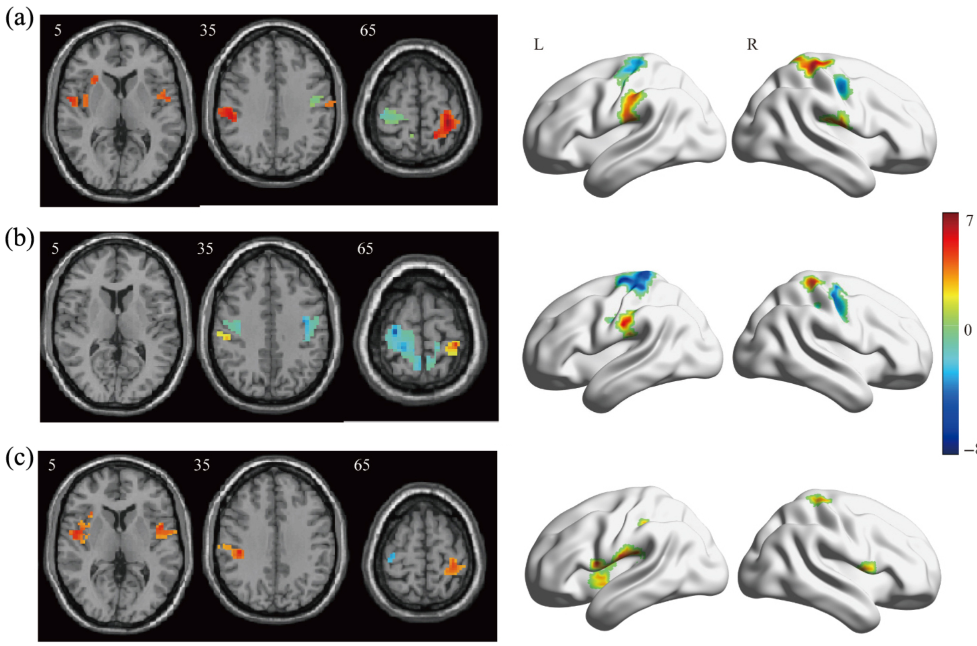

Fig. 9 Brain slice maps and three-dimensional (3D) images of the tactile stimulation of (a) #1, (b) #3, and (c) #5 fabric samples.

Table 4 Brain tactile activation information of the three fabric samples.

Sample	Anatomical region (voxel size)	Functional region: Brodmann area (BA) (voxel size)	Cluster size	Intensity *t*-value
#1	Insula_L (98); SupraMarginal_L (91); Postcentral_L (84); Rolandic_Oper_L (82); and Parietal_Inf_L (42);	SI:BA1(10)/BA2(36)/BA3(10); SII: BA40(23); and BA13(45)	468	4.94
	Postcentral_L (147); Precentral_L (117); and Paracentral_Lobule_L (49)	SI: BA3(66); MI: BA4(84); and MII: BA6(17)	334	−7.11
	Rolandic_Oper_R (135); Postcentral_R (54); and SupraMarginal_R (42)	SI:BA3(3); SII: BA40(18); and MII: BA6(15)	282	4.54
	Postcentral_R (173) and Precentral_R (54)	SI:BA1(4)/BA2(15)/BA3(33); MI: BA4(24); and SSA:BA5(24)	250	6.4
	Precentral_R (116)	MI: BA4(23) and MII:BA6(32)	142	−3.82
#3	Postcentral_L (342); Precentral_L (175); Paracentral_Lobule_L (86); and Precuneus_L (71)	SI:BA1(10)/BA2(18)/BA3(110); MI: BA4(91); MII: BA6(48); and SSA:BA5(21)/BA7(17)	723	−7.89
	Precentral_R (201) and Postcentral_R (125);	SI: BA2(11)/BA3(41); MI: BA4(43); and MII: BA6(66)	371	−6.29
	Postcentral_R (122)	SI:BA1(3)/BA2(11)/BA3(28)	124	12.26
	Postcentral_L (36); SupraMarginal_L (51); and Parietal_Inf_L (12)	SI: BA1(4)/BA2(17)/BA3(8) and MI: BA4(4)	104	6.80
	Postcentral_R (21) and Precuneus_R (27)	SI: BA3(3) and SSA: BA5(5)/BA7(8)	52	−4.33
#5	Insula_L (107); Rolandic_Oper_L (105); Postcentral_L (88); and SupraMarginal_L (54)	SI:BA2(17)/BA3(5); SII:BA40(17); and MII:A6(18)	484	5.4
	Rolandic_Oper_R (121) and Insula_R (55)	MII: BA6(13)	205	4.35
	Postcentral_R (137) and Precentral_R (11)	SI:BA1(3)/BA2(11)/BA3(31); MI: BA4(10); and SSA: BA5(14)	171	4.38
	Precentral_L (43) and Postcentral_L (20)	SI: BA3(14) and MI: BA4(17)	64	−3.4

Note: R: right hemisphere and L: left hemisphere. Postcentral: Postcentral *gyrus*; Precentral: Precentral *gyrus*; Parietal_Inf: Inferior parietal lobule; SupraMarginal: Supramarginal *gyrus*; Rolandic_Oper: Rolandic operculum; and SSA: Supplementary sensory area. The cluster-size criterion is 50, and $p < 0.05$.

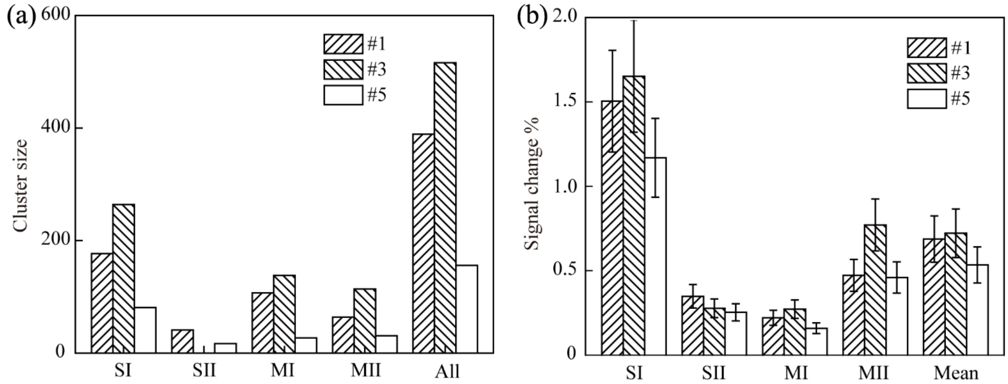

Fig. 10 (a) Activity areas and (b) PSCs of functional regions of the brain during perceiving the fabrics.

fineness and slipperiness due to the lowest surface roughness and warp–weft density of the fabric. Sample #3 had a medium critical buckling force and fiber diameter, and a medium surface roughness and warp–weft density of fabric, which induced multidimensional feeling of prickliness, fineness, and slipperiness. The results suggested that the fiber properties and fabric surface structures that caused the multidimensional feelings tended to enhance the neuronal response and corresponding sensing processing area of cerebral cortex, resulting in the large brain activation area, intensity, and PSC. More strictly, these findings require further confirmation, but aim to motivate research on significative topics.

4 Conclusions

This study systematically studied the tactile perception of fabrics based on a subjective evaluation, fiber features, surface friction and vibration, and the neurophysiological response of the brain. The conclusions are as follows.

For all fabric samples, the coefficient of friction increased with the increasing normal load, indicating that the skin deformation mechanisms are related with the friction of skin against fabrics.

A fine, prickly, and slippery perception of the fabric was in accordance with large values of SC and diameter, critical buckling force of fabrics, and a small value of the coefficient of friction, respectively. The features of SC, coefficient of friction, and diameter and critical buckling force of fibers have a strong correlation with the perceived fineness, slipperiness, and prickliness of fabrics, respectively.

The postcentral *gyrus*, supramarginal *gyrus*, and precentral *gyrus* with the corresponding functional regions of the SI, SII, MI, and MII involved in the perceptions of fabrics. The PSC and cluster size of the SI were higher than those of other brain areas. The fiber properties and fabric surface structures that caused the multidimensional feelings tended to induce the large area, intensity, and PSC of brain activity.

This study suggested that the combination of tribology, fMRI, and subjective evaluation methods is an effective means to studying the tactile perception of fabrics. SC, coefficient of friction, and critical buckling force are effective parameters to quantitatively characterize the tactile perception of fabrics.

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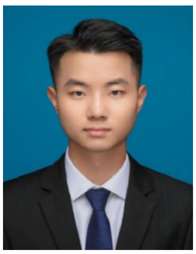

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