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# Tactile perception of fabrics with an artificial finger compared to human sensing

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**Abstract**

The assessment of fabric quality is highly dependent on the human tactile sense, which is affected by many factors. There is currently no approach to measure fabric quality directly. To build the relationship between tactile perception and fabric texture, vibration data obtained from a biomimetic sensor while scanning fabric surfaces were recorded and compared with the human judgments. Human subjective sensing experiments were performed with 20 volunteers by classifying texture into 10 grades according to three dimensions: Rough–Smooth, Coarse–Fine and Complex–Uniform. The vibrations and the coefficient of friction (COF) between the skin and fabric were measured using an artificial finger and a tribometer as the artificial finger scanned across various fabrics. Five characteristic values were extracted based on features of the fabric texture from the vibration data: peak average (PA), peak ratio (PR), spectral centroid (SC), power (P) and Shannon entropy (SE).These feature values were evaluated by comparison with those from human sensing experiments. It was found that P, SC, SE and COF could characterize the perceived Rough–Smooth, Coarse–Fine, Complex–Uniform and surface comfort, respectively.

**Keywords**

tactile perception, vibration, friction, fabrics

Surface properties cannot be sensed directly by sensory receptors in human skin: deformations and vibrations of skin induced by stimulus from fabrics evoke the sensory receptors' responses. Tactile perception of fabrics is highly dependent on the fabrics' surface properties.[1,2] Different receptors respond to different stimuli, such as mechanical and thermal stimuli. There are many mechanoreceptors: the Pacinian corpuscle, Meissner corpuscle, Merkel corpuscle, Ruffini ending, and so on.[3–7] The Pacinian corpuscle is the primary receptor that senses and codes the skin vibrations to nerve action potentials, whose sensitive frequency is 60–700 Hz.[8–10] The Meissner corpuscle is sensitive to the surface contour's structure. The Meissner corpuscle and Pacinian corpuscle are located in the dermis of the skin, as shown in Figure 1.

The Merkel corpuscle has a high spatial resolution and is sensitive to constant contact irritant on to skin. The Ruffini ending, located in the deep epidermis, can respond to tensile changes of skin caused by friction on the contact surfaces between skin and fabric. In addition, there are some other sensory receptors that respond to temperature or tickling stimuli.

The process of human tactile perception on fabric texture is shown in Figure 2(a). As the finger scans the fabric surfaces, the skin deformations and vibrations induced by friction force stimulate the sensory receptors of skin. Action potentials form while the sensory receptors respond to stimulus. Then, the potentials current carrying the surface information (which relies

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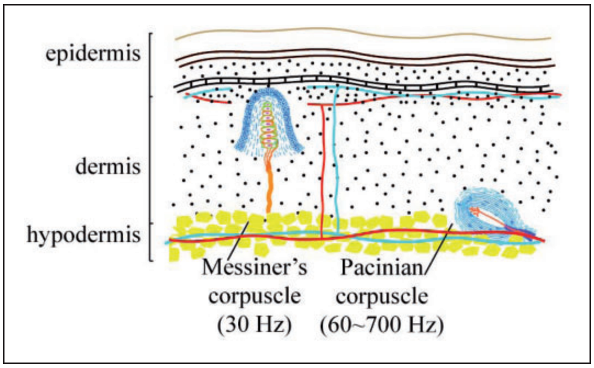

**Figure 1.** Schematics illustrating the Meissner corpuscle and Pacinian corpuscle and their sensitive frequency.

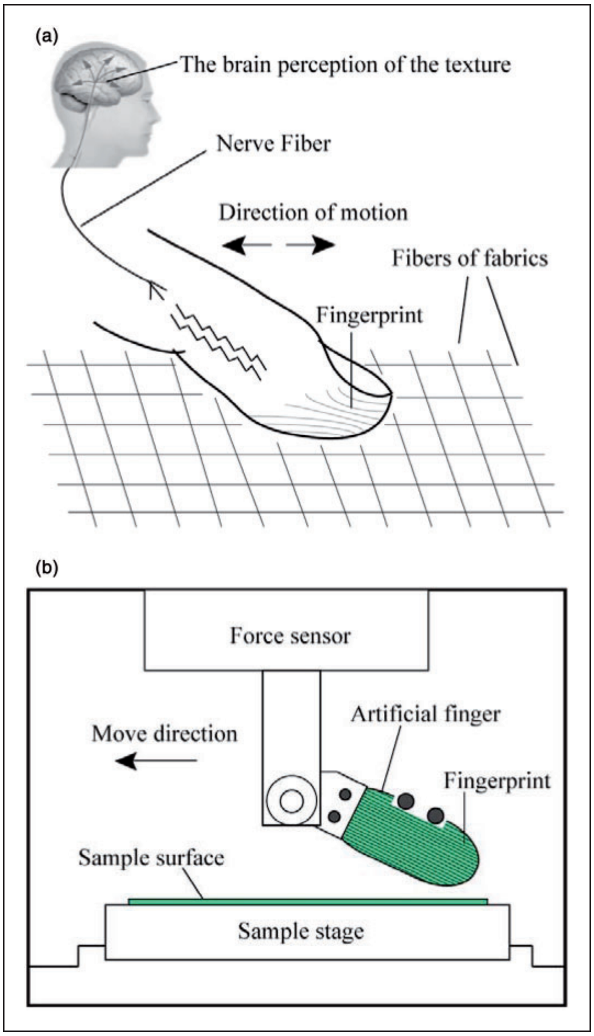

**Figure 2.** (a) Schematics illustrating the process of human tactile perception when the finger is moving on the surface of fabrics. (b) Schematics of the device with an artificial finger mounted on a tribometer to stimulate and assess the tactile perception during surface exploration.

on its direction, amplitude, lasting time, etc.) is transmitted to the sensory cortex of the brain along nerve fibers of different positions.[4,11] Johnson et al.[6] found that the induced discharge rate of receptors could indicate the characteristics of the contact surface texture based on electrophysiology experiment. Lastly, tactile perception is formed in the somatosensory cortex. Tactile sensation is related to not only the deformations and vibrations of skin, but also some other psychological factors, such as memory, personality, expectation, and so on.[12,13] Tactile sensing is integrated perception formed by receptors' responses induced by cutaneous mechanical stimulus.[14]

Previous studies on the tactile perception of fabrics focused on two methods: subjective and objective methods. The subjective evaluation is influenced by many random factors, such as personality, experiences, attention, memory, and so on.[15–19] In subjective experiments, some describing words are usually used to classify the fabrics: hard/soft, rough/smooth, fine/coarse, sticky/slippery, cold/warm, and so on.[3,17,18,20] Bolanowski et al.[3] proposed that three dimensions are enough to expound tactile sense for most objects: roughness, hardness and an uncertain dimension. Bergmann Tiest and Kappers[20] found that four dimensions are needed at least to describe objects' surfaces, as a result of observing 125 kinds of surfaces, and not all the dimensions can be connected to a special property of surface. Human sensing experiments are prohibitive in terms of time and cost, with hundreds of fabrics to examine.[21] The objective method is usually performed using some instruments to characterize and evaluate the fabrics quantitatively. The computerized image processing technique is a visual method widely applied in the textile industry by obtaining three-dimensional structure data of objects,[22–24] which always focus on the yarn spacing and fiber content of fabrics, missing plenty of useful information about surface properties only conveyed from touch, such as softness and roughness. The other objective method is usually performed by comparing object properties with the human sensing experiment to get an intelligent system assessment,[25] which is a straightforward and comprehensive method to assess fabrics. Kawabata and Niwa[26] developed a mechanical system to evaluate fabric styles. Tanaka et al.[27] proposed a PVDF (Polyvinylidene Fluoride) sensor to measure and evaluate tactile sensations, and found this sensor could describe human tactile perception very well. Kikuuwe et al.[28] presented a finger-mounted tactile sensor for extracting information on fine surface properties of objects such as textile fabrics.

In this paper, the relationship between tactile perception and surface properties is discussed. Five features are obtained from an artificial finger, together with the coefficient of friction (COF) obtained from a tribometer, which could reflect tactile perception of the fabrics. For human sensing experiments, as referred to in previous researches,[3,17,18,20] we chose Rough–Smooth and Coarse–Fine to describe tactile perception of surface texture. We also propose Complex–Uniform as the third dimension in addition to overall feeling.

Five characteristic features of tactile perception were extracted from vibration signals of an artificial finger: peak average (PA), average power (P), peak ratio (PR), spectral centroid (SC), and Shannon entropy (SE). Figure 2(b) shows the way in which the artificial finger is mounted on the tribometer. The features are extracted based on physical meanings of the surface texture. PA and P indicate the Rough–Smooth dimension; PR and SC are related to the Coarse–Fine dimension; SE represents the Complex–Uniform dimension; the COF can describe the comprehensive feel of the fabrics.

It is known that rough surfaces produce a more granule feel than smooth surfaces, which can be reflected from greater amplitudes of vibration signals, so we propose the peak average to characterize the Rough–Smooth dimension. According to Bensmaïa and Hollins,[10] P is correlated with perceived roughness. The more energy transmits, the rougher surface will be perceived.

The Coarse–Fine dimension is primarily related to the threads counts per centimeter. The Coarse–Fine dimension can also be described as the distance of sensed neighbor peaks of fabrics, so PR is proposed to represent the Coarse–Fine dimension. High PR indicates a finer fabric surface. SC is a common parameter for texture discrimination. Fishel and Loeb[18] used SC as the measurement of texture fineness over more than 100 surfaces. Higher frequency indicates that the fabric has a higher thread count, which means that a large value of SC lead to fine texture and a small value leads to relatively coarse texture.

The Complex–Uniform dimension is a comprehensive feature including a complex surface, rich details and variation of texture. It is generally known that surface properties are sensed by skin during surface exploration; in other words, the surface transmits its information containing surface properties to the skin. Thus, the Complex–Uniform is chosen to be one dimension to quantify the amount of information exchange between the skin and fabric surface. Meanwhile, SE is a feature of complexity of the surface. Large SE represents a uniformity and complex surface. Fabrics with large SE are rich in texture properties and changes, and are fluffy, elastic and easy recovery from deformations.

Surface comfort is a comprehensive feeling, which could be affected by surface texture and subjective factors. There are many studies on characterized comfort of fabrics.[21] The COF is a comprehensive and common feature used to evaluate the surface comfort, which can be obtained from tribometer data directly. The COF could be affected by structure and mechanical properties.

## Experimental details

### Sample preparation

Fabrics are commonly used for clothing in daily life. They have similar appearances and surface properties. To make the result have significant differences, 10 fabrics with relatively distinct differences were chosen as experiment samples: Parramatta, polyester, denim, leather, Lycra, linen, viscose, gauze, oxford and silk. Fiber composition, yarn counts, thread count, and surface density of the 10 fabrics are shown in Table 1.

**Table 1.** Composition, yarn count, warp-weft density and surface density of fabric samples

| Number | Name | Composition | Yarn counts (tex) | Warp-weft density (/10 cm) | Surface density (g/m$^2$) |
|---|---|---|---|---|---|
| 1 | Parramatta | 80% Cotton 20% Wool | 44.9 | 30 × 30 | 360 |
| 2 | Polyester | Polyester | 18.5 | 108 × 58 | 140 |
| 3 | Denim | Cotton | 72.9 | 103 × 54 | 340 |
| 4 | Leather | Lambskin | – | – | 400 |
| 5 | Lycra | 90% Cotton 10% Spandex | 18.2 | 96 × 75 | 180 |
| 6 | Linen | Linen | 27.8 | 58 × 72 | 160 |
| 7 | Viscose | Bamboo fiber | 14.8 | 140 × 96 | 112 |
| 8 | Gauze | Cotton | 14.6 | 65 × 52 | 62 |
| 9 | Oxford | Cotton | 14.6 | 153 × 80 | 126 |
| 10 | Silk | Silk | 9.7 | 317 × 127 | 95 |

For vibration and friction measurements, fabrics were cut into 50 mm × 50 mm samples and were attached to sample pucks with rapidly drying glue to ensure the fabrics had no wrinkles and good dimension stability. Then the samples were leveled for 30 minutes under ambient condition (22°C, relative humidity (RH) 40–55%).

### Human subjective sensing experiments

Human subjective sensing experiments were performed first and independently from the other experiments of this study. It is not necessary to have real human in vivo fingers move in the same way as the artificial finger during the vibration measurements.

Twenty volunteers, aged from 20 to 40, washed their hands first and then relaxed in the experiment room at 25°C and 50% RH, freely reading. In the other experiment room, where experiments were performed one person at a time, fabric samples were put into 10 covered boxes with one side open to prevent the participants from seeing the fabrics. The boxes were placed randomly but at fixed positions. The 20 volunteers scored each of the 10 fabrics between 1 and 10 according to the three dimensions (i.e., Rough–Smooth, Coarse–Fine and Complex–Uniform) using their index fingers to scan the fabric surfaces along the warp direction. Higher scores indicated smooth, fine and uniform fabrics. For each sample, no frequency of touch was required but a time limit of 3 minutes was imposed. No limits on the normal load and velocity were imposed: these values were allowed to depend on the comfort of each individual volunteer. Before formal experimentation began, pretests were performed on several uncovered fabric samples to improve the reliability and validity of the experiments. The final scores of each dimension are shown as the average of the scores given by all 20 volunteers for one sample in the formal experiments.

Surface comfort is a comprehensive feeling of the fabric. It was also scored by the volunteers with the same protocol as the other three dimensions. Fabrics with high surface comfort achieve high scores.

### Vibration and friction measurements

As shown in Figure 2(b), vibration and friction measurements were performed with a commercial artificial finger (BioTac, SynTouch LLC, Los Angeles, CA) mounted on a tribometer (UMT-2, Center for Tribology Inc., Campbell, CA) at the angle of 30 degrees from the horizontal. The artificial finger was controlled by the tribometer to scan fabric samples along their warp direction at the constant speed of 10 mm/s over a scanning distance of 30 mm. The experiments were repeated five times for each fabric. Vibration signals were obtained from the artificial finger and frictional parameters were obtained from the tribometer. Before formal experimentation began, the influence of the normal load during surface exploration was studied for more than 50 types of materials using the normal load between 0.5 and 2 N.[29] These tests showed that the characteristic features changed little with the increased normal load due to large deformations between the biomimetic sensor and the samples. Behmann[30] found that higher force used by the fingers touching the surface yielded higher perceived roughness. Considering the conditions of the experiment devices, the regular exploration normal load of 1.5 N was chosen as optimal in accordance with the literatures.[1,31]

### Vibration signal processing and feature selection

Vibration signals from the artificial finger were first filtered. The noise from the tester and environment that influenced the vibration signals were removed from the original signal. A typical signal de-noising process is shown in Figure 3. Firstly, the no-load signal, which was the vibration signal collected by the artificial finger in the condition of no-load, was separated from the original signal. Then, the other noises (e.g., from the tester and the environment) were filtered out. Lastly, the final signals were filtered with a band pass filter ranging from 20 to 700 Hz to simulate the frequency response of the Pacinian corpuscles, which are thought to mediate tactile perception and eliminate low frequency oscillations from contributing to this estimate.[18]

Then, five characteristic features were extracted based on features of the fabric textures from vibration signals using a MATLAB program: PA, P, PR, SC and SE. Together with the COF obtained from the tribometer, six features were classified into four categories of tactile perception: Rough–Smooth, Coarse–Fine, Complex–Uniform and comprehensive feelings. There are also some other characteristic features that could be extracted from the vibration signals. Tang et al.[29] used six characteristics from the artificial finger that showed better results on surface explorations.

The definition and the equation of the features are discussed based on the schematic diagram of the vibration curve, as shown in Figure 3(e).

1. PA

   PA is calculated as the average of all absolute values of the peak vibration signals:

$$PA = \frac{1}{n} \cdot \sum_{i=1}^{n} y_{\max\ i} \tag{1}$$

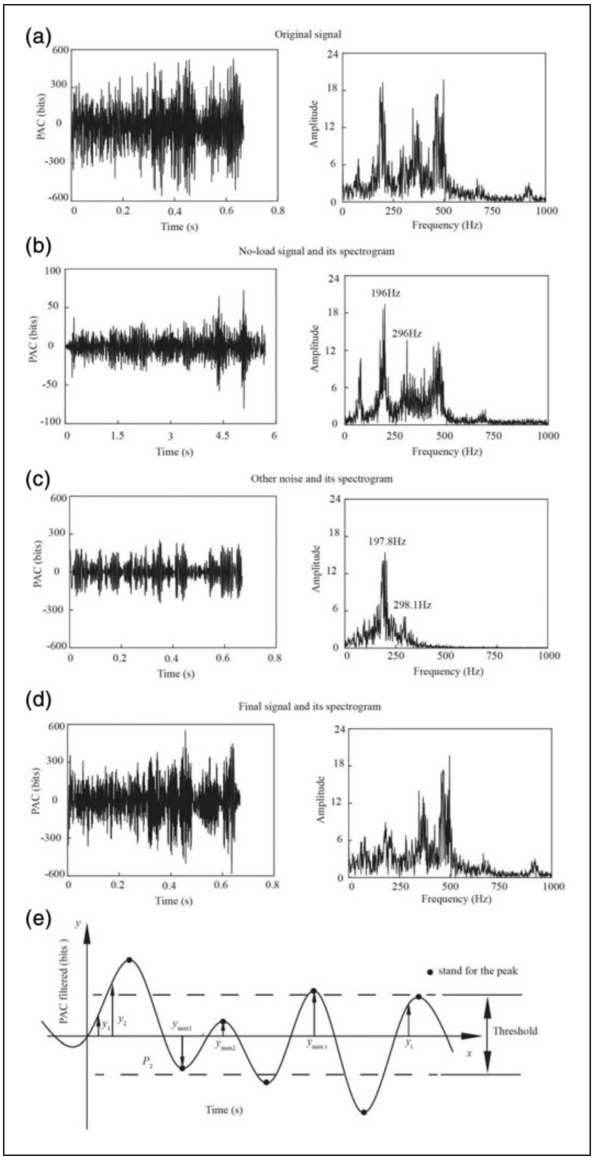

**Figure 3.** Typical signals during an exploratory movement: (a) original signal and its spectrogram (PAC is the dynamic fluid pressure of the artificial finger); (b) no-load signal and its spectrogram; (c) other noise and its spectrogram; (d) final signal and its spectrogram; (e) schematic diagram of the vibration curve.

where $y_{\max\ i}$ are the peak vibration signals and $n$ is the number of $x_{\max}$ values.

2. P

   The average power of the vibration can describe the transmitted energy between two surfaces. P is given by the following equation:

$$P = \frac{1}{n} \cdot \sum_{i=1}^{n} (y_i)^2 \tag{2}$$

   where $y_i$ is the voltage amplitude of the vibration signals and $N$ is the number of all vibration signals.

3. PR

   The fraction of the highest peaks is expressed in the following equation:

$$PR = \frac{n_a}{N} \tag{3}$$

   where $n_a$ is the number of large peaks beyond the threshold, which is set at 2100 bits based on observing the vibration signals, and $N$ is the number of all peak vibration signals.

4. SC

   Spatial periodicity is a common parameter for texture discrimination.[32–35] However, it is found that the spectral centroid, as proposed by Fishel and Loeb,[18] is better at describing texture density of fabrics than the spatial periodicity, because spatial periodicity is no longer linear for some finer textures and higher velocities. SC is closely related to the vibrational frequency while touching the surface.[18] SC is calculated from the vibration signals according to the following equation:

$$SC = \frac{\sum_i \left( fft(y_i)^2 \cdot f_i \right)}{\sum_i fft(y_i)^2} \tag{4}$$

   where $f_i$ is the frequency, $y_i$ is the voltage amplitude of the vibration signals, $fft(y_i)$ indicates that the signal is analyzed based on the Fourier transform and $i$ is the index of the point of $fft$.

5. SE

   The entropy is a measure of complexity of the surface. Wavelet entropy is a good characteristic of the vibration signals, due to the combination of wavelet transform and the advantage of the information entropy theory. SE is a feature of complexity and level of chaos for surfaces. Firstly, vibration signals are decomposed into wavelet packet coefficients ($e_i$); the next step is to analyze and process the coefficients as follows:

$$S_i = |e_i|^l \Big/ \sum_i |e_i|^l, l \geq 1 \tag{5}$$

$$SE = -\sum_i \left( s_i^2 \cdot \log\left(s_i^2\right) \right) \tag{6}$$

## Results

### *Results of human evaluations*

Table 2 summarizes the results of the human evaluating experiment for the 10 fabrics. The 10 fabrics were numbered according to their surface comfort scores. For fabrics, surface comfort is significantly related to surface texture. Silk is the smoothest, finest and simplest fabric based on the scores; Parramatta is its opposite.

**Table 2.** Scores and standard deviation of Rough–Smooth, Coarse–Fine, Complex–Uniform dimensions and surface comfort of the fabric samples

| Number | Name | Rough–Smooth | Coarse–Fine | Complex–Simple | Surface comfort |
|---|---|---|---|---|---|
| 1 | Parramatta | 2.0 ± 1.8 | 1.5 ± 1.3 | 2.0 ± 1.1 | 1.5 ± 0.7 |
| 2 | Polyester | 9.3 ± 0.8 | 6.6 ± 1.3 | 3.5 ± 1.3 | 2.5 ± 1.0 |
| 3 | Denim | 1.2 ± 1.0 | 5.2 ± 0.4 | 3.2 ± 1.1 | 3.7 ± 0.9 |
| 4 | Leather | 5.9 ± 0.9 | 9.5 ± 1.0 | 6.0 ± 0.8 | 4.3 ± 0.8 |
| 5 | Lycra | 4.3 ± 0.9 | 4.9 ± 2.0 | 5.1 ± 0.5 | 5.3 ± 0.7 |
| 6 | Linen | 2.7 ± 1.0 | 3.5 ± 1.3 | 1.7 ± 0.8 | 6.2 ± 0.8 |
| 7 | Viscose | 7.1 ± 0.6 | 7.3 ± 0.7 | 8.2 ± 1.0 | 7.3 ± 1.6 |
| 8 | Gauze | 5.1 ± 0.6 | 2.6 ± 1.6 | 6.8 ± 1.2 | 7.9 ± 0.9 |
| 9 | Oxford | 3.7 ± 1.6 | 8.1 ± 0.3 | 7.7 ± 0.9 | 8.7 ± 0.8 |
| 10 | Silk | 8.4 ± 0.8 | 9.2 ± 0.4 | 9.4 ± 0.5 | 9.7 ± 0.5 |

Some fabrics have high Rough–Smooth and Coarse–Fine dimensions but a low Complex–Simple dimension, resulting in a lower surface comfort, such as polyester. Oxford shows a low Rough–Smooth dimension, but the scores of the Coarse–Fine and Complex–Simple dimension are relatively high, leading to high scores of surface comfort. Gauze has a low Coarse–Fine dimension, but still has high surface comfort. For linen, the scores of the three dimensions are not very high but it has comfortable hand feel.

## *Results of the relationship between the characteristic features and human tactile perception*

As discussed in the *Vibration signal processing and feature selection* section, five features in addition to the COF were extracted to compare with the results of the human sensing experiments.

*Rough–Smooth dimension.* From the $x$-axis of Figure 4, it is shown that the standard deviations of the Rough–Smooth dimension are large when the scores are beyond 5. PA does not show a significant trend along with the changes of the Rough–Smooth dimension, as shown in Figure 4(a). The values of P, which quantify the surface's comprehensive perceived roughness, are shown for every fabric in Figure 4(b). The results show that P decreases with increasing Rough–Smooth dimension.

*Coarse–Fine dimension.* It is shown in Figure 5 that standard deviations are very high for the Coarse–Fine dimension of every fabric. However, considering the relative differences, silk, oxford and denim still have the highest Coarse–Fine dimension.

The trend of PR values in Figure 5(a) is not a monotonic curve versus the scores of the Coarse–Fine dimension, which is the same as that of PA. It is shown from Figure 5(b) that SC increases as the Coarse–Fine dimension increases. Silk and viscose have large values of SC. For denim, the Coarse–Fine dimension is around 5, but the SC value is small.

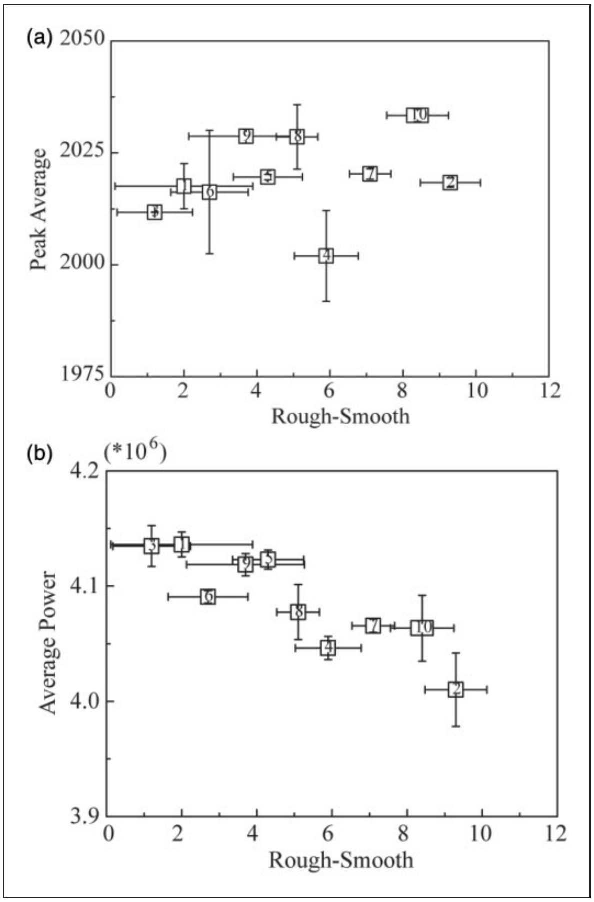

**Figure 4.** The variation of (a) peak average and (b) power versus the Rough–Smooth dimension for the 10 fabrics.

*Complex–Uniform dimension.* As shown in Figure 6, the scores of the Complex–Uniform dimension have large

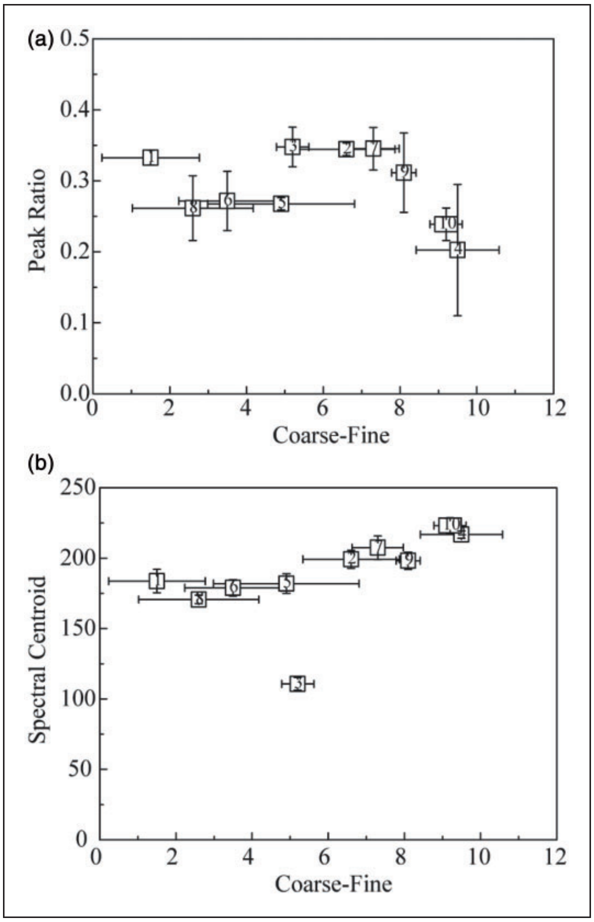

**Figure 5.** The variation of (a) peak ratio and (b) spectral centroid versus the Coarse–Fine dimension for the 10 fabrics.

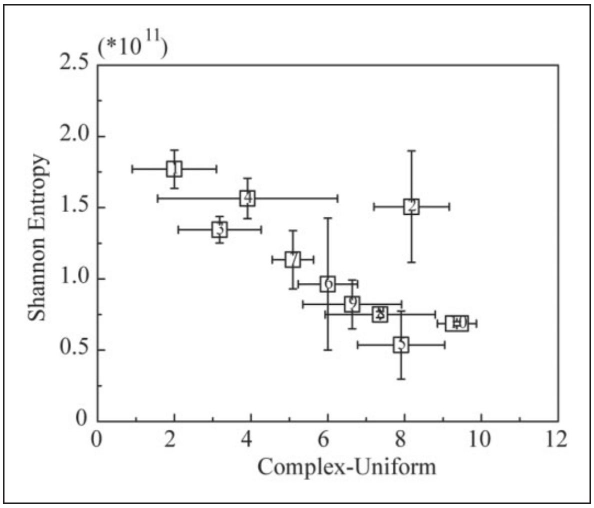

**Figure 6.** The variation of Shannon entropy versus the Complex–Uniform dimension for the 10 fabrics.

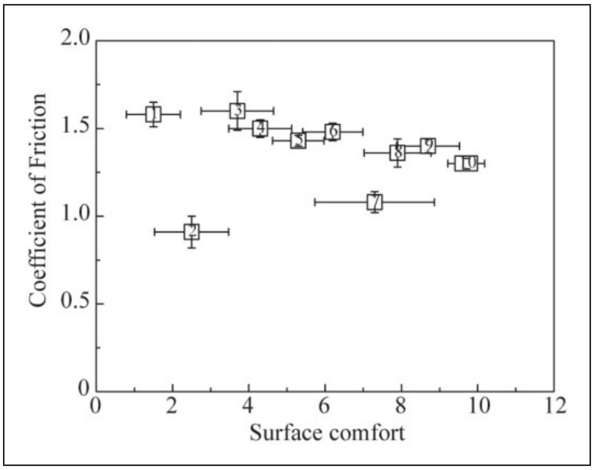

**Figure 7.** The variation of coefficient of friction versus surface comfort for the 10 fabrics.

standard deviations, particularly with regard to polyester. SE is shown to decrease as the Complex–Uniform dimension increases.

*Comprehensive feelings and the coefficient of friction.* As shown in Figure 7, the COF shows a slight decrease along with increasing surface comfort except for polyester, which indicates that fabrics with a lower COF generally produce more comfortable feelings. The COF of most fabrics is above 1.0. When the COF is below 1.0 or above 1.5, the surface comfort is lower, as in polyester and denim. When the COF is approximately 1.3, the fabric's surface comfort is maximum, such as with silk and oxford.

## Discussion

### Relationship between the human tactile sense and the surface texture properties of fabrics

Comparing Table 1 with Table 2, it is shown that human tactile senses on the fabric surface are significantly related to the surface texture properties. Usually, fabrics with high thread counts and low yarn counts (in tex) usually have high scores of Coarse–Fine, Rough–Smooth and surface comfort. Oxford cloth and silk are the most comfortable fabrics because they are smooth, fine and uniform; conversely, denim does not feel as good as the other fibers due to its relatively rough, coarse and hard surface. The hand feels of oxford, gauze and denim differ, although they are all made of cotton; this is caused by different thread counts and area densities. Thus, tactile perception of fabrics is due to their surface properties and compositions.

### Relationship between characteristic features and human tactile perception

Figure 8(a) schematically shows the process of the artificial finger scan on the fabric surface. Kim et al.[36]

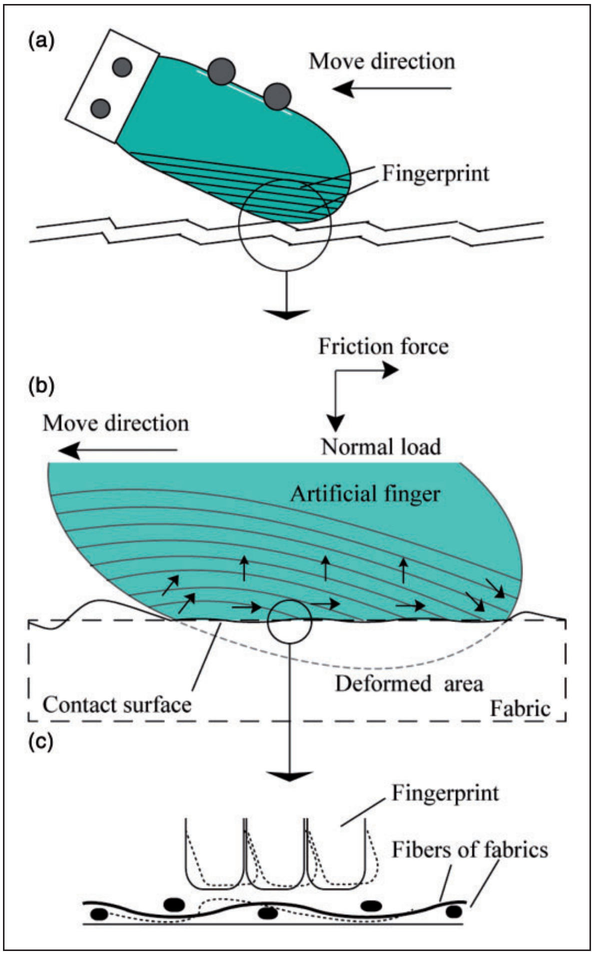

**Figure 8.** (a) Schematics illustrating the artificial finger scanning the fabrics. (b) The interaction between the artificial finger and the fabrics on the contact surface. (c) The actions of a fingerprint when an artificial finger scans the fabrics.

found that the rough feeling on a hard texture is related to asperities. For viscoelastic materials, asperities also play an important role in describing roughness. The shape, size and number of asperities are all significant when an artificial finger slides on fabrics. Deformation between the fibers and the artificial finger constitutes a complex mechanical behavior.[37] The possible contact surfaces are shown in Figure 8(b). Figure 8(c) shows the actions of a fingerprint during surface exploration. Fingerprints can increase the sensitivity of the artificial finger.[38] Force sensors in the artificial finger are triggered to measure the forces against the artificial finger,[18,39,40] just like mechanical sensory receptors in human skin that code stimuli from the environment.[30] Fishel and Loeb[39] used the biomimetic sensor to measure surface textures and found that the data from the biomimetic sensor is correlated well with human descriptions. Besides, the sensitivity of the artificial finger to detecting the fabric surface differences needs further study, since it is valuable for development of the artificial finger.

*Rough–Smooth dimension.* The feelings of Rough–Smooth are primarily affected by surface texture, mechanical properties and the applied normal load.[41–43] For smooth fabrics, human senses are relatively consistent. For rougher fabrics, people seem to have different viewpoints because the standard vibrations are large. Thus, it is shown that people have different tolerances of the Rough–Smooth dimension. This is because the volunteers have different personalities, experience, and so on. The artificial finger is more objective than human feelings.

PA is shown to be related to fabric textures, particularly the yarn count and thread counts. However, PA does not show a significant trend along with changes in the Rough–Smooth dimension. A possible explanation is that the artificial finger and fabrics are viscoelastic. As shown in Figure 8(b), the deformed area is large, and the contact surfaces are near each other; thus, the peak vibrations are blurred and weakened. PA is thus not suitable to quantify the hand feel of fabrics. Leather has a small PA value because its softness also affects PA values. Leather has a large surface density, making it thick and soft. There are a few apparent peaks on vibration signals that lead to small PA values.

P can reflect the human sensing of the Rough–Smooth dimension because of the significant trend shown. Larger P seems to produce rougher hand feel, because the mean vibration energy induces stronger stimulus to sensory receptors, resulting in rougher feelings.

*Coarse–Fine dimension.* The Rough–Smooth dimension above describes the feeling of roughness primarily in the vertical direction. The Coarse–Fine dimension is a horizontal measurement of tactile perception on the surface. Silk and oxford have low coarseness due to their large yarn counts and warp-weft density. Denim is shown to be coarse, likely because of its clear threads and salient textures.

PR is not an easy feature for the human tactile sense to evaluate. Different results also occurred in the literature.[18] That study noted that the biomimetic sensor could match human sensing based on the extraction of peaks because they used small forces (e.g., 0.2 and 0.5 N) to load the biomimetic sensor, whereas the normal load in this study was 1.5 N. Thus, the peak vibration signals are not clear due to the large contact area and elastic contact surfaces. Texture information is easily ignored as the artificial finger scans a fabric surface.

Larger SC indicates a finer texture due to higher thread and lower yarn counts; as a result, silk and viscose provide fine hand feel. For denim, the Coarse–Fine dimension is approximately 5, and thus, denim has fine hand. However, the SC of denim is small due to its small warp-weft density. SC is thus a good feature value that connects physical properties to human feeling.

*Complex–Uniform dimension.* Fabrics with uniform texture have small values of SE; these fabrics include silk and oxford. With these fabrics, there is less perceived texture information on the surface, leading to a smaller value of SE. For polyester and viscose, surface textural details are common but do not produce large values of SE due to imperceptible changes in the surface. SE can thus be used as a feature to evaluate the Complex–Uniform dimension of fabrics.

*Comprehensive feelings – coefficient of friction.* Friction is regarded to be a parameter that reflects the surface properties of fabrics in many studies. Konyo et al.[44] described the relationship between surface properties and friction vibration by studying the force–distance curve when skin was in contact with the fabric surface. Friction is related to not only surface roughness,[18,45] but also surface adhesion and softness. According to Table 2 and Figure 2(b), soft fabrics also have larger deformations between the artificial finger and fabrics, leading to larger friction force and COF. The COF is similar for all 10 fabrics due to similar surface properties and the same experimental environment. For fine fabrics, increasing the energy used to move the artificial finger against the fabric resistance (i.e., friction) increases the COF.

The COF of most fabrics is above 1.0 because the artificial finger and fabrics are both viscoelasticity materials; deformation and the adhesion between the surfaces will result in a high COF. Denim's COF is above those of other fabrics, indicating rough and coarse surface textures that lead to low comfort. For polyester, the COF is less than 1.0; thus, its hand feeling is the worst of the fabrics investigated. In addition, the influence of softness for polyester on friction signals is small due to its thin surface and hard sample puck. The softer fabrics have more comfortable feelings and typically larger deformations between the artificial finger and fabrics, leading to larger friction force and COF. When the COF is approximately 1.3, the fabric's surface comfort is maximum. The results show that the fabric's surface comfort is normally correlated to the COF. Thus, the surface comfort could be described by the COF.

## Conclusions

In this study, the characteristic features from vibration and friction signals are proposed to quantify the tactile perception associated with subjective human evaluation.

Three dimensions could describe the tactile perception of fabrics: Rough–Smooth, Coarse–Fine and Complex–Uniform. All of the results for the human sensing experiments have large standard deviations due to different tolerances of the participants' subjective sense.

PA, P, PR, SC, SE and the COF are discussed with regard to whether they can be used to quantify Rough–Smooth, Coarse–Fine, Complex–Uniform and comprehensive features of fabric. PA and PR do not match well with the Rough–Smooth and Coarse–Fine dimensions, respectively. P can describe the Rough–Smooth dimension; SC seems to describe the Coarse–Fine dimension accurately; SE shows an inverse trend along with increasing Complex–Uniform dimension. The COF is a comprehensive feature that can describe the surface comfort of the fabrics. When the COF is approximately 1.3, the fabric will provide the maximum surface comfort. P, SC, SE and COF are considered to be good features to characterize the tactile perception of Rough–Smooth, Coarse–Fine, Complex–Uniform and surface comfort.

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