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A Review on Fabric Smoothness-roughness Sensation Studies

Xiao Liao, Junyan Hu, Yi Li*, Quanhai Li, Xinxing Wu

The Hong Kong Polytechnic University, Hong Kong

Abstract

This paper aims to review the latest researches on smoothness-roughness sensation of fabric, which is considered as one of the important factors that affect clothing comfort. To begin with, the definition of clothing comfort and position of smoothness-roughness sensation within clothing comfort were classified. Further the physical and neurophysiological understanding of sensation with research gap was reviewed. Lastly sensation evaluation methods were reviewed for further development of new instruments. This papers aims to be a reference in future for related studies.

Keywords: Fabric Smoothness; Fabric Roughness; Neurophysiological Sensation Study; Review; Evaluation Methods

1 Introduction

Fabric smoothness-roughness has been considered as one of the most important factors of clothing comfort [1-10]. It is also a significant factor in today's consumer buying decision [11].

This paper reviewed over 60 related researches from 1930 until 2010. These researches can be divided into several categories. The following Fig. 1 indicates different categories of smoothness-roughness sensation studies and the relationship between them.

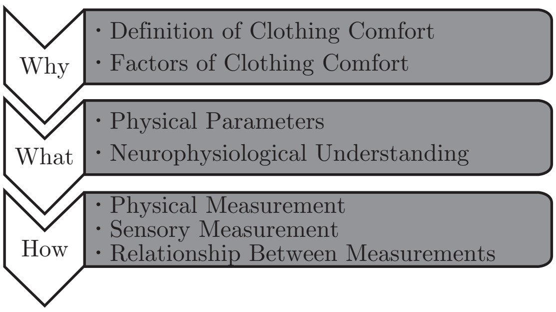

Fig. 1: Framework of smoothness-roughness sensation studies.

*Corresponding author.
Email address: tcliyi@polyu.edu.hk (Yi Li).

Revision in this paper started from the basic concept of clothing comfort. Reasons for studying fabric smoothness-roughness sensation can be found from definition and factors of clothing comfort. Researches from the second category studied physical and neurophysiological definition of smoothness-roughness sensation in order to classify the qualitative identifications. The last categories of researches include physical and sensory evaluation, psychological explanations and neurophysiological understanding. These studies performed quantitative analysis of smoothness-roughness sensation and designed varieties of instruments used for sensation evaluation.

This review paper aims to systematically summarize the previous fabric smoothness-roughness sensation studies and clears the existing research gaps identified so far. It can also be used as a reference for future research.

2 Definition of Clothing Comfort

Clothing comfort is attracting consumers' attention nowadays. Research shows that comfort is already the most important factor for consumers in Australia, Asia and Europe in 2002 [11].

Clothing comfort was first described as a kind of consumers' perception by Peirce in 1930: The comfort perception is generated when consumer wear clothing. And such perception depends on multiple factors such as time, place, season, fashion and personal preferences." [12]. However Peirce's definition excluded factors related to physical properties of clothing. Relatively in 1975, LaMotte described that clothing comfort was greatly influenced by the tactile and thermal sensation arising from the contact between skin and the immediate environment [13].

To combine physical definition and previous consumers' perception definition, Kawabata made a new evaluation method that contains both mechanical interactions and material's intended end use to describe fabrics' comfort level. And this system (KES-F) is still widely used in today's hand feeling evaluation of clothing [14].

Later on, Slater and Li summed up to give a more clear definition of fabric comfort, which is "Comfort is affected by multiple interactions with the surrounding environment including physical, psychological and physiological factors." [15, 16]. This concept has been further developed as comfort generated when clothing interacts with the skin on the body dynamically and continuously while wearing. It was affected by interaction of thermal ventilation construction and assessment factors [17].

As Li summarized, perception of clothing comfort includes physical, psychological and physiological factors [15]. Within these three sensation levels, Li and Wong described the mechanisms of clothing comfort perception in four stages: Physical processes; Physiological process; Neurophysiological process; and Psychological process [17].

3 Factors of Clothing Comfort

In the first level – physical process, where consumers "feel" the fabric properties, researchers managed to specify these physical properties into different categories in order to obtain better understanding and investigation. Howorth and Oliver distinguished the physical properties to 7 categories in their research from 1958 to 1964 as smoothness, softness, coarseness, thickness, weight, warmth and stiffness [6, 7].

Hollies enriched this list and obtained a list of sensory descriptors as follows: snug, loose, heavy, lightweight, stiff, sticky, non-absorbent, cold, clammy, damp, clingy, picky, rough and scratchy in his research from 1965 to 1979 [2-5]. The number of sensory descriptors in this list increased and in 1998 Li studied up to 26 sensory descriptors [9]. Li further summed up those descriptors and condensed them into 19 descriptors in three categories: Thermal-Wet: Damp, Clammy, Hot, Sticky, and Cold; Pressure: Stiff, Snug, Loose, Soft, and Smooth; and Tactile: Itch, Scratch, Prickle, and Rough [8, 10]. Thermal and wet sensation was also studied by Bakers in 2002, which includes a form of physical activity that induces sweating and heating of the body [1].

From the above researches [1-10], smoothness-roughness sensation was always listed as a parameter for describing clothing comfort. The studies about fabric smoothness-roughness sensation are closely related in developing a better clothing comfort feeling in the future.

4 Definition of Smoothness-roughness Sensation

4.1 Physical Factors

To better understand smoothness-roughness sensation, Ekman's research found that smoothness-roughness sensation has a power function related to the surface's friction coefficient [18]. Later Li also found relationship to surface roughness, compression, fiber diameter and fiber and fabric tensile properties [8]. In the definition of Kawabata's fabric handle properties evaluation system, a factor named “Numeri” (Smoothness) is related to bending, surface (friction and roughness) and compression properties [14]. Recent research by Bishop concluded that roughness is associated with friction, shear, bending stiffness, and thickness [19]. Chen represented the strength and form of the sensation and physical properties using the regression model through 37 different materials and four physical measurements [20]. Conclusion of these studies stated that smoothness-roughness sensation was related to surface's friction coefficient and roughness. Fig. 2 shows a summary of these related properties.

Previous studies reached a common result that measurements on fabric surface's friction coef-

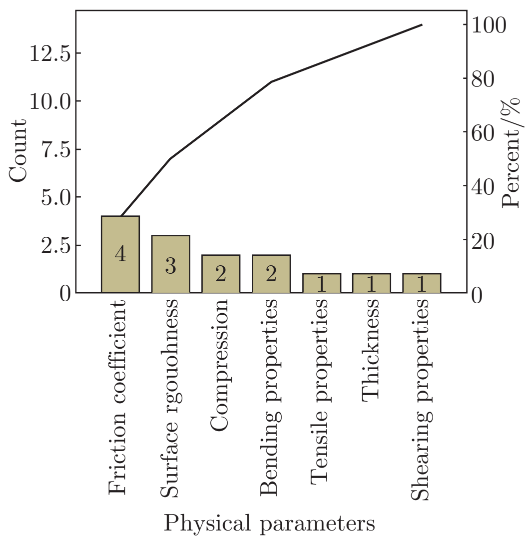

Fig. 2: Physical parameters related to smoothness-roughness sensation

ficient and roughness are better physical parameters that can be used to evaluate smoothness-roughness sensation.

4.2 Neurophysiological Understanding

There are many ways to distinguish human skin receptors (nerve endings). One of them is to distinguish corpuscular endings and non-corpuscular endings. Referring to Coren's research in 1989 [21], corpuscular nerve endings are responsive to touch stimuli. The others are associated with cold fibers or pain fibers.

Iggo in another way distinguished sensory receptors by their functions [22]. Table 1 summaries two distinguish methods about human skin receptors. Major sensory receptors include:

– Mechanoreceptors: Mechanical contact with external objects;

– Thermoreceptors: Temperature changes due to heat flow to or from the body surface;

– Nociceptors: Damaging traumatic and chemical insults.

Table 1: Category of Human Skin Receptors (Nerve Endings)

Method	Categories	Description
Structure	Corpuscular Endings	Responsive to touch stimuli
	Non-corpuscular Endings	Associated with cold fibers or pain fibers
Functions	Mechanoreceptors	Mechanical contact with external objects
	Thermoreceptors	Temperature changes due to heat flow to or from the body surface
	Nociceptors	Damaging traumatic and chemical insults

As a result, researches related to smoothness-roughness sensation focused on studies of corpuscular endings or mechanoreceptors.

Lederman in 1972 found two factors relevant to touchiness [23]:

1. Spacing between neighboring ridges;
2. Applied force only related to coetaneous mechanoreceptors.

Later in 1980, Darian found two factors as follows [24]:

1. The spatial period of a stimulus cannot be related to the firing rate of individual mechanoreceptors.
2. Each type of mechanoreceptor has a particular sensitive range of temporal frequency.

Goodwin did a lot of research from 1987 to 1989 and found three factors as follows [25-27]:

1. The response rate of all mechanoreceptors increased with the increase in groove width from 0.18-2.0 mm

2. Small increase in ridge response rate with increasing ridge width;

3. The response rate decreased with increased velocity

To explore the neural coding mechanisms of smoothness-roughness sensation, combined psychophysical and neurophysiological studies had tested many different hypotheses of the neural basis of smoothness-roughness sensation. They used same textured surfaces in their experiments and the hypotheses were rejected only when no consistent relationship with human subjective judgments was shown. Within these studies, Connor and Blake rejected neural codes based on Pacinian (PC) and cutaneous Rapidly Adapting (RA) afferent responses [28, 29] Connor also rejected temporal codes [21, 30]. Three studies did agree on one hypothesis of neural code – mean impulse rate of a population of central neurons that computes the spatial variation in slowly adapting type 1 (SA1) firing rates. Such neurons were also proved by DiCarlo in primary somatosensory (SI) cortex [31]. The limitation of this hypothesis is that it was only proved when element spacing of stimuli are 1 mm or more [32]. As shown in Table 2, many studies have been perform to test these hypothesis.

Table 2: Neural Coding Mechanisms

Hypothesis	**Status**	**Remarks**
SA1	Agreed [28-31]	when element spacing of stimuli are 1 mm or large
RA	Rejected [28]	no consistent relationship
Pacinian Receptors	Rejected [29]	no consistent relationship
Temporal Codes	Rejected [30]	no consistent relationship

To improve the limitation of this hypothesis, Yoshioka performed psychophysical and neurophysiological experiments and concluded a neural mechanism that can both account for the smoothness-roughness perception of fine and coarse surfaces [32]. This mechanism measures the difference in firing rates between SA1 afferent fibers with receptive field centers separated by 2–3 mm. Yet now the remaining questions are the cortical mechanisms that still need to be explained after the consistency test.

5 Measurement of Smoothness-roughness Sensation

From previous reviews on factors of smoothness-roughness sensation, friction is one of the most important physical parameters related to smoothness-roughness sensation. Baussan in 2010 developed a two-phase fabric friction physical model as follows: Phase 1: yarns rotate from initial to final angle (without sliding); Phase 2: sliding of probe along yarns in final direction [33]. Yarns are divided into two groups: under probe and in front of probe. Total friction force is assumed to be the sum of that of individual yarns.

This model solved the issue that usual solid surface friction models are not suitable for textiles as no attritions occurs during skin-fabric touching. However, Baussan's model ignored the effect of adhesion in this specified research [33]. A fabric friction model including both deformation and adhesion still needs to be developed when writing this review paper.

5.1 Physical Evaluation

Though a single measurement or characterization of roughness remains elusive [34], most commonly used smoothness sensation test instruments are part of total hand feeling sensation equipments, including Kawabata Evaluation System (KES-F) and Ring Method. Hu stated that current hand sensory test methods have limitations including lack of appropriate objective measurement methods to evaluate fabric comfort properties in many areas [35].

5.1.1 KES-F

In this instrument, the sample is pulled tight by applying a tension load of 20 gf/cm and a detector of 10 parallel piano wires is pressed against the fabric with a force of 50 gf (1 piano wire with 10 gf when measuring roughness). Output includes coefficient of friction, geometric roughness, and standard deviation of friction coefficient [36].

5.1.2 Ring Method

In this method, the sample fabric is pulled through a flexible light funnel. The funnel is believed to be a better medium for simulation of drop ability, stretching, internal sample compression, lateral pressure and surface friction. The force is measured as a function of time and the curve generated is called hand profile, with four zones that simulate the measurement of different properties [37, 38].

5.1.3 Optical Method

Optical method is also widely used in measurement of fabric surface properties, i.e. roughness. Kang did a series of researches [39-41] from 2000 to 2005 using optical method to evaluate fabric surface smoothness. Following AATCC Test Method 124, which evaluates fabric smoothness by visual assessment using standard replica [42], Kang developed new grading methods based on 3D vision and the fractal dimension [39-41]. Xin recently used silhouette image analysis on textile surface roughness as well [43]. Following is a table to summary the physical evaluation methods of fabric smoothness-roughness sensation.

Table 3: Physical Evaluation Methods

Evaluation Methods	Typical Example	Test Time	Physical Index
Physical	KES-F	Long	Roughness, Friction
Ring Method	PhabrOmeter	Fast	None
Optical Method	N/A	Medium	Roughness

5.2 Sensory Evaluation

Many researchers did sensory evaluation in the past. In the following section we reviewed the sensory evaluation methods in terms of judges/subject type, rating scales & methods and semantics.

5.2.1 Judges/Subject Type

In 1972 Matsuo firstly chose types of trained judges depending on the purpose and objectives of the study being conducted [44]. Kawabata selected expert panel members as part of a committee to evaluate fabric hand instead [14]. Winakor did a combined method in which evaluations done by trained or expert judges were compared with measures of physical properties, while quantifiable responses from consumers were compared with consumers' preferences [45].

5.2.2 Rating Scales and Methods

Three rating scales includes: the semantic differential scale, which measures people's reactions to stimulus words and concepts in terms of ratings on bipolar scales defined with contrasting adjectives at each end [45-49]; the unforced scales; and the paired comparison found in previous researches. Overall, multiple measures are more effective than any single technique. The sum of several items gives a more accurate measurement than a single measurement [50].

5.2.3 Semantics

There are basically two kinds of semantics, single method and bipolar method. Single method means using a single descriptor term and a scale where subject rates how well the terms describe the fabric as Kawabata did [14]. Bipolar method means using two descriptor terms that are anonyms and the subjects make ratings on a scale between the two terms [45]. Following table shows a summary of sensory evaluation methods of fabric smoothness-roughness sensation.

Table 4: Sensory Evaluation Methods

Judge/Subject Type	**Rating Scales**	**Semantics**
Trained Judges/ Expert	Semantic Differential Scale	Single Method
Normal Subjects	Unforced Scales	Bipolar Method
Expert and Customer	Paired Comparison	

6 Psychological Evaluation

Stepwise-linear-regression was used by Kawabata in his famous KES-F hand feel testing system [36]. Hu in 1993 compared subjective perception to KESF using linear functional, mixed linear and log-linear function, Webber-Fechner law and Steven's law. The study found preference in Steven's law to conduct psychological evaluation [51]. Later researches found out that Artificial Neural

Network based predictive model was good in practice [52-54]. Meanwhile, as Anttila pointed out, these methods only compare and predict the fabric hand sensation symbols with fabric physical properties [55] but do not explain the mechanism of hand feeling sensations generation [56].

7 Conclusion

In this paper a systematic review on fabric smoothness-roughness sensation studies has been completed, covering three aspects including definition of clothing comfort, physical and neurophysiological definition of smoothness-roughness sensation, and physical, sensory and psychological measurements of smoothness-roughness sensation. Few research gaps related to smoothness-roughness sensations include 1. Cortical mechanisms of smoothness-roughness sensation which still need to be explained. 2. A fabric friction model including both deformation and adhesion which also cannot be found. 3. Lack of rapid and users-friendly test instruments which also needs to be developed.. Future studies and researchers in fabric smoothness-roughness field can follow research methodologies stated in this paper and target on filling these research gaps.

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