Doctoral Dissertation (Shinshu University)

Study on psychophysiological methods of evaluating tactile comfort of textiles

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1.1.1 Definition

1.1.1.1 Textiles

“Textile products”, or rather “textiles”, is defined as “any raw, semi-worked, worked, semi-manufactured, manufactured, semi-made-up or made-up products which are exclusively composed of textile fibers, regardless of the mixing or assembly process employed” in Regulation (EU) No. 1007/2011. In practice, however, products containing at least 80% by weight of textile fibers, as well as products incorporating textile components that constitute at least 80% by weight of textile fibers, are also treated as textile products (textiles). According to the differences in end-uses, textile products can be divided into three categories: home textiles, apparel textiles, and industrial textiles. Home textiles are textile products commonly used in the living room, bedroom, bathroom, and kitchen, including curtains, carpets, cushions, bedding (e.g., bed linen, duvets, quilts, pillows and blankets), towels, and so on. Home textiles play an important role in the improvement of our living environment [1]. Apparel textiles mainly refer to textile products related to apparel, especially varieties of ready-to-wear clothes. Apparel products worn next to the skin play an important role in body shaping and body protection (e.g., cold protection and bacteria growth inhibition), and apparel products worn over underclothes play an important role in body protection and body decoration [2]. Industrial textiles are commonly referred to as technical textiles. Technical textiles are textile products manufactured primarily for their technical performance and functional properties rather than aesthetic or decorative characteristics. To be specific, technical textiles involve protective clothing (e.g., heat and radiation protective clothing for fire fighters, molten metal protective clothing for welders and bulletproof vests), textiles for filtration, textiles for medical treatment (e.g., bandages and implants), textiles in transportation (e.g., seat coverings in automobiles, trains, aircrafts and passenger vessels), geotextiles for embankment reinforcement, agrotextiles for crop protection, and so on [3]. Among the three categories of textile products, home textiles and apparel textiles are highly associated with our daily life, and they contribute a lot to the comfort we feel.

1.1.1.2 Tactile comfort

"Comfort" was defined in different ways by Slater and Hatch. Slater described "comfort" as "a pleasant state of physiological, psychological and physical harmony between a human being and the environment" in 1985 [4]. This definition suggests that comfort is a positive/pleasant feeling experienced by a human being in a given environment, and it mainly involves three aspects, namely physiological comfort, psychological comfort and physical comfort. Physiological mechanisms for keeping the human body alive and functioning normally are closely related to the physiological comfort. Emotional and behavioral responses of a human being which are dependent on natural instincts and social environments of a human being (e.g., immediate physical surroundings, social relationships and cultural milieus) are closely related to the psychological comfort. The interaction between physical characteristics of the environment and motions of the human body in time domain and space domain, which may involve acoustics, optics, mechanics, thermodynamics, electromagnetics and so on, are closely related to the physical comfort [5, 6]. Hatch described "comfort" as "a freedom from pain and discomfort, which is a neutral state" in 1993 [4]. In this definition, comfort is described as a neutral feeling experienced by a human being after the release from a painful/suffering condition, and it is taken as a feeling against discomfort. Compared with comfort, discomfort is easy to understand for most of us, as it can be described with such specific terms as cold, itch, prickle and pain. Comfort/discomfort is usually perceived through sensory organs, and it is primarily dependent on three aspects: the inherent quality of external stimuli, the perceptual capability of sensory organs, and the past experiences and present desires kept in the mind of a human being [5, 6]. According to the differences in sensory organs involved in the perception of comfort, it can be subdivided into five categories: visual comfort (the comfort perceived by sight), auditory comfort (the comfort perceived by hearing), gustatory comfort (the comfort perceived by taste), olfactory comfort (the comfort perceived by smelling), and tactile comfort (the comfort perceived by touch) [7].

In terms of textile products, visual comfort, auditory comfort, olfactory comfort and tactile comfort all contribute to the consumer preference [8]. However, compared the other three types of sensory comfort, tactile comfort is receiving more and more attention along with the improvement of living conditions nowadays. Tactile comfort refers to the overall sensation experienced as the texture of a textile product is handled by touch. It is primarily dependent on several specific tactile sensations. According to the findings of a number of researches, the principal sensations contributing to tactile comfort can be divided into five categories: coolness/warmness, moistness/dryness, roughness/smoothness, hardness/softness and stickiness/slipperiness [9]. Among the five types of tactile sensations, roughness/smoothness and hardness/softness are perceived to be the fundamental sensations for tactile comfort. As per the contributions to tactile comfort, roughness/smoothness is perceived to be superior to hardness/softness in most cases [10-13]; hardness/softness is perceived to be superior to roughness/smoothness in some cases [14]; in other cases, they are perceived to be equally important [15-17]. In terms of stickiness/slipperiness, it cannot be separated from roughness/smoothness at times; therefore, it is removed from the category list in some cases [18, 19]. In a broad sense, coolness/warmness and moistness/dryness are taken as the determinants of tactile comfort; in a narrow sense, they are referred to as the determinants of thermal comfort. Whether coolness/warmness and moistness/dryness are embodied in the tactile sensations or not, the perception of any of the other sensations is usually accompanied by perceptions of coolness/warmness and moistness/dryness.

1.1.2 Evaluation methods

1.1.2.1 Instrumental measurement

A number of mechanical devices, including KES-F (Kawabata Evaluation System for Fabrics), FAST (Fabric Assurance by Simple Testing) and UST (Universal Surface Tester), have been developed to objectively characterize the tactile sensations of textile materials. As measured with these devices, textile materials are subjected to deformations similar to those applied by the hand of an expert, using the same modes and rates [19].

Among the devices developed for low-stress mechanical property measurement, KES-F is the most popular one. KES-F is comprised of four individual instruments: KES-FB1 Tensile and Shear Tester, KES-FB2 Pure Bending Tester, KES-FB3 Automatic Compression Tester, and KES-FB4 Automatic Surface Tester. With the force-strain curves recorded by KES-FB1, the parameters of tensile properties are calculated; with the force-angle curves recorded by KES-FB1, the parameters of shear properties are calculated; with the torque-angle curves recorded by KES-FB2, the parameters of bending properties are calculated; with the pressure-thickness curves recorded by KES-FB3, the parameters of compression properties are calculated; with the variation curves of friction coefficient and thickness recorded by KES-FB4, the parameters of surface properties are calculated [20, 21]. Moreover, KES-F7 Precise and Fast Thermal Property-Measuring Instrument Thermo Lab II has been developed to measure heat transfer properties of textile materials.

The instrumental measurement method is usually fast, repeatable and well understood; however, the measured parameters cannot directly reflect tactile sensations in a precise way, as tactile sensations perceived by touching textile materials involve not only physical and mechanical factors but also physiological, perceptional and social factors [19]. In order to close the gap between physical and mechanical parameters and tactile sensations, a few researchers have tried to correlate them through establishing prediction models. Both multivariate statistical analysis (e.g., principal component analysis, multiple regression analysis) and intelligent techniques (e.g., neural networks, fuzzy logic) are commonly applied in the establishment of prediction models [22-25].

1.1.2.2 Sensory evaluation

Sensory evaluation (sensory analysis) is a scientific discipline that analyzes and measures human responses towards physical and mechanical properties of textile materials [26-28]. During the sensory evaluation, the skin is taken as the instrument, and thermoreceptors and mechanicoreceptors in the skin take charge of responding to varieties of tactile stimuli like heat, pressure and vibration [29, 30]. In general, sensory evaluation methods can be divided into three categories [31]:

(1) Affective tests

Affective tests are used to determine the degree of preference or acceptability for a product. In a preference test, the preference is a forced choice; in an acceptance test, the panelist is asked to indicate the degree of preference for one or more samples. To be specific, affective tests are conducted in the following ways:

- Paired preference: The panelist is asked to indicate which one of two samples he/she prefers. It is a simple and easy-to-perform test, and can be used when the desirability of one sample is known.
- Ranking for preference: The panelist is asked to rank two or more samples as per the preference.
- Hedonic scale: The panelist is asked to express his/her degree of preference for a particular product. The nine-point scale is most often used. Besides the nine-point scale, other odd-numbered scales can also be used.

(2) Descriptive tests

Descriptive tests are used to describe and quantify the perceived sensory attributes of a product. What is worth noting is that, descriptive tests must be performed by experienced or trained panelists, as high discrimination is required in descriptive tests. In a descriptive test, individual characteristics are rated on a structured or unstructured scale by panelists. A structured scale is a scale labeled with numbers and/or descriptive terms. The terms should not be subjective (too rough, just right, not rough enough), but objective (very rough, rough, not rough). The specific intervals on the scale are later converted to numbers for statistical analysis. An unstructured scale is a scale having verbal anchors at the ends and/or the center. The panelist marks the position of each sample on the scale. A numerical value is later assigned by the experimenter based on the position of the mark (usually by measuring distance on the line). Through descriptive tests, the size, intensity, and direction of the differences can be determined. Later on, the statistical analysis (e.g., analysis of variance (ANOVA)) can be applied to ascertain whether the differences are significant or not.

(3) Discriminative tests

Discriminative tests, which are also referred to as difference tests, can be used to determine whether there are detectable differences between the samples or not. Discriminative tests can be performed by either trained or untrained panelists (consumers). In general, discriminative tests are carried out in the following ways:

- Triangle tests: After receiving three coded samples, the panelist is told that two samples are alike and one is different, and then he/she is asked to identify the odd sample. The analysis result is to compare the number of correct answers with the number you expect to get by chance alone. The triangle test does not usually indicate the degree of difference, and the panelist is asked to specify the characteristic that is different.
- Duo-trio tests: Three samples are presented to the panelist: one is labeled as R (reference), and the other two are coded. One of the coded samples is identical to R, whereas the other one is different from R. The panelist is asked to identify the odd sample. This test is less efficient than the triangle test, as the probability of selecting the correct answer by chance is 50%.
- Paired comparison tests: A pair of coded samples is presented to compare for a specific characteristic. Paired comparison results indicate whether there is a detectable difference between

two samples or not, but not indicate the degree of difference. The probability of selecting the right sample by chance is 50%.

- Multiple comparison tests: They are similar to paired comparison tests except that a reference or a standard sample (labeled as R) is presented together with several coded samples. Each coded sample is compared with the reference sample for a specific characteristic. Numerical scores can be assigned to the ratings and statistical analysis can be performed to examine the statistical significance of the results.

- Ranking tests: After receiving three or more coded samples, the panelist is asked to rank the samples as per a specific characteristic. The statistical significance of the results can be tested with prepared tables. It is a rapid way to test several samples at once, and is often used to screen for one or two best samples in a group.

1.1.2.3 Psychophysiological measurement

Psychophysiological measurement is concerned with observing the interactions between physiological and psychological phenomena. It can be used to examine the concepts of emotion, behavioral states, stress, cognitive task performance, personality and intelligence [32-34].

(1) Central nervous system

The central nervous system (CNS) receives information from and sends information to the peripheral nervous system. It consists of two main organs: the spinal cord and the brain. The spinal cord serves as a conduit for signals between the brain and the rest of the body. It also controls simple musculoskeletal reflexes without input from the brain. The brain is responsible for integrating most sensory information and coordinating body function, both consciously and unconsciously. The techniques used to observe the activity of the brain include: electroencephalography (EEG), magnetoencephalography (MEG), cerebral blood flow (CBF) and local brain temperature. The electrical activity generated by the mass action of neurons within the cortex and midbrain structures can be measured with EEG. Based on EEG, the percentage of brain waves in various frequency bands can be predicted by means of power spectral analysis. Through observing the changes in the percentage of brain waves in different frequency bands, the mental status of a human being can be approximately predicted. As reported, when a human being is in an unconscious state or is sleeping soundly, δ wave (below 4 Hz) occurs frequently; when a human being feels sleepy, θ wave (4 Hz ~ 7 Hz) occurs frequently; when a human being keeps still, relaxed and concentrated, α wave (8 Hz ~ 13 Hz) occurs frequently; when a human being feels nervous, β wave (14 Hz ~ 30 Hz) occurs frequently; when a human being feels uneasy, angry or excited, δ wave (over 30 Hz) occurs frequently.

(2) Autonomic nervous system

The autonomic nervous system (ANS) is a part of the peripheral nervous system. It has two branches: the sympathetic nervous system (SNS) and the parasympathetic nervous system (PSNS). The SNS is often considered as the "fight or flight" system, while the PSNS is often considered as the "rest and digest" or "feed and breed" system. In many cases, the two systems have "opposite" actions, that is, while one system activates a physiological response, the other system will inhibit it. The ANS mainly controls involuntary actions, such as blood pressure, heart rate, breathing rate, and body temperature. In turn, the activity of ANS can be predicted through observing cardiovascular actions, respiratory actions and so on. The traditional way to study the activity of ANS is to analyze the heart rate variability (HRV). The R-R intervals (RRI) calculated from the electrocardiography (ECG) are often used for HRV analysis.

(3) Peripheral circulation system

Blood pressure (BP) is the pressure exerted by circulating blood upon the walls of blood vessels and is one of the principal vital signs. The sphygmomanometer (pressure cuff) and stethoscope can be used to detect BP. Blood volume measurement (plethysmography) is used to assess the amounts of blood that are present in various areas of the body during particular activities. Conventionally, the photoplethysmography (PPG) can be used to detect the amount of blood passing in tissue.

(4) Musculoskeletal system

Muscle activity can be measured with electromyography (ECG), in which the electrical potentials are associated with contractions of muscle fibers.

(5) Others

Pupillary response and eye movements can be measured with electrooculography (EOG). EOG is concerned with assessing muscular activity around the eye, and evaluating the change in voltage potential between the positively charged cornea and negatively charged retinal segment of the eye. Sweat gland activity is responsive to the changes in emotionality and cognitive activity. It can be observed by measuring electrical activity on the surface of the skin (galvanic skin response)

1.2 Objective of this thesis

Nowadays, along with the improvement of living conditions, the baseline quality request for home and apparel textiles has changed from "not painful/uncomfortable" to "more comfortable/pleasant". Accordingly, tactile comfort is playing a more and more important role in determining the consumer preference. In order to enhance the level of tactile comfort, there is a necessity to find some effective ways to evaluate tactile comfort. Herein, tactile comfort should be interpreted as "at least not painful/stressful".

With respect to the topic of tactile comfort, most efforts have been made to study the negative effects of discomfort on the human body, rather than the positive effects of comfort on the human body. Considering that the request for "better comfort" is a general trend in the future, we would like to establish an objective evaluation system that can be used to differentiate between different levels of tactile comfort.

According to the definition, tactile comfort is an overall psychophysiological response caused by touching textile materials. In our opinion, it may be possible to find a way to evaluate tactile comfort by correlating psychophysiological measurement techniques with the perception tactile comfort. In this thesis, some preliminary efforts we made to verify this supposition will be introduced.

1.3 Composition of this thesis

The main body of this thesis includes three studies we did to verify our supposition.

In chapter 2, the study on coolness and moistness discrimination differences between active hand touch and passive forearm touch will be introduced. When textile materials are touched, whether actively by hand or passively by forearm, to perceive a specific sensation, the temperature difference between the skin and the materials will always lead to the perceptions of coolness and/or moistness. The perceptions of coolness and moistness may play a role in activating or suppressing the perception of the target sensation, and therefore affect its contribution to tactile comfort. In general, the results in this study suggest that coolness and moistness are much more perceptible (higher intensity and longer duration) as passive forearm touch is involved. Therefore, when passive forearm touch is applied to perceive a specific sensation during the psychophysiological measurement, the coolness and moistness differences between samples should be better controlled to ensure the contribution of the target sensation to tactile comfort.

In chapter 3, the study on cardiac reactions to tactile smoothness will be introduced. Tactile smoothness is a fundamental sensation contributing greatly to tactile comfort. When textures different in tactile smoothness are touched in the same way, either by means of active hand touch or by means of passive forearm touch, the differences in tactile smoothness should be the major factor that lead to the differences in tactile comfort. In general, the results in this study suggest that the average heart rate tends to decease more after the dynamic contact with a rough and uncomfortable texture than after the dynamic contact with a smooth and comfortable texture.

In chapter 4, the study on cardiovascular and respiratory reactions to tactile softness will be introduced. Tactile softness is another fundamental sensation contributing greatly to tactile comfort. When materials different in tactile softness are touched actively by hand, the differences in tactile softness may lead to the differences in ease of movement, and therefore result in the differences in tactile comfort. In general, the results in this study suggest that the variations of low-frequency (LF) and high-frequency (HF) components of blood pressure tend to change with the differences in tactile softness, and then lead some parameters calculated with them, such as HF/(LF+HF) and LF/HF, to change with the differences in tactile softness.

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Chapter 2

Study on coolness and moistness discrimination differences between active hand touch and passive forearm touch

Chapter 2: Study on coolness and moistness discrimination differences between active hand touch and passive forearm touch

2.1 Introduction

2.1.1 “Tezawari” and “Hadazawari”

In Japan, there are two types of sensory test methods that can be used to evaluate textile materials’ textures subjectively. In Japanese, one type of sensory test method is usually referred to as “Tezawari”, and the other type of sensory test method is usually referred to as “Hadazawari” [1-3]. In English, “Tezawari” can be literally translated as “hand touch”, and “Hadazawari” can be literally translated as “skin touch” (“Te” means “hand”, “Hada” means “skin”, and “Zawari” means “touch”). As two types of sensory test methods, “Tezawari” and “Hadazawari” are mainly different from each other in the aspects of touch modes and skin types involved in the evaluation. In a “Tezawari” test, the hand skin is commonly used, and it is used to touch textile materials actively. In a “Hadazawari” test, the skin type involved is dependent on the end uses of textile materials. For example, in terms of stockings, the foot skin may be involved; in terms of gloves, the hand skin may be involved; in terms of scarf, the neck skin may be involved. In most cases, the forearm skin is preferred when textile materials are evaluated with the “Hadazawari” test method. In general, the skin involved in a “Hadazawari” test is used to touch textile materials passively. Taking into account of these differences, “Tezawari” in Japanese should correspond to “active hand touch” in English, and “Hadazawari” in Japanese should correspond to “passive skin touch” in English, in our opinion.

Both active touch and passive touch can be static or dynamic. In terms of active touch, the movement is self-generated by the perceiver; in terms of passive touch, the movement is generated by the material [4, 5]. Owing to the active touch mode, exploratory movements such as grasping, rubbing, groping, palpating, and hefting are allowed in the “Tezawari” test. In terms of the skin type, the glabrous skin of the hand and the hairy skin of the forearm have different anatomical structures and tactile experiences, and therefore may result in sensitivity differences between “Tezawari” and “Hadazawari” test methods [6, 7].

Significance of coolness and moistness

It is reported that the perceptions of coolness/warmness and moistness/dryness are caused by heat and moisture transfer [6]. Therefore, as long as there is a direct contact between the skin and the material, the perceptions of coolness/warmness and moistness/dryness will be aroused independently from or accompanying with the other perceptions. Along with heat and moisture transfer, the skin temperature will be changed. Because of the change in skin temperature, the sensitivity of thermoreceptors and mechanicoreceptors in the skin may be enhanced or impaired; accordingly, the awareness of tactile texture, which depends mostly on the perception of smoothness/roughness and the perception of softness/hardness, will change [8-10].

2.1.3 Objective of this study

In this study, the coolness and moistness discrimination differences between active hand touch (“Tezawari”) and passive forearm touch (“Hadazawari”) are to be investigated. In order to minimize the effects of between-sample differences on the evaluation results, and facilitate the understanding of the effects of testing conditions on the evaluation results, three types of single jersey fabrics manufactured with the same techniques are to be chosen as the samples.

2.2 Experimental details

2.2.1 Materials

2.2.1.1 Specifications

Three types of single jersey fabrics produced by Asahi Kasei Fibers Corporation in Japan were selected as the samples. Table 2-1 shows material and structural characteristics of the three types of samples. The sample indicted by "CO" contained 95% cotton (CO) fibers and 5% polyurethane (PU) fibers by weight; the sample indicated by "MD" contained 95% modal (MD) fibers and 5% PU fibers by weight; the sample indicated by "CU" contained 95% cuprammonium (CU) fibers and 5% PU fibers by weight. The yarn counts of dominant contents of the three types of samples were very similar, which were between 11tex and 12tex. The stitch densities of the three types of samples were almost equal in both course and wale directions. In the wale direction, the stitch densities were around 55 courses per inch (CPI), and in the course direction, the stitch densities were around 45 wales per inch (WPI). The thickness of the three types of samples decreased in the order of CO, MD, and CU. Figure 2-1 shows face and back surface features of the three types of samples. The hairiness of the three types of samples decreased in the order of CO, MD and CU on both face and back surfaces.

Table 2-1 Material and structural characteristics of single jersey fabrics used in the sensory tests

Symbol	Fiber content	Yarn count	Stitch density		Thickness (mm)
			CPI	WPI	
CO	95% CO & 5% PU	CO 50s/1 (≈11.8tex) & PU 2.2tex/2f	53 ± 1	44 ± 0	0.72 ± 0.04
MD	95% MD & 5% PU	MD 50s/1 (≈11.8tex) & PU 2.2tex/2f	54 ± 1	46 ± 1	0.69 ± 0.01
CU	95% CU & 5% PU	CU 11tex/60f & PU 2.2tex/2f	56 ± 1	46 ± 1	0.53 ± 0.01

CO: Cotton; MD: Modal; CU: Cuprammonium; PU: Polyurethane.
CPI: Courses per inch; WPI: Wales per inch.

F: Face; B: Back; CO: Cotton; MD: Modal; CU: Cuprammonuium.

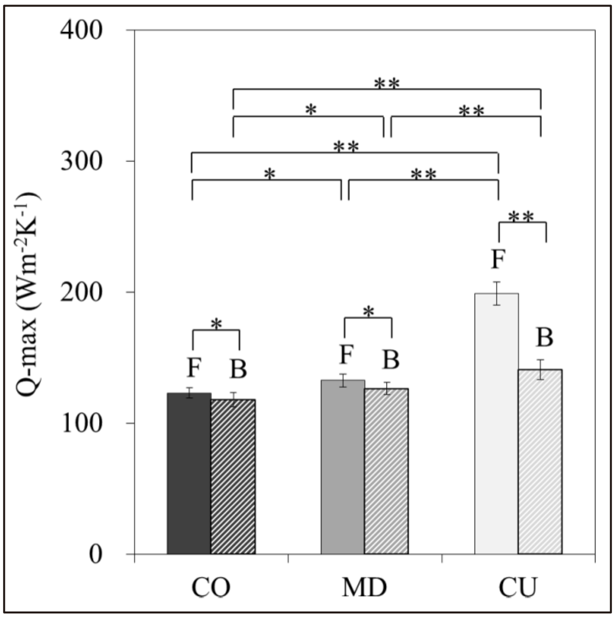
Figure 2-1 Surface features of single jersey fabrics used in the sensory tests

2.2.1.2 Thermal and moisture properties

Thermal properties (i.e., q-max and heat conductivity) and moisture regain rates of the three types of samples were measured under the environmental condition of "20℃ ± 2℃, 65% ± 4% RH". Thermal properties were measured with KES-F7 Precise and Fast Thermal Property-Measuring Instrument Thermo Lab II (Kato tech Co., Ltd., Kyoto, Japan). Moisture regain rates were measured as per the criterion specified by Japanese Industrial Standards (JIS L 1096:2010). Moisture desorption rates of the three types of samples were measured by moving them from the environmental condition of "20℃, 90% RH" to the environmental condition of "20℃, 65% RH".

Figure 2-2 (A) shows the measurement results for q-max. The one-way ANOVA and the Bonferroni's post-hoc test were conducted to examine the statistical significance of between-sample differences in q-max on each surface. The independent-samples T test was applied to examine the statistical significance of the between-surface difference in q-max for each type of sample. The corresponding significance test results are indicated in Figure 2-2 (A). According to Figure 2-2 (A), on both face and back surfaces, the q-max value of MD was significantly larger than that of CO ($p < 0.05$), and the q-max value of CU was significantly larger than that of MD ($p < 0.01$). That is to say, the q-max values of the three types of samples decreased in the order of CU, MD and CO on both face and back surfaces. In terms of CO and MD, the q-max value measured on the face surface was larger than that measured on the back surface at a significance level of 0.05. In terms of CU, the q-max value measured on the face surface was larger than that measured on the back surface at a significance level of 0.01. What is worth noting is that the q-max value of CU measured on the face surface was much larger than the corresponding q-max value measured on the back surface. Vivekanadan *et al.* and Raj *et al.* have found that q-max increases with the increase in surface smoothness, as a smoother surface is beneficial to the increase of contact area [11]. Therefore, it is supposed that the absence of hair must have led the back surface of CU to be much rougher than the face surface of CU. Owing to the greater surface roughness, when q-max values of CU were measured, the real contact area between the copper plate and the back surface became even smaller than that between the copper plate and the face surface; as a result, the q-max value measured on the back surface of CU was much smaller than that measured on the face surface of CU. To verify this supposition, the SMD values of the three types of samples were measured with KES-FB4 Automatic Surface Tester (Kato tech Co., Ltd., Kyoto, Japan) under the environmental condition of "20℃ ± 2℃, 65% ± 4% RH". SMD is a physical indicator of the geometrical surface roughness of fabrics. The rougher the measured surface is, the greater the value of SMD is. Figure 2-3 shows the measurement results for SMD. On the face surface, the overall roughness of the three types of samples decreased in the order of CO, MD and CU; on the back surface, the overall roughness of the three types of samples increased in the order of CO, MD and CU; in terms of CU, the overall roughness of the back surface was much greater than that of the face surface. These results suggest that the absence of hair tends to increase the smoothness of the face surface and decrease the smoothness of the back surface; as a result, a great smoothness difference between face and back surfaces of CU arises, and it results in a great difference in q-max.

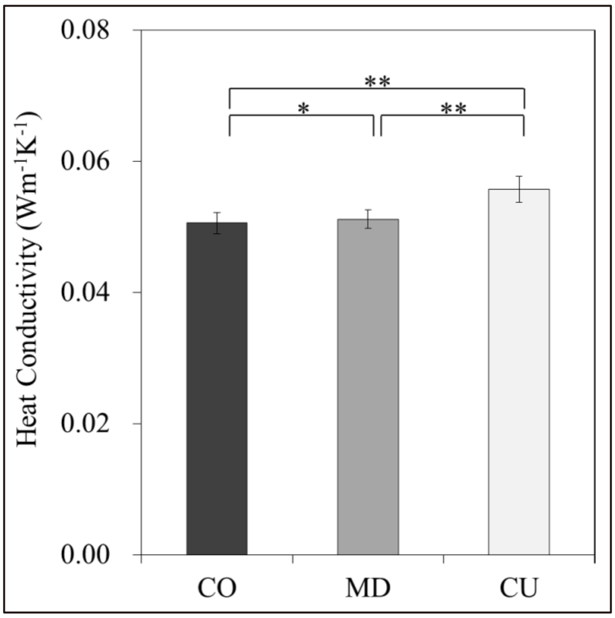
**: $p < 0.01$ *: $p < 0.05$



F: Face; B: Back.
CO: Cotton; MD: Modal; CU: Cuprammonuium.

(A) Q-max

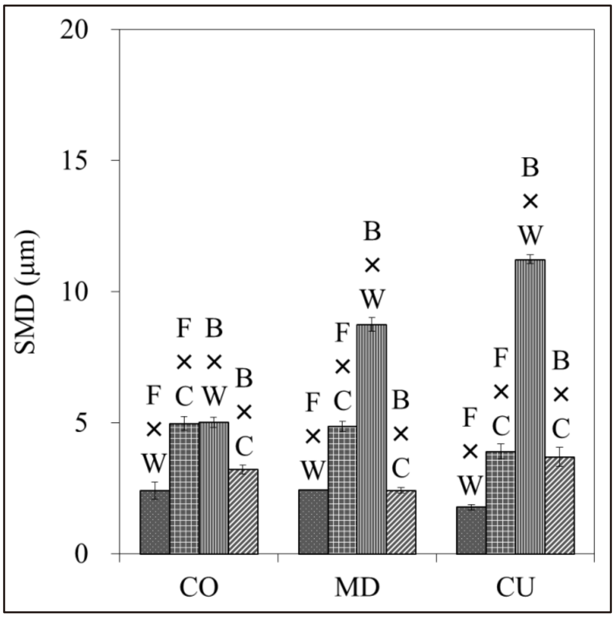
**: $p < 0.01$ *: $p < 0.05$



CO: Cotton; MD: Modal; CU: Cuprammonuium.

(B) Heat conductivity

Figure 2-2 Measurement and significance test results for thermal properties



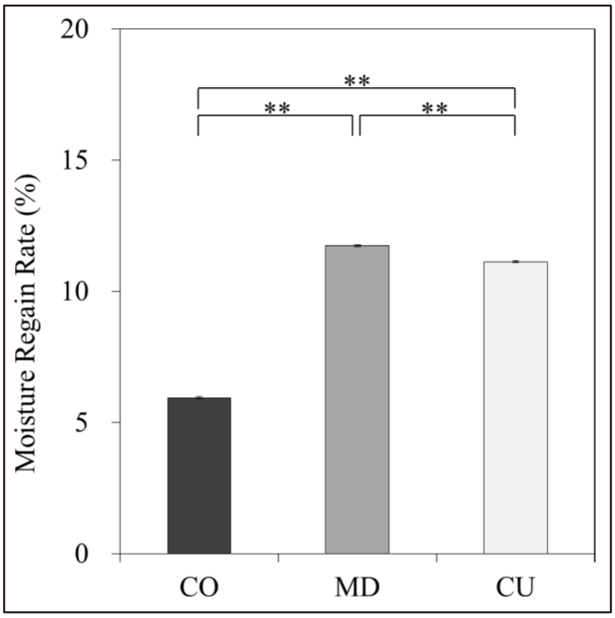
F: Face; B: Back; W: Wale; C: Course.
CO: Cotton; MD: Modal; CU: Cuprammonuium.

Figure 2-3 Measurement results for the geometrical surface roughness

Figure 2-2 (B) shows the measurement results for heat conductivity. The one-way ANOVA and the Bonferroni's post-hoc test were carried out to examine the statistical significance of between-sample differences in heat conductivity. The corresponding significance test results are indicated in Figure 2-2 (B). According to Figure 2-2 (B), the heat conductivity of MD was significantly larger than that of CO ($p < 0.05$), and the heat conductivity of CU was significantly larger than that of MD ($p < 0.01$). In brief, the heat conductivity of the three types of samples increased in the order of CO, MD and CU.

Figure 2-4 (A) and Figure 2-4 (B) show the measurement results for the moisture regain rate and the moisture desorption rate, respectively. The one-way ANOVA and the Bonferroni's post-hoc test were conducted to examine the statistical significance of between-sample differences in moisture properties. According to Figure 2-4 (A), the moisture regain rate of CO was the lowest, the moisture regain rate of MD was the highest, and the moisture regain rate of CU was significantly higher than that of CO ($p < 0.01$) and lower than that of MD ($p < 0.01$). In a word, the moisture regain rates of the three types of samples decreased in the order of MD, CU and CO. According to Figure 2-4 (B), there was no significant difference between moisture desorption rates of MD and CU, but the moisture desorption rate of CO was significantly lower than that of MD ($p < 0.01$).and that of CU ($p < 0.01$).

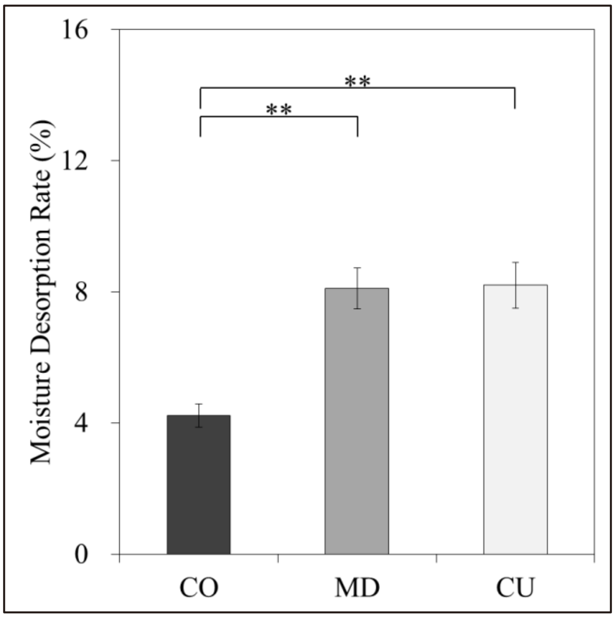
**: p < 0.01 *: p < 0.05



CO: Cotton; MD: Modal; CU: Cuprammonuium.

(A) Moisture regain rate

**: p < 0.01 *: p < 0.05



CO: Cotton; MD: Modal; CU: Cuprammonuium.

(B) Moisture desorption rate

Figure 2-4 Measurement and significance test results for moisture properties

2.2.2 Sensory tests

2.2.2.1 Subjects

Twenty healthy university students aged between twenty-two and twenty-nine years old participated in the experiment. There were ten females and ten males. Table 2-2 shows the average physical characteristics of the subjects. All of the subjects had experience in fabric handle evaluation. During the six hours before the starting of a "Tezawari" or "Hadazawari" test, the subjects were banned from drinking coffee, drinking alcohol and doing strenuous exercise.

Table 2-2 Physical characteristics of subjects

Gender	Number	Age (years)	Height (cm)	Weight (kg)
Male	10	23.4 ± 2.1	171.8 ± 4.3	61.6 ± 6.2
Female	10	24.9 ± 2.7	158.8± 5.0	50.9 ± 4.4

2.2.2.2 Specimens

All of the specimens were cut into the size of "35 cm × 35 cm". Before the specimens were used in the sensory tests, they had been hung up in the climate chamber and conditioned for 24 hours under the environmental condition of "24℃ ± 1℃, 50% ± 2% RH". A total of ten sets of specimens were prepared, and each set of specimens included a piece of CO, a piece of MD and a piece of CU. The ten sets of specimens were used in both "Tezawari" and "Hadazawari" tests, with each set of specimens evaluated by two fixed subjects.

2.2.2.3 Evaluation terms and techniques

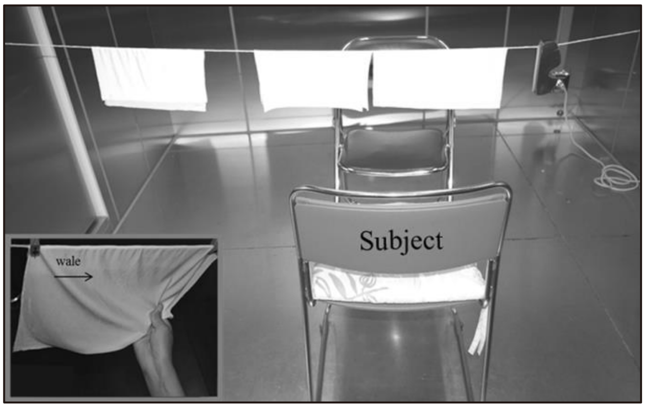
Table 2-3 shows the evaluation terms and techniques applied in the sensory tests. Two terms were screened out to evaluate the coolness of samples: "Cool" was used to evaluate the coolness instantaneously perceived at the moment of contact; "Warm" was used to evaluate the coolness perceived after several seconds of contact. One term was screened out to evaluate the moistness of samples: "Moist" was used to evaluate the moistness perceived after several seconds of contact.

Table 2-3 Evaluation terms and techniques applied in sensory tests

Perception	Term	Description	Technique	
			"Tezawari"	"Hadazawari"
Coolness	Cool	Low-temperature	Pinch the fabric with the fingers of one hand, hold it for 1~2 seconds, and then let it go	Drop the fabric down onto the forearm, and remove it after 1~2 seconds
	Warm	High-temperature	Pinch the fabric with the fingers of one hand, hold it for 4~5 seconds, and then let it go	Drop the fabric down onto the forearm, and remove it after 4~5 seconds
Moistness	Moist	High-moisture	Pinch the fabric with the fingers of one hand, rub it for 4~5 seconds, and then let it go	Drop the fabric down onto the forearm, and remove it after 4~5 seconds

2.2.2.4 Test scheme

The sensory tests were conducted in a climate chamber under the environmental condition of "24℃ ± 1℃, 50% ± 4% RH". Figure 2-5 shows the general arrangements of "Tezawari" and "Hadazawari" tests. After entering the climate chamber, each subject was asked to put on a short-sleeve T-shirt and be seated in the chair to have a rest. When the subject was taking a rest, the experimenter took charge of cleaning the right arm/forearm of the subject with a wet cotton towel and explaining the evaluation terms and techniques to the subject. After thirty minutes, the surface temperatures of the specimens and the skin temperature of the right hand/forearm of the subject were measured with FLIR E60 Infrared Camera (FLIR Systems Japan K.K., Tokyo, Japan). According to the temperature measurement results, the average surface temperatures of the three types of samples were around 24℃ (CO: 24.2℃ ± 0.3℃; MD: 24.3℃ ± 0.3℃; CU: 24.1℃ ± 0.3℃), and the average skin temperatures of right hands and right forearms of the subjects were around 32.5℃ (palm: 32.7℃ ± 0.6℃; finger: 32.5℃ ± 0.8℃; forearm: 32.0℃ ± 0.7℃). The Scheffe's paired comparison method modified by Ura was applied to conduct the sensory tests [12]. In the "Tezawari" test, the experimenter took charge of changing the specimens presented in pairs in front of the subject. The subject took charge of touching the specimen on the left side and the specimen on the right side in succession and scoring the difference between two specimens by taking the left one as the reference sample. In the "Hadazawari" test, the experimenter took charge of changing the specimens presented in pairs in front of the subject and placing the specimen on the left side and the specimen on the right side in succession onto the forearm of the subject. The subject took charge of scoring the difference between two specimens by taking the left one as the reference sample. All of the subjects were blindfolded with a pair of lightproof sunglasses throughout each sensory test. The face surfaces of the three types of samples were involved in coolness and moistness discrimination in the experiment. The rating scale used in the sensory tests was from "-3" to "3". Herein, "3, 2 and 1" meant the feeling indicated by a term could be "extremely, moderately and slightly" experienced in order; "-3, -2 and -1" meant the feeling opposite to what was indicated by a term could be "extremely, moderately and slightly" experienced in order; "0" meant neither the feeling indicated by a term nor the feeling opposite to what was indicated by a term could be definitely experienced.



(A) "Tezawari" test

(B) "Hadazawari" test

Figure 2-5 General arrangements of the sensory tests

2.2.2.5 Data analysis

The ANOVA method introduced by Nagazawa *et al.* was applied to examine the statistical significance of main effects of the sample type, the combination pattern and the presentation order on coolness and moistness discrimination [12]. Average preference scores of the three types of samples for each evaluation term were calculated, and the Yardstick method introduced by Nagazawa *et al.* was applied to examine the statistical significance of between-sample differences in the average preference score [12].

2.3 Results

2.3.1 Evaluation results related to the perception of coolness

Table 2-4 ANOVA results for the rating of the "Cool" feeling

(A) "Tezawari"

**: p < 0.01; *: p < 0.05

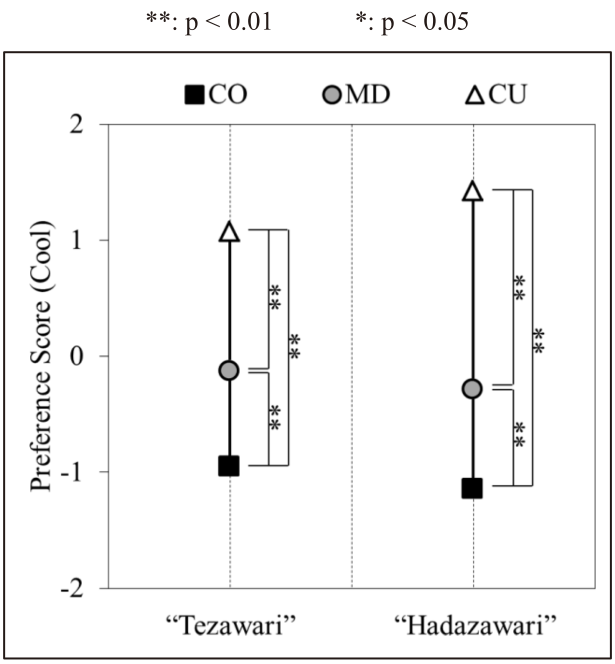
Source	SS	df	MS	F	p	
Sample	248.85	2	124.43	185.15	0.000	**
Combination	2.70	1	2.70	4.02	0.050	*
Order	10.80	1	10.80	16.07	0.000	**
Error	39.65	59	0.67			
Total	302	120				

(B) "Hadazawari"

**: p < 0.01; *: p < 0.05

Source	SS	df	MS	F	p	
Sample	409.72	2	204.86	206.26	0.000	**
Combination	7.01	1	7.01	7.06	0.010	*
Order	21.68	1	21.68	21.82	0.000	**
Error	58.60	59	0.99			
Total	497	120				

Table 2-4 shows the ANOVA results for the rating of the “Cool” feeling (i.e., the coolness perceived at the moment of contact). According to Table 2-4, the difference in the sample type had significant effects on the rating of the “Cool” feeling in both “Tezawari” and “Hadazawari” tests ($p < 0.01$). In other words, whether the “Tezawari” or “Hadazawari” test method was used, there were significant between-sample differences in perceived intensity of coolness at the moment of contact. Figure 2-6 shows the average preference scores of the three types of samples relevant to the “Cool” feeling, with corresponding significance test results indicated. According to Figure 2-6, all of the between-sample differences in the average preference score for the “Cool” feeling were statistically significant ($p < 0.01$). In general, the perceived coolness of the three types of samples decreased in the order of CU, MD and CO in both “Tezawari” and “Hadazawari” tests. This order was consistent with the order of q-max, which is a physical indicator of the perception of coolness. In brief, these results indicated that both “Tezawari” and “Hadazawari” test methods were effective enough in discriminating instantaneous coolness differences between samples. However, compared with the between-sample differences in perceived coolness based on “Tezawari” test results, the corresponding between-sample differences based on “Hadazawari” test results were even greater. These results indicated that the coolness differences between samples were even more detectable when discriminated with the “Hadazawari” test method. Above all, from these results, it can be concluded that the “Hadazawari” test method is even more efficient in instantaneous coolness discrimination than the “Tezawari” test method.



CO: Cotton; MD: Modal; CU: Cuprammonuium.

Figure 2-6 Average preference scores and corresponding significance test results relevant to the "Cool" feeling

Table 2-5 ANOVA results for the rating of the "Warm" feeling

(A) "Tezawari"

**: $p < 0.01$; *: $p < 0.05$

Source	SS	df	MS	F	p	
Sample	62.07	2	31.03	13.82	0.000	**
Combination	0.41	1	0.41	0.18	0.671	
Order	8.01	1	8.01	3.57	0.064	
Error	132.52	59	2.25			
Total	203	120				

(B) "Hadazawari"

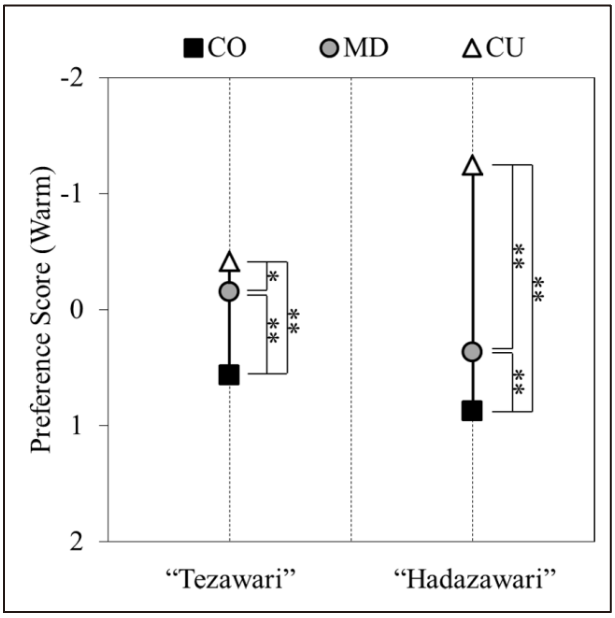
**: $p < 0.01$; *: $p < 0.05$

Source	SS	df	MS	F	p	
Sample	293.02	2	146.51	135.98	0.000	**
Combination	0.21	1	0.21	0.19	0.662	
Order	10.21	1	10.21	9.47	0.003	**
Error	63.57	59	1.08			
Total	367	120				

Table 2-5 shows the ANOVA results for the rating of the "Warm" feeling (i.e., the coolness perceived after several seconds of contact). According to Table 2-5, both "Tezawari" and "Hadazawari" test results revealed that the rating of the "Warm" feeling was significantly affected by the difference in the sample type ($p < 0.01$). That is to say, in both "Tezawari" and "Hadazawari" tests, there were significant differences in perceived intensity of coolness between the three types of samples after several seconds of contact. Figure 2-7 shows the average preference scores of the three types of samples relevant to the "Warm" feeling, with corresponding significance test results indicated. According to Figure 2-7, most of the between-sample differences in the average preference score for the "Warm" feeling were significant at a significance level of 0.01. In general, the perceived warmness of the three types of samples increased in the order of CU, MD and CO in both "Tezawari" and "Hadazawari" tests; however, the layouts of the average preference scores for perceived warmness based on "Tezawari" and "Hadazawari" test results were very different. To be specific, the largest warmness difference discriminated with the "Hadazawari" test method, which was between CO and CU, was much greater than that discriminated with the "Tezawari" test method, which was also between CO and CU; the warmness difference between MD and CU was more detectable in the "Hadazawari" test but less detectable in the "Tezawari" test, whereas the warmness difference between CO and MD was more detectable in the "Tezawari" test but less detectable in the "Hadazawari" test. These results indicated that the between-sample differences in perceived warmness, or rather in perceived coolness after several seconds of contact, were more detectable when discriminated with the "Hadazawari" test method. By comparing the average preference scores for the "Warm" feeling with those for the "Cool" feeling, it was found that all of the between-sample differences in perceived intensity of coolness became less detectable over time, and the perceived coolness of CU decreased dramatically in the "Tezawari" test after several seconds of contact. It is speculated that the mechanism for the decrease in between-sample differences in perceived coolness over time might be like this:

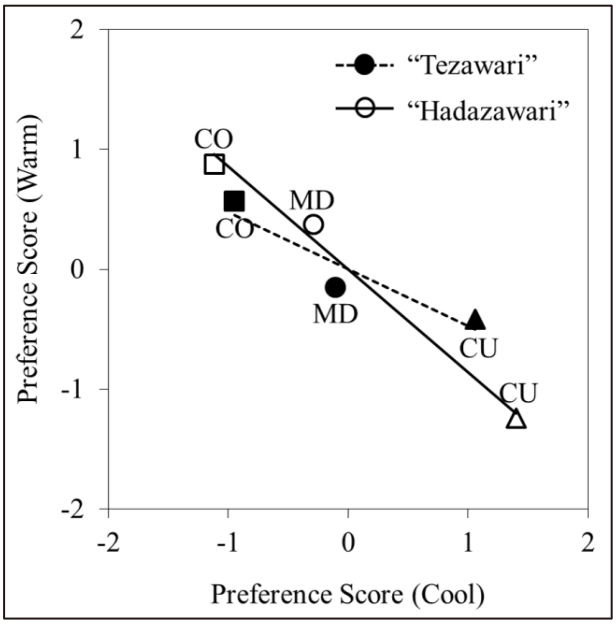
owing to heat transfer, the temperature differences between the skin and the three types of smaples deceased over time; as a result, the perceived coolness of each type of sample became less intense over time, and the between-sample differences in perceived coolness decreased accordingly. As per this mechanism, during the several seconds of contact in the “Tezawari” test, the outstanding heat conductivity of CU must have led the temperature of CU to change more rapidly than that of CO and that of MD; as a result, the coolness of CU decreased rapidly within a short time, and it became difficult to discriminate the coolness of CU from that of MD and that of CO very soon. Figure 2-8 shows the correspondence between average preference scores for the “Warm” feeling and those for the “Cool” feeling. It is obvious that the perceived coolness of the three types of samples decreased almost equivalently over time in the “Hadazawari” test. Consequently, the consistency between the evaluation results for coolness before and after the several seconds of contact was much better in the “Hadazawari” test. To sum up, these results convince us that the “Hadazawari” test method has better tolerance for contact duration than the “Tezawari” test method. When some fabrics of outstanding heat conductivity are involved, the better tolerance for contact duration may be very helpful to the discrimination of between-sample differences in perceived coolness.

**: $p < 0.01$ *: $p < 0.05$



CO: Cotton; MD: Modal; CU: Cuprammonuium.

Figure 2-7 Average preference scores and corresponding significance test results relevant to the "Warm" feeling

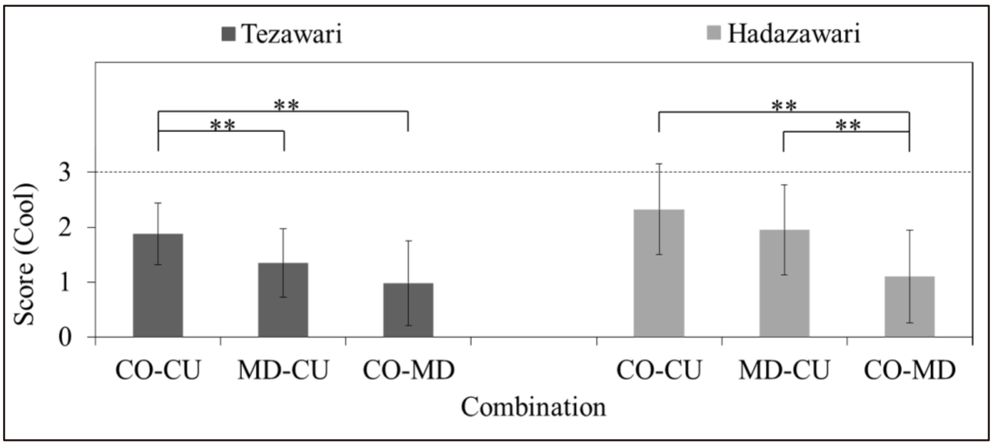


CO: Cotton; MD: Modal; CU: Cuprammonuium.

Figure 2-8 Correspondence between average preference scores for the "Cool" feeling and those for the "Warm" feeling

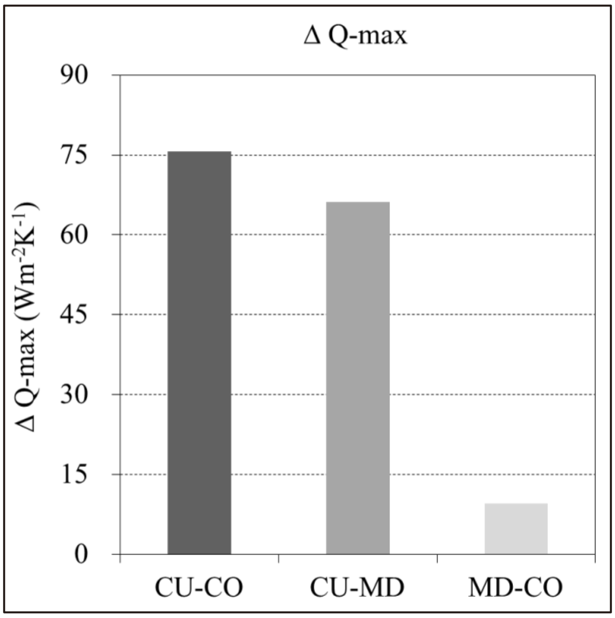
With the three types of samples compared in pairs, three combination patterns (i.e., CO vs. CU, MD vs. CU, and CO vs. MD) were involved in the sensory tests. According to Table 2-4, the difference in combination pattern had significant effects on the rating of the "Cool" feeling in both "Tezawari" and "Hadazawari" tests ($p < 0.05$). The Bonferroni's post-hoc test was carried out to examine the statistical significance of effects of the combination pattern on the rating of the "Cool" feeling. Figure 2-9 shows the average scores and corresponding significance test results for all of the combination patterns. Herein, the average score for a combination pattern is the average score for the coolness difference between two combined samples. Obviously, the average score for each combination pattern based on "Hadazawari" test results was higher than the corresponding average score based on "Tezawari" test results. According to the significance test results relevant to the "Tezawari" test, there was no significant difference between the average scores for the combination MD vs. CU and the combination CO vs. MD, but the average score for the combination CO vs. CU was significantly higher than the average score for the combination MD vs. CU ($p < 0.01$) and that for the combination CO vs. MD ($p < 0.01$). According to the significance test results relevant to the "Hadazawari" test, there was no significant difference between the average scores for the combination CO vs. CU and the combination MD vs. CU, but both of the average scores for the combination CO vs. CU and the combination MD vs. CU were significantly higher than the average score for the combination CO vs. MD ($p < 0.01$). Figure 2-10 shows the between-sample differences in q-max. It demonstrated that the inherent coolness difference between CO and CU was a little higher than that between MD and CU and far higher than that between CO and MD. The average scores for the three combination patterns based on "Hadazawari" test results generally conformed to this trend. To some extent, these results confirm that the "Hadazawari" test method is superior to the "Tezawari" test method in the discrimination of between-sample differences in instantaneous coolness.

**: $p < 0.01$ *: $p < 0.05$



CO: Cotton; MD: Modal; CU: Cuprammonuium.

Figure 2-9 Average scores and corresponding significance test results for all of the combination patterns

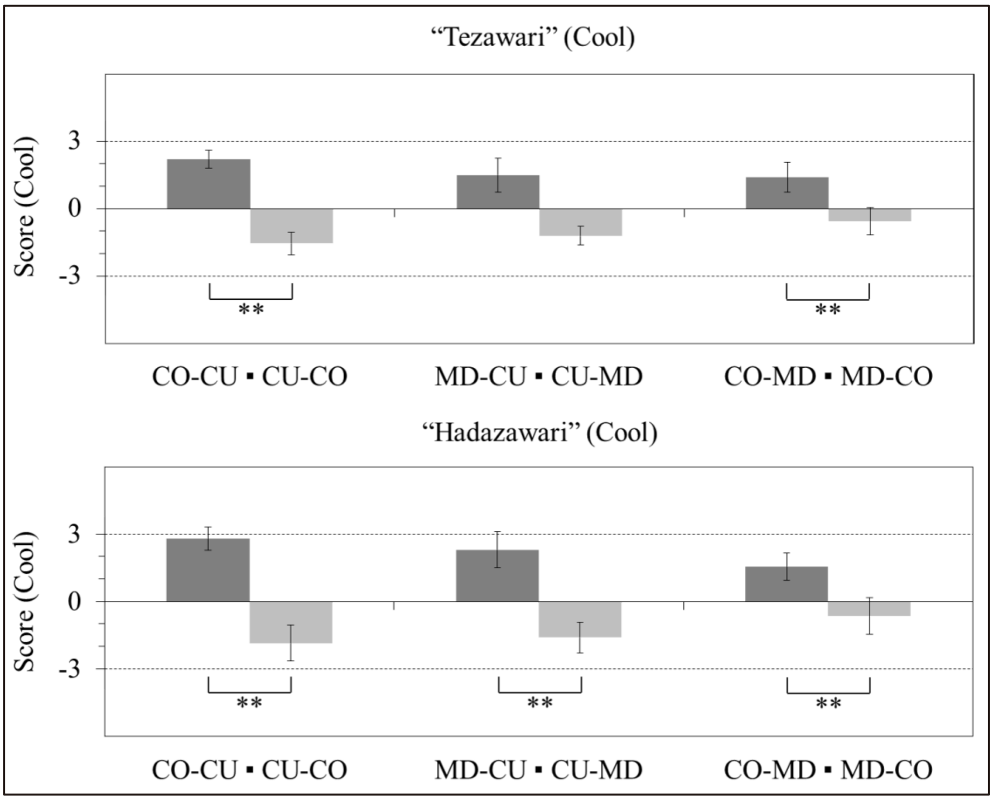


CO: Cotton; MD: Modal; CU: Cuprammonuium.

Figure 2-10 Between-sample differences in q-max

In each combination pattern, the coolness/warmness difference between two combined samples were evaluated in two ways. One is to perceive the warmer one firstly, perceive the cooler one secondly, and then score for the difference between them by taking the warmer one as a reference; the other is to perceive the cooler one firstly, perceive the warmer one secondly, and then score for the difference between them by taking the cooler one as a reference. Consequently, the coolness/warmness rating for every combination pattern involved two presentation orders. Table 2-4 shows that the difference in presentation order had significant effects on the rating of the “Cool” feeling in both “Tezawari” and “Hadazawari” tests ($p < 0.01$). Table 2-5 (B) shows that the difference in presentation order had significant effects on the rating of the “Warm” feeling in the “Hadazawari” test ($p < 0.01$). The independent-samples T test was conducted to examine the statistical significance of effects of the presentation order on the ratings of the “Cool” feeling and the “warm” feeling in each combination pattern. Figure 2-11 shows the average scores for each combination pattern relevant to different presentation orders, with corresponding significance test results for order effects indicated. Figure 2-11 (A) shows the results relevant to the “Cool” feeling in both “Tezawari” and “Hadazawari” tests, and Figure 2-11 (B) shows the results relevant to the “Warm” feeling in the “Hadazawari” test. In Figure 2-11, the results relevant to the first and the second presentation order mentioned above are shown on the left and the right side of each combination pattern respectively. All of the graphs in Figure 2-11 showed a trend that the absolute average score on the left side was higher than the absolute average score on the right side in each combination pattern, and in most cases, the difference between the two absolute average scores was significant at a significance level of 0.01. These results indicated that, when two samples having a detectable difference in coolness were compared, the pre-experience of a warmer sample tended to lead the coolness difference between the two samples to be more detectable. However, Figure 2-11 (A) also showed that, no matter which presentation order was involved, the average score based on “Hadazawari” test results was higher than the corresponding average score based on “Tezawari” test results in each combination pattern. These results indicated that the effects of the presentation order must have contributed little to the difference between “Tezawari” and “Hadazawari” test methods in the discrimination of coolness.

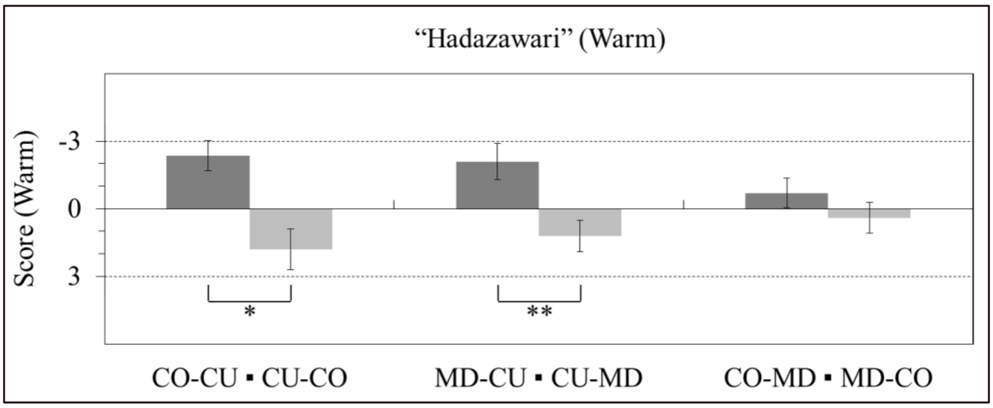
**: $p < 0.01$ *: $p < 0.05$



CO: Cotton; MD: Modal; CU: Cuprammonuium.

(A) Results relevant to the “Cool” feeling

**: $p < 0.01$ *: $p < 0.05$



CO: Cotton; MD: Modal; CU: Cuprammonuium.

(B) Results relevant to the “Warm” feeling

Figure 2-11 Average scores for each combination pattern in different presentation orders and corresponding significance test results for the order effects

2.3.2 Evaluation results related to the perception of moistness

Table 2-6 shows the ANOVA results for the rating of the "Moist" feeling. According to Table 2-6, both "Tezawari" and "Hadazawari" test results revealed that the difference in the sample type led to significant differences in the rating of the "Moist" feeling ($p < 0.01$). Figure 2-12 shows the average preference scores of the three types of samples relevant to the "Moist" feeling, with corresponding significance test results indicated. It is obvious that the perceived moistness of the three types of samples significantly decreased in the order of CU, MD and CO in both "Tezawari" and "Hadazawari" tests ($p < 0.01$). This order was not consistent with the order of the moisture regain rate (a physical indicator of the moisture content) or the order of the moisture deposition rate (a physical indicator of the rate of moisture transfer) at all. Such a result was in agreement with the findings of Tanaka *et al.* [13]. It suggests that the moisture content and the moisture transfer rate cannot be the determining factors of perceived intensity of moistness. In general, the average preference scores for the "Moist" feeling based on "Tezawari" test results and those based on "Hadazawari" test results were similar in the variation range but different in the layout. That is to say, the largest moistness difference between the three types of samples was almost equivalently discriminated with the two sensory test methods; however, the moistness difference between MD and CU was more detectable in the "Hadazawari" test but less detectable in the "Tezawari" test, whereas the moistness difference between CO and MD was more detectable in the "Tezawari" test but less detectable in the "Hadazawari" test. It seems that the general layout of the average preference scores for the "Moist" feeling was very similar to that of the average preference scores for the "Warm" feeling. Figure 2-13 shows the correspondence between average preference scores for the "Moist" feeling and those for the "Warm" feeling. Both "Tezawari" and "Hadazawari" test results revealed that there was a high negative correlation between the average preference scores for the "Moist" feeling and those for the "Warm" feeling. It meant that the between-sample differences in perceived moistness correlated very well with the between-sample differences in perceived coolness. Such a result supports the view of Li *et al.* and Hu *et al.* that the perception of coolness and the perception of moistness correlate with each other [14, 15]. Moreover, the “Hadazawari” test results also revealed that the absolute between-sample differences in perceived coolness were greater than the corresponding absolute between-sample differences in perceived moistness. This result suggests that the perceptual information used for moistness discrimination might be relevant to but not the same as the perceptual information used for coolness discrimination. In summary, based on these results, it is hard to determine whether the “Tezawari” test method or the “Hadazawari” test method is more efficient in moistness discrimination. However, if the dependence between the perception of moistness and the perception of coolness is strong enough, the “Hadazawari” test method, which is considered to be a superior method of discriminating coolness differences, seems to be a better choice for the moistness discrimination, too.

Table 2-6 ANOVA results for the rating of the “Moist” feeling

(A) “Tezawari”

**: $p < 0.01$; *: $p < 0.05$

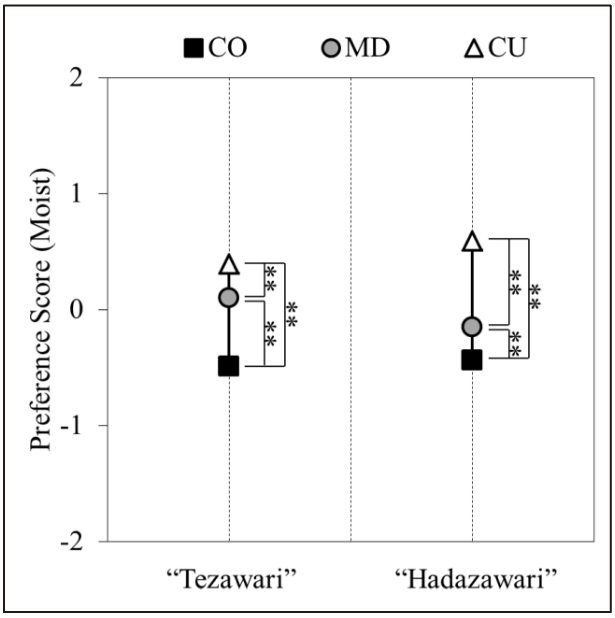
Source	SS	df	MS	F	p	
Sample	48.62	2	24.31	6.63	0.003	**
Combination	0.83	1	0.83	0.23	0.635	
Order	2.13	1	2.13	0.58	0.449	
Error	216.42	59	3.67			
Total	268	120				

(B) “Hadazawari”

**: $p < 0.01$; *: $p < 0.05$

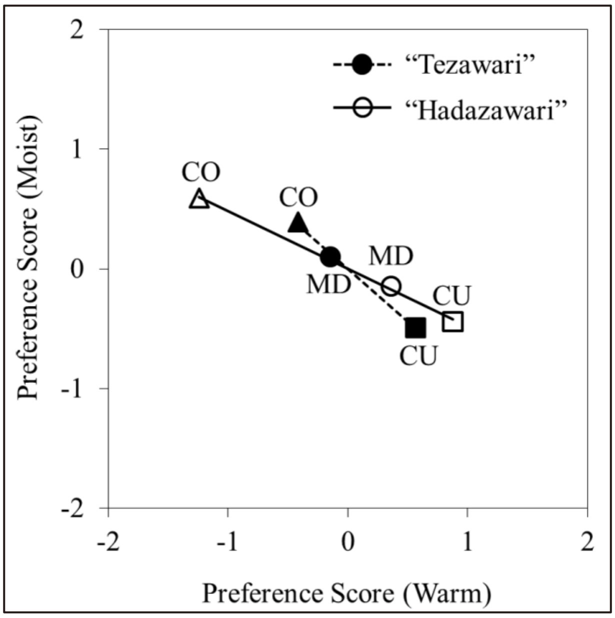
Source	SS	df	MS	F	p	
Sample	68.12	2	34.06	10.16	0.000	**
Combination	0.03	1	0.03	0.01	0.921	
Order	4.03	1	4.03	1.20	0.277	
Error	197.82	59	3.35			
Total	270	120				

**: $p < 0.01$ *: $p < 0.05$



CO: Cotton; MD: Modal; CU: Cuprammonuium.

Figure 2-12 Average preference scores and corresponding significance test results relevant to the “Moist” feeling



CO: Cotton; MD: Modal; CU: Cuprammonuium.

Figure 2-13 Correspondence between average preference scores for the “Warm” feeling and those for the “Moist” feeling

2.4 Discussion

2.4.1 Mechanisms for better coolness discrimination

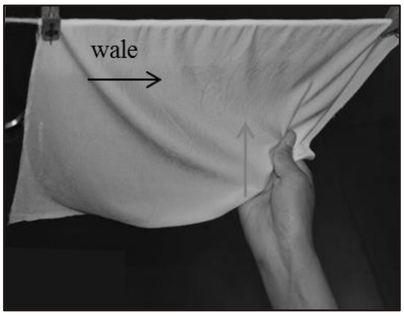
When the skin temperature is between 30℃ and 36℃, a cool/warm sensation is aroused by the decrease/increase in skin temperature [16]. Cold receptors in the skin take charge of detecting the decrease in skin temperature. Warm receptors in the skin take charge of detecting the increase in skin temperature. According to the findings of a number of studies, the factors contributing to the perceived intensity of coolness/warmness mainly include: the skin temperature, thermal properties of the material, the stimulated region of the skin, the area of stimulation and the duration of stimulation [17, 18].

The function of the skin temperature is to determine the baseline responsiveness of thermoreceptors. As reported, when the skin temperature is between 5℃ and 43℃, cold receptors are responsive to the decrease in skin temperature, and the responsiveness of cold receptors reaches the maximum at temperatures between 20℃ and 30℃; when the skin temperature is between 30℃ and 50℃, warm receptors are responsive to the increase in skin temperature, and the responsiveness of warm receptors reaches the maximum at temperatures between 40℃ and 45℃ [19]. In this study, the palmar hand was involved in the "Tezawari" test, and the average skin temperature of the palmar hand was around 32.5℃; the anterior forearm was involved in the "Hadazawari" test, and the average skin temperature of the anterior forearm was around 32℃. The two temperatures were so similar that the responsiveness of thermoreceptors involved in "Tezawari" and "Hadazawari" tests must have been almost equivalent. Therefore, the difference in skin temperature would not be the determining factor that led to the coolness discrimination difference between the two sensory test methods.

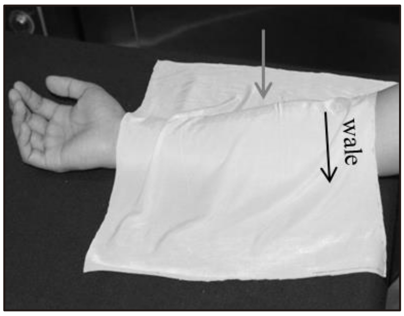
The function of the material's thermal properties is to determine the rate of temperature change. For example, if the temperature difference between the skin and the material is greater, a greater driving force for heat transfer will be generated, and the rate of temperature change will be increased; if the heat conductivity of the material is greater, the heat will move faster through the material, and the rate of temperature change will also be increased [20]. In this study, the specimens used in “Tezawari” and “Hadazawari” tests were completely the same, and the surface temperatures of the specimens were identically controlled at about 24℃. Therefore, the rate of temperature change caused by the contact with each type of sample must have been almost equivalent in “Tezawari” and “Hadazawari” tests. Since the surface temperatures of the specimens were lower than the skin temperatures of the palmar hand and the anterior forearm, in both “Tezawari” and “Hadazawari” tests, the contact with each type of sample definitely caused a cool sensation rather than a warm sensation at the moment of contact. Moreover, whether in the “Tezawari” or “Hadazawari” test, the between-sample differences in perceived intensity of coolness should be attributed to the between-sample differences in heat conductivity. In our opinion, the between-sample differences in heat conductivity might have something to do with the order effects. It is hypothesized that the mechanism for the order effects observed in this study might be like this: If a sample of lower heat conductivity is firstly presented, the decrease in skin temperature within a specific contact duration is less; as a result, the temperature difference between the skin and the secondly-presented sample is greater, and the perceived intensity of the coolness difference between the two samples is higher. In contrast, if a sample of higher heat conductivity is firstly presented, the skin temperature decreases more within a specific contact duration; accordingly, the temperature difference between the skin and the secondly-presented sample is smaller, and the perceived intensity of the coolness difference between the two samples is lower.

The function of the stimulated region of the skin is to determine the average thermal sensitivity of a region of the skin. It is reported that the glabrous skin of the palmar hand is far more sensitive to cold and warm stimuli than the hairy skin of the anterior forearm [21]. Therefore, without being affected by other factors, a thermal stimulus should be more detectable when touched by hand than by forearm. However, whether in the glabrous or hairy skin, there are many more cold receptors than warm receptors. Therefore, all regions of the body are more sensitive to cold stimuli than to warm stimuli [20, 21]. In the "Tezawari" test, it must have been the outstanding cold sensitivity of the glabrous skin that enabled the subjects to discriminate coolness differences between samples very well only with several fingers. However, besides the regional differences in thermal sensitivity, there must have been some other factors that affected the perceived intensity of coolness greatly; otherwise, the "Tezawari" test method should have outperformed the "Hadazawari" test method in the discrimination of coolness.

The function of the area of stimulation is to determine the overall thermal sensitivity of a region of the skin. It has been proved by many a study that thermal sensations have a "spatial summation" property [17, 18, 22]. That is to say, as the area of stimulation is increased, a thermal stimulus is perceived to be more intense, rather than just larger. Therefore, if the area of stimulation is increased, a warm or cold stimulus will become more detectable. It is reported that the spatial summation property of thermal sensations does not need the stimulated regions to be contiguous. When two symmetrical regions of the body (e.g., both forearms) are stimulated simultaneously, the thermal stimulus in one region will be perceived to be more intense than when only a single region is stimulated [16]. According to Figure 2-14, in the "Tezawari" test, the contact area was mainly determined by the overall area of several fingers; in the "Hadazawari" test, the contact area was mainly determined by the overall area of the anterior forearm. Obviously, the total area of the anterior forearm was much larger than that of the fingers. Therefore, it must have been the availability of a large contact area that led the "Hadazawari" test method to be more sensitive to cool stimuli and made it outperform the "Tezawari" test method in coolness discrimination.



(A) “Tezawari”



(B) “Hadazawari”

Figure 2-14 Evaluation techniques involved in the sensory tests

The function of the duration of stimulation is to affect the responsiveness of thermoreceptors over time. On the one hand, the temperature difference between the skin and the material becomes smaller over time because of heat transfer. The decrease in temperature difference will lead the rate of change in skin temperature to decrease during the contact, and therefore cause the perceived intensity of coolness/warmness to decrease over time [23]. On the other hand, the continuous exposure to a thermal stimulus leads to “thermal adaptation”, which is a temporal property of thermal sensations. The occurrence of thermal adaptation will cause the coolness/warmness of a material to be undetectable, even when there is still a temperature difference between the skin and the material [24]. In general, if the contact duration is short, for example, several seconds, the perceived coolness/warmness of a material will change with the temperature decrease/increase of the material; if the contact duration is long, for example, several quarters, the perception of coolness/warmness will be suppressed due to the perceptual insensitiveness caused by thermal adaptation [25]. As shown in Figure 2-14 (A), in the “Tezawari” test, the coolness was evaluated by holding a fabric between fingers. With the fabric warmed simultaneously on both surfaces by fingers, a skin-fabric-skin interface was formed. This interface was good for heat retention but bad for heat dissipation. When fabrics like CU were evaluated via the skin-fabric-skin interface, the thin thickness and the outstanding heat conductivity would lead the fabric temperature to increase rapidly. As a result, the temperature difference between a fabric and the skin became undetectable very soon, and the perceived intensity of coolness decreased dramatically within a short time. As shown in Figure 2-14 (B), in the "Hadazawari" test, the coolness was evaluated by placing a fabric on the forearm. The skin-fabric interface below the fabric was convenient for heat conduction, and the fabric-air interface above the fabric was convenient for heat convection. Owing to the concurrence of heat conduction and heat convection, the skin-fabric-air interface allowed the fabric temperature to increase slowly within a short time. Consequently, the consistency between coolness evaluation results before and after several seconds of contact was much better in the "Hadazawari" test.

In summary, benefiting from the high thermal sensitivity of the palmar hand skin, the "Tezawari" test method is effective enough in instantaneous coolness discrimination. However, the contact duration should be strictly controlled to get comparable results as the "Tezawari" method is used. Owing to the availability of a large contact area on the anterior forearm, the "Hadazawari" test method is even more efficient in coolness discrimination. Moreover, the "Hadazawari" test method has a better tolerance for contact duration, which is very beneficial when some fabrics of thin thickness and outstanding heat conductivity are included. In a word, the "Hadazawari" test method is better choice for coolness discrimination.

2.4.2 Mechanisms for better moistness discrimination

The mechanism for the perception of moistness is still unclear. As no receptors directly responding to the moisture content can be found in the skin, the mechanism for the perception of moistness may be very complex. According to the findings of a few researchers, the changes in skin temperature and moisture content are closely related to the perception of moistness. Li *et al*. found that the brief temperature drop at the skin surface occurring at the moment of contact correlated with the subjectively perceived moistness, and during the skin contact, fabrics with moisture content in excess of equilibrium regain but below fiber saturation depressed the skin temperature less than those with moisture content above fiber saturation [14]. Plante *et al*. found that the differences in perceived moistness became smaller as the ambient humidity or the moisture content of fabrics increased [26]. Niedermann *et al*.

found that it was not able to differentiate the dryness of fabrics as long as the fabrics contained water [27]. These findings suggest that heat and moisture transfer within fabrics and heat and moisture exchange between the skin and fabrics are critical factors that influence the perception of moistness. In addition, Filingeri *et al*. found that, when cold-dry stimuli were applied on the back with high pressure, the perception of moistness was significantly attenuated. This finding suggests that local pressure plays a role in modulating the perception of moistness [28]. Based on the information given above, it is hypothesized that thermal inputs from peripheral thermoreceptors are critical in characterizing the perception of moistness, and the intra-sensory interaction with mechanicoreceptors plays a role in modulating the perception of moistness. Tamura concluded that the perceived intensity of moistness is mainly affected by three factors: the texture change due to the presence of moisture, the rate of moisture transfer caused by the water vapor pressure difference between the skin and the ambient air, and the rate of change in skin temperature caused by latent heat transfer (via moisture evaporating and diffusing through the skin) [23]. In the "Tezawari" test, the moistness was evaluated by means of rubbing a fabric between fingers. In such a process, the change in fabric texture and the change in skin temperature could be perceived simultaneously. In the "Hadazawari" test, the moistness was evaluated by means of leaving a fabric on the forearm. In such a process, the change in skin temperature and local pressure could be perceived simultaneously. Although different kinds of cutaneous information were involved in the perception of moistness in "Tezawari" and "Hadazawari" tests, the moistness perceived within a given time turned out to be almost linearly correlated to the coolness perceived within the same time in both "Tezawari" and "Hadazawari" tests. These results suggest that the change in skin temperature plays a primary role in ranking the perception of moistness, and other factors such as local pressure may play a role in suppressing the perception of moistness. Owing to the dependence of the perception of moistness on thermal cues, the "Hadazawari" test method may be a better choice for moistness discrimination, too.

2.5 Conclusions

In this study, the coolness and moistness discrimination differences between active hand touch ("Tezawari") and passive forearm touch ("Hadazawari") were investigated by taking three types of single jersey fabrics as the samples. Based on the comparative analysis results, the following conclusions are drawn:

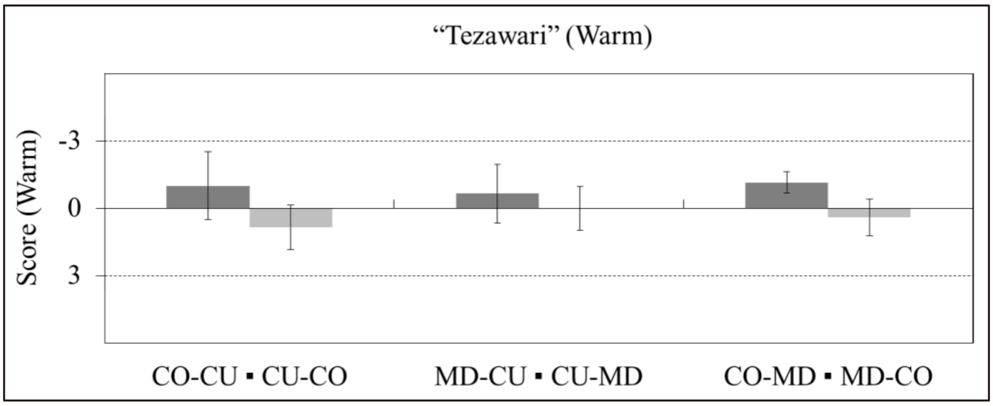
(1) When discriminated via passive forearm touch, the coolness and moistness differences between materials are even more detectable (higher intensity and longer duration); therefore, as a sensory touch method, passive forearm touch is a better choice for coolness and moistness discrimination.

(2) When materials definitely different in perceived coolness are compared in pairs, the presentation order has a significant effect on the perceived intensity of coolness, whether active hand touch or passive forearm touch is involved.

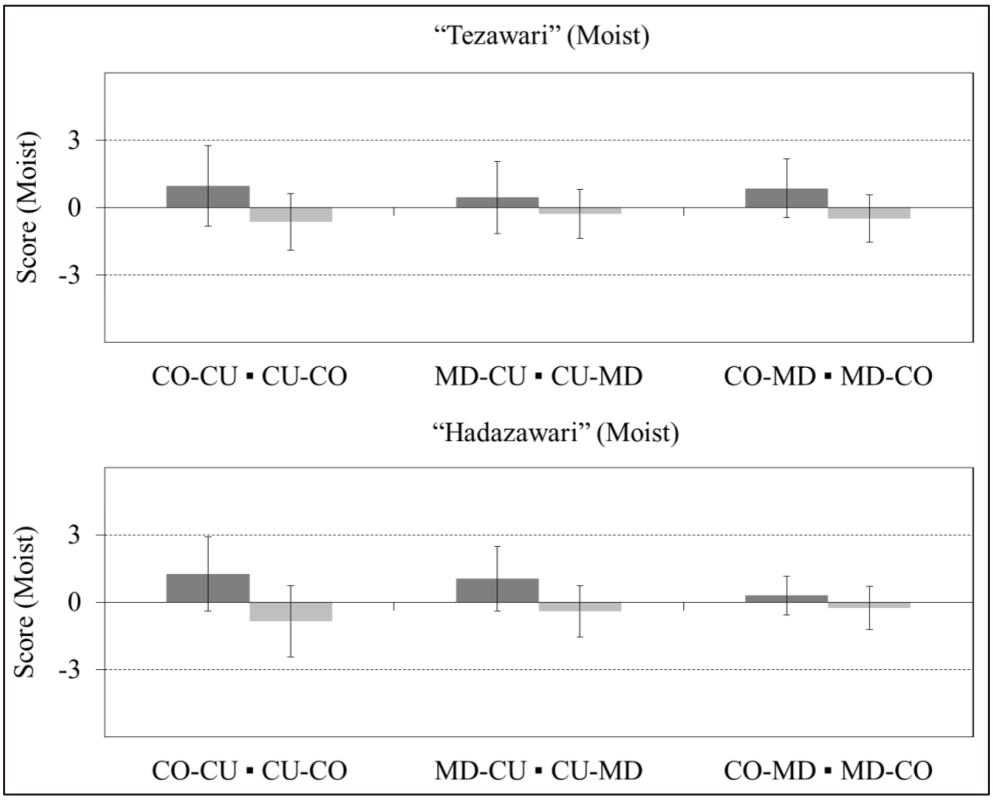
(4) Because of the dependence of the perception of moistness on the change in skin temperature, the relative perceived intensity of moistness correlates very well with the relative perceived intensity of coolness perceived within the same time.

(5) Since passive forearm touch is extremely sensitive to coolness and moistness with the help of a large contact area, as it is used to perceive a specific sensation during the psychophysiological measurement, the coolness and moistness differences between materials should be better controlled; or else, the perception of the target sensation will be greatly affected.

Additional data



(A) Results relevant to the "Warm" feeling



(B) Results relevant to the "Moist" feeling

Figure 2-15 The results relevant to order effects not discussed under the subsection 2.3.1

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Chapter 3

Study on cardiac reactions to tactile smoothness

– based on ECG analysis –

Chapter 3: Study on cardiac reactions to tactile smoothness: based on ECG analysis

3.1 Introduction

3.1.1 Mechanisms for the perception of roughness/smoothness

According to the findings of a few researches, for coarse textures with spatial periods greater than 1 mm, the perception of roughness/smoothness was primarily denpendent on the spatial form; for finer textures, the perception of roughness/smoothness was not directly related to the spatial form [1, 2]. In terms of coarse surfaces, the rougness/smoothness was almost equally discriminable under moving and stationary conditions; in terms of fine surfaces, the rougness/smoothness became indistinguishable due to the absence of movement [3]. What is more, the presence/absence of initiative had a negligible influence on the perception of roughness/smoothness [4-6]. These findings suggest that the perception of roughness/smoothness should be accounted for with a duplex theory. In terms of coarse textures, the spatial variation cues are sufficient for roughness/smoothness discrimination; in terms of fine textures, the temporal variation cues (spatial vibration and/or friction variation) related to the relative movement are necessary for roughness/smoothness discrimination [7-10]. In other words, whether explored actively or passively, the roughness/smoothness differences between fine textures are detectable as long as reletive movement is involved. That is to say, with reletive movement involved, active touch and passive touch are equally suitable for roughness/smoothness discrimination.

With regard to the neural encoding mechanism for the perception of roughness/smoothness, it is hypothesized that the slowly adaption type I (SAI) system and the rapidly adaption type II (RAII) system respond strongly to coarse textures, whereas the rapidly adaption type II (RAII) system reponds strongly to fine textures [11-14]. The SAI system is comprised of Merkel disks and afferents ending in Merkel disks. With the help of the SAI system, we are able to perceive sustained pressure and discriminate the spatial distribution of coarse textures.The RAI system is comprised of Meissner corpuscles and afferents ending in Meissner corpuscles.This system is sensitive to low-frequency vibrations (20 - 50 Hz) but insensitvie to static skin deformation. As reported, the RAI system is four times more sensitive to dynamic skin deformation than the SAI system. With the help of the RAI system, we are able to perceive localized movements and textures that are too slight to activate the SAI system. The RAII system is comprised of Pacinian corpuscles and afferents ending in Pacinian corpuscles. Pacinian corpuscles are responsive to high-frequency vibrations (200 - 300 Hz) and adapt even more rapidly to sustained pressure than Merissner corpuscles. In general, the RAII system is characterized by extreme sensitivity to light pressure, absence of spatial resolution and intense filtering of low-frequency stimuli. With the help of the RAII system, we are able to perceive subtle temperal variaions caused by moving fine textures.

3.1.2 R-R interval, Q-T interval and R-T interval

Figure 3-1 shows the ECG (electrocardiography) signal recorded within a cardiac cycle. The P-wave is the small change in potential caused by the initial excitation of the atrial (upper heart chambers) muscles just prior to their contraction. The QRS-complex represents the contraction of the left and right ventricular (lower chambers of the heart) muscles that pump blood from the ventricular chambers to the lungs and rest of the body. The R-wave is the point of maximum ventricular excitation. The T-wave indicates repolarization of ventricular muscle.

RRI (R-R interval: the interval between the peak points of two adjacent R-waves) represents the duration of a cardiac cycle. With the data of RRI, the heart rate variability (HRV: the beat-to-beat fluctuations of cardiac cycles) can be evaluated in both time and frequency domains [16, 17]. The variations of heart rate (HR) are basically regulated by the autonomic nervous system (ANS). Through HRV analysis, it is possible to evaluate the autonomic nervous activity (the sympathetic and parasympathetic innervation of HR). Table 3-1 shows the parameters commonly used for HRV analysis.

The average value of RRI is inversely proportional to the average HR. When we are under stressful/painful conditions, the average HR tends to increase; accordingly, the average value of RRI tends to decrease [18, 19]. In contrast, when we are under relaxing conditions, the average HR tends to decrease; accordingly, the average value of RRI tends to increase [20]. As reported, the increase of HR is main y due to the enhancement of sympathetic innervation of HR, whereas the decrease of HR is primarily due to the enhancement of parasympathetic innervation of HR [21]. The coefficient of variation (CV) of RRI is usually taken as an indicator of the parasympathetic innervation of HR [22]. It increases with the alleviation of physical and/or mental stress and decreases with the aggravation of physical and/or mental stress [23, 24]. By means of fast Fourier transformation (FFT), the power spectrum of RRI can be estimated. In general, the power spectrum of RRI is characterized by three frequency bands. The power of components in the very-low-frequency band (VLF: $\leq$ 0.04 Hz) is supposed to be affected by the thermal and hormonal regulation [25]; the power of components in the low-frequency band (LF: 0.04 Hz - 0.15 Hz) is thought to be associated with both sympathetic and parasympathetic innervation [26]; the power of components in the high-frequency band (HF: 0.15 Hz - 0.4 Hz) is proved to be closely related to the respiratory rhythm and the parasympathetic innervation [27]. The ratio of LF to HF and the normalized HF are two indicators of the balance between sympathetic and parasympathetic innervation of HR [28]. At times, the ratio of LF to HF is taken as an indicator of the sympathetic innervation of HR, whereas the normalized HF is taken as an indicator of the parasympathetic innervation of HR [29, 30].

QTI (Q-T interval: the interval between the starting point of a Q-wave and the ending point of the following T-wave) represents the overall duration of ventricular depolarization and repolarization [30]. In pathology, the prolonged QTI is regarded as a marker of imbalanced sympathetic innervation of HR [31]. As reported, QTI is primarily determined by RRI (i.e., HR), and the dependence of QTI on RRI (i.e., HR) is considered to be an intrinsic property of the ventricular myocardium [32]. If the Q-wave is not present in the ECG signal, RTI (R-T interval: the interval between the starting point of an R-wave and the ending point of the following T-wave) can be taken as an alternative of QTI to indicate the duration of ventricular depolarization and repolarization [33].

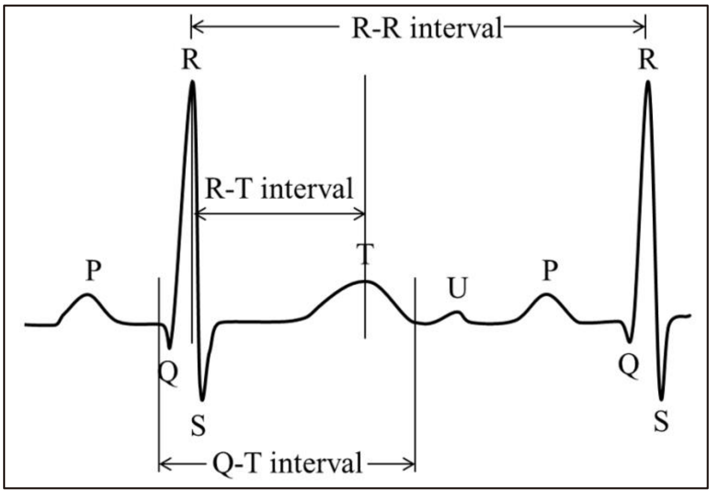


Figure 3-1 Traditional calculation methods of RRI, QTI and RTI

Table 3-1 Parameters used for heart rate variability analysis

Classification	Parameter	Unit	Description
Time domain	RRI (mean)	s	Average value of R-R intervals
	RRI (cv)	%	Coefficient of variation of R-R intervals
Frequency domain	VLF	s^2	Power of very-low-frequency components (≤ 0.04 Hz)
	LF	s^2	Power of low-frequency components (0.04 Hz - 0.15 Hz)
	HF	s^2	Power of high-frequency components (0.15 Hz - 0.4 Hz)
	LF/HF		Ratio of LF to HF
	HFnorm	%	Normalized HF, HFnorm = HF / (LF + HF) × 100%

3.1.3 Objective of this study

We suppose that the frequent and dynamic contact with such products as towels, which are characterized by varieties of tactile textures, may make the human body suffering or delighted and then lead to different levels of stress/ease; accordingly, the cardiac reactions regulated by ANS may show different change trends. Two types of towels different in tactile smoothness and overall comfort are to be chosen to examine this supposition. Active touch and passive touch are considered to be equally sensitive in the perception of smoothness, as long as relative movement is involved. However, as a few researchers have found that the hairy skin of the forearm contains C-tactile afferents, which are necessary for pleasant touch (emotional responses) [34, 35]. Taking into account of the two aspects, the "Hadazawari" test method is to be applied to perceive tactile smoothness during the psychophysiological measurement.

3.2 Experimental details

3.2.1 Materials

3.2.1.1 Specifications

Dozens of wash towels that could be found in the laboratory and in the supermarket were collected. Firstly, those towels were ranked according to the level of perceived smoothness. Secondly, the towels perceived to be cool were removed. In the end, from the towels left, the one perceived to be the smoothest and the one perceived to be the roughest but not painful were selected as the samples used in the physiological test. The two types of samples were labelled as "T1" and "T2", respectively.

Figure 3-2 shows the general images of the two types of samples. T1 was a towel made of 100% polyester, and T2 was a towel made of 62% nylon and 38% polyester. The surface of T1 was characterized by fluffy looped piles, and the surface of T2 was characterized by rugged patterns.

Figure 3-2 Samples used in the physiological test

3.2.1.2 Surface properties

The surface properties of the two types of samples were measured with TL-201Ts (Trinity-lab Inc., Tokyo, Japan) (as shown in Figure 3-3) under the environmental condition of "20℃ ± 2℃, 65% ± 4% RH". The load applied to the surface to be measured was set as 50 g, the movement speed of the sensor was set as 1 mm/sec, and the maximum displacement distance was set as 20 mm. Figure 3-4 shows the measurement results for the average value and standard deviation (SD) of kinetic friction coefficient. The average kinetic friction coefficient signifies the magnitude of surface friction. It is a physical indicator of surface stickiness/slipperiness. The SD of kinetic friction coefficient signifies the variation range of surface friction. It is a physical indicator of frictional surface roughness/smoothness. The independent-samples T test was conducted to examine the statistical significance of between-sample and between-direction differences in the average value and SD of kinetic friction coefficient. The corresponding significance test results are indicated in Figure 3-4.

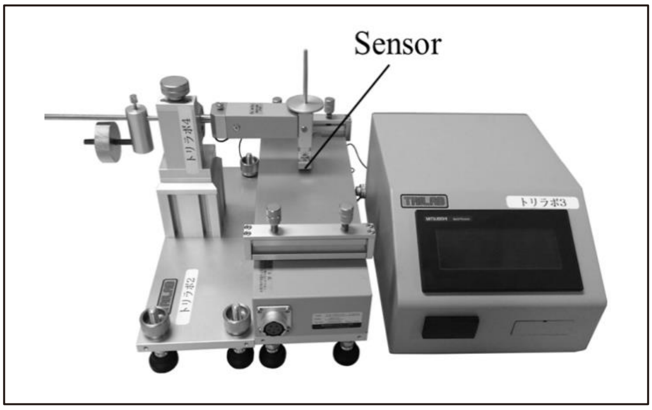


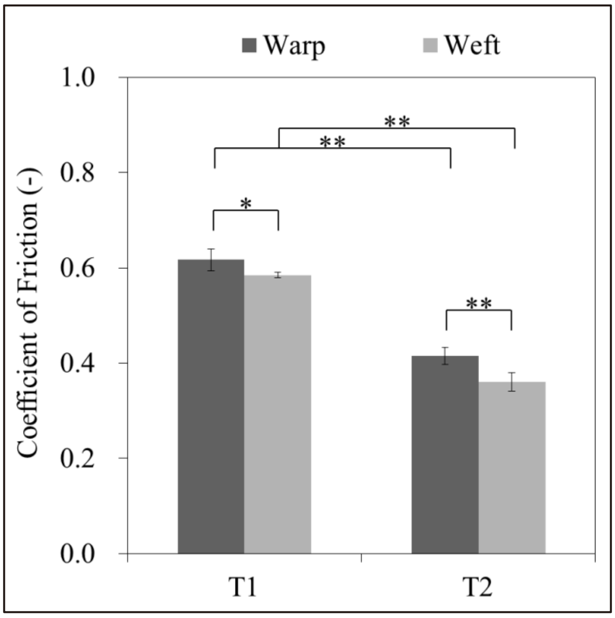
Figure 3-3 TL-201Ts used for surface property measurement

According to Figure 3-4 (A), the average value of kinetic friction coefficient relevant to T1 was significantly larger than that relevant to T2 in both warp and weft directions; in terms of T1, the average value of kinetic friction coefficient measured in warp direction was larger than that measured in weft direction at a significance level of 0.05; in terms of T2, the average value of kinetic friction coefficient measured in warp direction was larger than that measured in weft direction at a significance level of 0.01. These results indicated that the surface friction of T1 was greater than that of T2 in general. Therefore, the surface of T2 ought to be slipperier than the surface of T1.

According to Figure 3-4 (B), in both warp and weft directions, the SD of kinetic friction coefficient relevant to T1 was significantly larger than that relevant to T2 ($p < 0.01$); besides, the SD of kinetic friction coefficient measured in warp direction was significantly larger than that measured in weft direction ($p < 0.01$). These results indicated that the variation of the surface friction of T1 was greater than the variation of the surface friction of T2 in general.

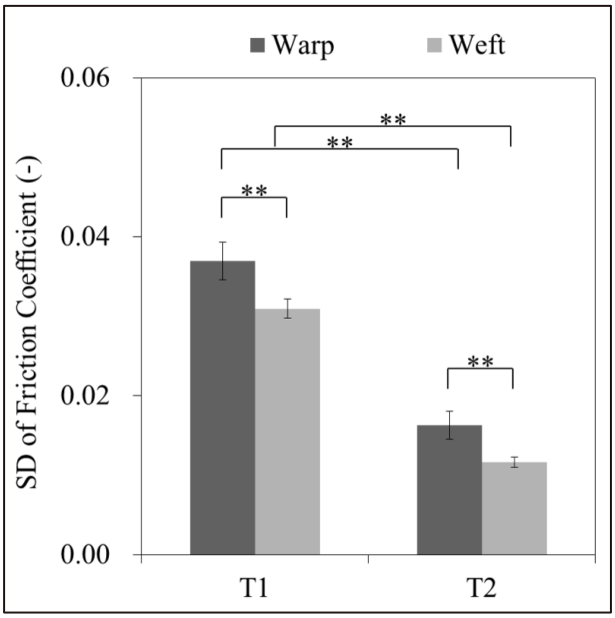
Figure 3-5 shows the friction coefficient curves of T1 and T2. Obviously, the friction coefficient curves of T1 varied delicately along with the progress of the sensor, whereas the friction coefficient curves of T2 varied irregularly along with the progress of the sensor. It suggests that the surface of T1 ought to be evener than the surface of T2.

**: p < 0.01 *: p < 0.05



(A) Average kinetic friction coefficient

**: p < 0.01 *: p < 0.05



(B) Standard deviation of kinetic friction coefficient

Figure 3-4 Measurement and significance test results for surface properties

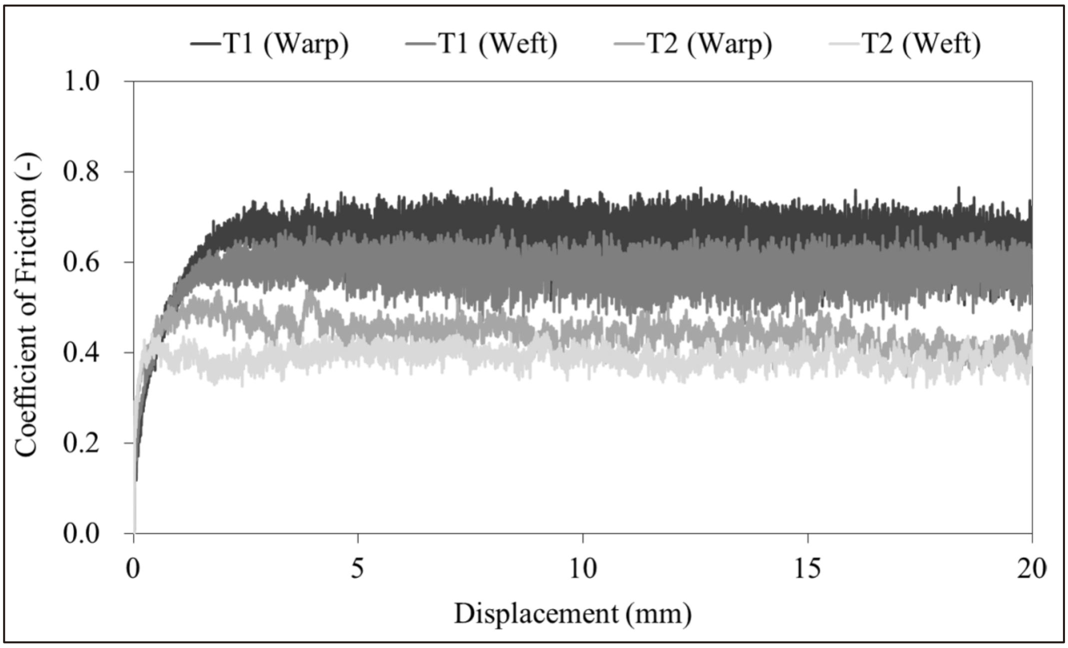


Figure 3-5 Friction coefficient curves measured with TL-201Ts

3.2.1.3 Sensory attributes

The sensory attributes of the two types of samples were investigated via a "Hadazawari" test that was carried out under the environmental condition of "24℃ ± 1℃, 50% ± 2% RH" in a climate chamber. Six pairs of terms, namely "Cool – Warm, Damp – Dry, Hard – Soft, Sticky – Slippery, Rough – Smooth and Uncomfortable – Comfortable", were involved in the sensory test. The rating scale was designed with the semantic differential (SD) method, which ranged from "-3" to "3". "-3, -2 and -1" meant the feeling indicated by the term on the left side could be "extremely, moderately and slightly" experienced in order; "3, 2 and 1" meant the feeling indicated by the term on the right side could be "extremely, moderately and slightly" experienced in order; "0" meant neither the feeling indicated by the term on the left side nor the feeling indicated by the term on the right side could be definitely experienced.

Figure 3-6 shows the sensory test results. The perceived warmness and dryness of the two types of samples were very similar. In general, T1 was perceived to be a relatively soft, slippery, smooth and comfortable material, whereas T2 was perceived to be a relatively hard, sticky, rough and uncomfortable material. The perceived softness, slipperiness and smoothness might all have contributed to the tactile comfort, and the contributions of perceived slipperiness and smoothness were even greater than that of perceived softness. What is more, the result that the slipperiness of T1 was perceived to be better than that of T2 was not consistent with what was indicated by the average kinetic friction coefficient. It is supposed that the perception of slipperiness might have been obscured by the perception of smoothness. Therefore, the perceived smoothness might have contributed mostly to the tactile comfort.

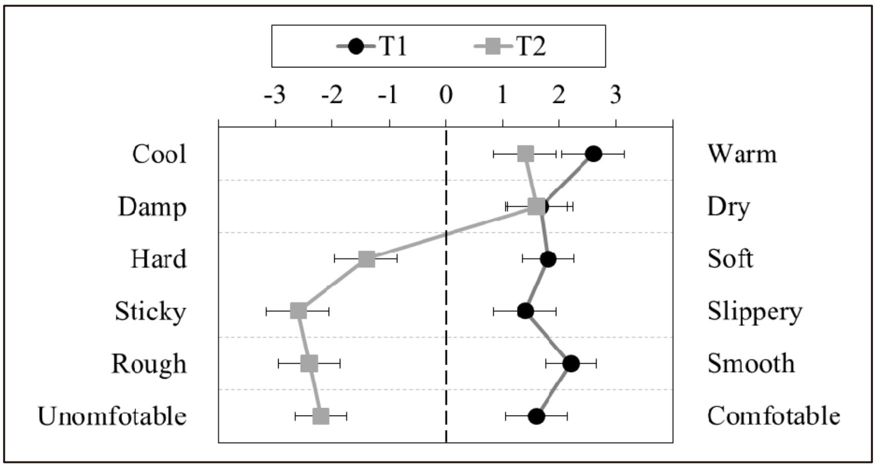


Figure 3-6 Sensory attributes of the samples

3.2.2 Subjects

Fifteen healthy university students (eight females and seven males) aged from twenty-two to twenty-eight years old participated in the experiment. None of them had a medical history of perceptual disturbance. Each of them was required to refrain from smoking, drinking coffee and black tea and doing intensive exercise six hours before the physiological test. Table 3-2 shows the basic physical characteristics of the subjects.

Table 3-2 Physical characteristics of the subjects

Gender	Number	Age (years)	Height (cm)	Weight (kg)	Forearm temperature (℃)
Male	7	23.6 ± 2.1	170.9 ± 4.3	60.3 ± 6.5	31.7 ± 0.8
Female	8	24.9 ± 2.2	159.0 ± 5.7	49.6 ± 3.9	32.4 ± 0.8

3.2.3 Psychophysiological measurement

The physiological tests were conducted in a climate chamber under the environmental condition of "24℃ ± 1℃, 50% ± 2% RH". Before the starting of each physiological test, the samples had been conditioned for more than twelve hours under the same environmental condition.

The MP 100 data acquisition system (BIOPAC Systems Inc., New York, USA) was used to record the ECG signal in the physiological tests. The ECG signal was detected by three ECG electrodes. Figure 3-7 shows the locations of the three ECG electrodes. A digital metronome (DM100, Seiko Instruments Inc., Tokyo, Japan) was used to control the respiratory rate of the subjects.

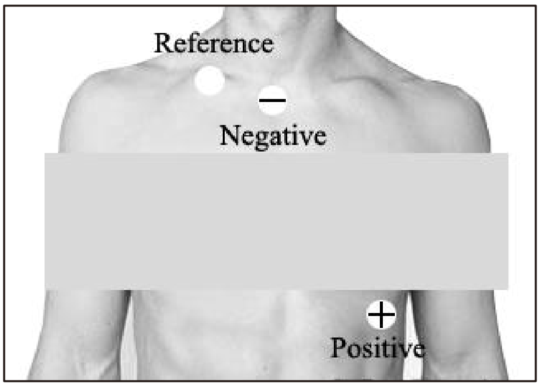


Figure 3-7 Locations of ECG electrodes

The subjects were dressed in short-sleeve T-shirts made of 100% cotton on the upper body when tested. All of the physiological tests were carried out between 2 o'clock and 5 o'clock in the afternoon. Figure 3-8 shows the procedure of physiological measurement. Each subject went through two physiological tests in succession within about one hour. Between the two physiological tests, there were five to ten minutes for a subject to have a rest. During the twenty minutes before the starting of the first physiological test, a subject had to sink into the chair and have a rest, and the experimenter had to take charge of equipping the subject with the MP 100 data acquisition system. As shown in Figure 3-8, each physiological test lasted for six minutes in total, and it was comprised of three successive conditions: "Rest" condition for two minutes, "Task" condition for two minutes, and "Re-rest" condition for two minutes. Under the three successive conditions, a subject just had to keep being seated in the chair with the right arm placed on the table and keep quiet. The experimenter had to take charge of monitoring the recorded ECG signal under "Rest" and "Re-rest" conditions and rubbing the right forearm of the subject repeatedly with a towel (T1 or T2) under "Task" condition. The sequence that T1 and T2 were used in the two physiological tests was randomly determined. During each physiological test, a subject was blindfolded with a pair of lightproof glasses, and the respiratory rate of the subject was controlled at fifteen breaths per minute.

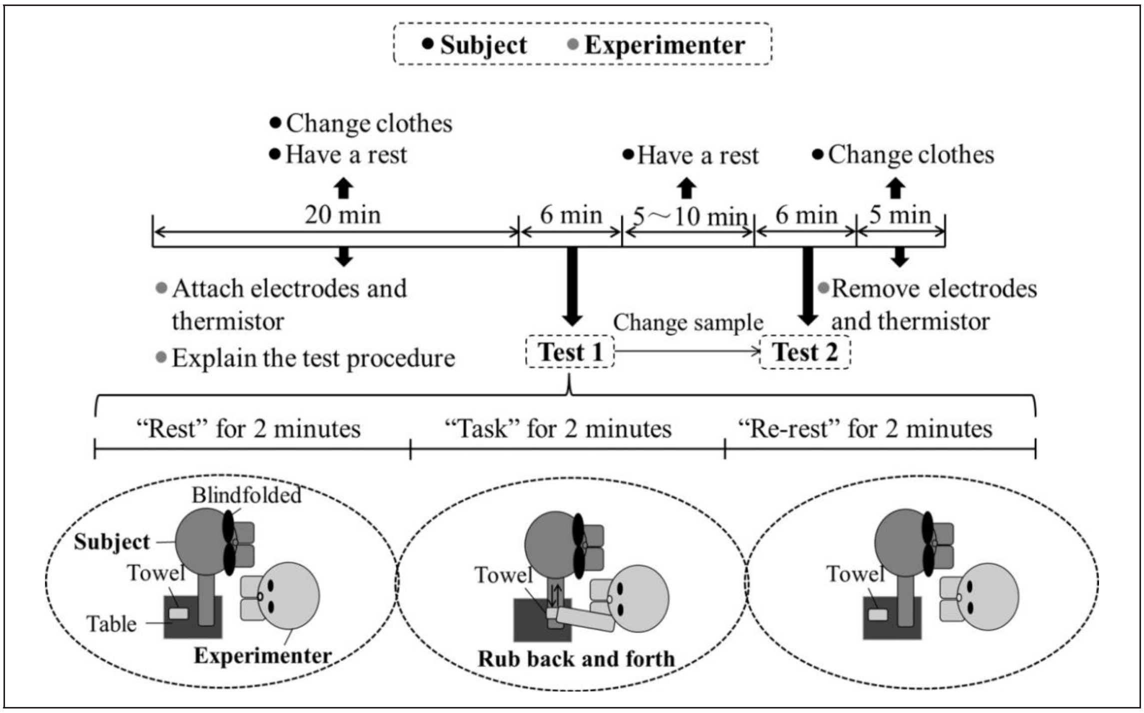


Figure 3-8 The procedure of physiological measurement

3.2.4 Data acquisition

Figure 3-9 shows the ECG signal measured with the MP 100 data acquisition system. The data of RRI were calculated to study the variability of HR (HRV), and the data of RTI were calculated to study the variability of ventricular depolarization and repolarization duration. Unlike traditional ways, the interval between the peak point of an R-wave and the peak point of the following T-wave was calculated as RTI in this study.

The data between the 15th second and the 105th second were taken as the valid data under “Rest” condition, the data between the 135th second and the 225th second were taken as the valid data under “Task” condition, and the data between the 255th second and the 345th second were taken as the valid data under “Re-rest” condition. Under the three conditions, the average value of RRI (“RRI (mean)”), the average value of RTI (“RTI (mean)”), and the value of normalized HF of RRI (“HFnorm (RRI)”) were calculated to examine changes in average HR, average duration of ventricular depolarization and repolarization, and balance between sympathetic and parasympathetic innervation of HR, respectively.

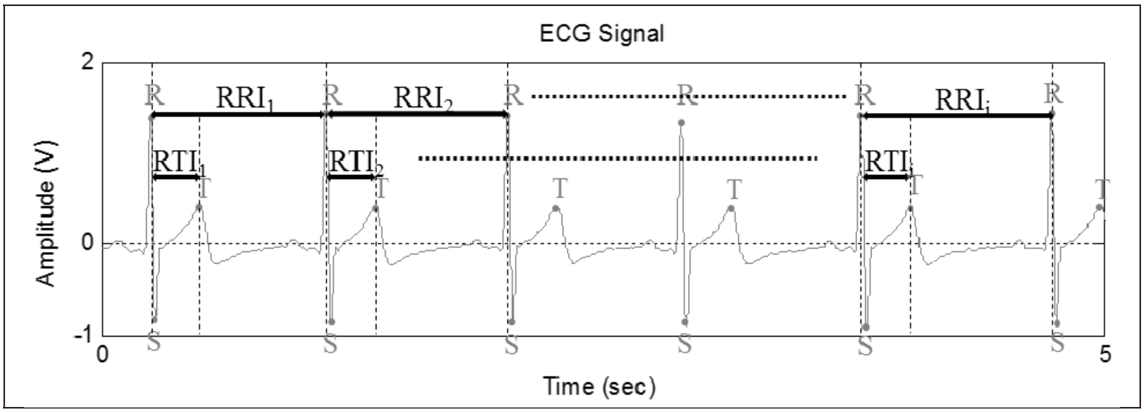


Figure 3-9 The ECG signal used for data acquisition

3.2.5 Data analysis

The calculated values of each parameter were standardized as per the expressions shown in Figure 3-10. The standardized values of each parameter were used for significance test.

$$\text{Standardized Rest (T1)} = \frac{\text{Rest (T1)}}{\frac{\text{Rest (T1)} + \text{Rest (T2)}}{2}} \qquad \text{Standardized Rest (T2)} = \frac{\text{Rest (T2)}}{\frac{\text{Rest (T1)} + \text{Rest (T2)}}{2}}$$

$$\text{Standardized Task (T1)} = \frac{\text{Task (T1)}}{\frac{\text{Rest (T1)} + \text{Rest (T2)}}{2}} \qquad \text{Standardized Task (T2)} = \frac{\text{Task (T2)}}{\frac{\text{Rest (T1)} + \text{Rest (T2)}}{2}}$$

$$\text{Standardized Re-rest (T1)} = \frac{\text{Re-rest (T1)}}{\frac{\text{Rest (T1)} + \text{Rest (T2)}}{2}} \qquad \text{Standardized Re-rest (T2)} = \frac{\text{Re-rest (T2)}}{\frac{\text{Rest (T1)} + \text{Rest (T2)}}{2}}$$

Figure 3-10 Expressions used for data standardization

3.3 Results

3.3.1 Cardiac reactions to the experience of dynamic contact with towels

The two-way ANOVA was applied to examine the statistical significance of main effects of the "sample" type (T1 and T2) and the test "condition" (Rest and Task) on the variation of each parameter. The two-way ANOVA results are shown in Table 3-3.

Table 3-3 Two-way ANOVA results relevant to the experience of dynamic contact with towels

(A) Dependent variable: RRI (mean)

**: $p < 0.01$; *: $p < 0.05$

Source	SS	df	MS	F	p
Sample	0.012	1	0.012	3.745	0.058
Condition	0.001	1	0.001	0.291	0.592
Sample × Condition	0.001	1	0.001	0.383	0.539
Error	0.177	56	0.003		
Total	60.662	60			

(B) Dependent variable: RTI (mean)

**: $p < 0.01$; *: $p < 0.05$

Source	SS	df	MS	F	p
Sample	0.001	1	0.001	2.402	0.127
Condition	0.000	1	0.000	0.687	0.411
Sample × Condition	0.000	1	0.000	0.120	0.730
Error	0.017	56	0.000		
Total	60.243	60			

(C) Dependent variable: HFnorm (RRI)

**: $p < 0.01$; *: $p < 0.05$

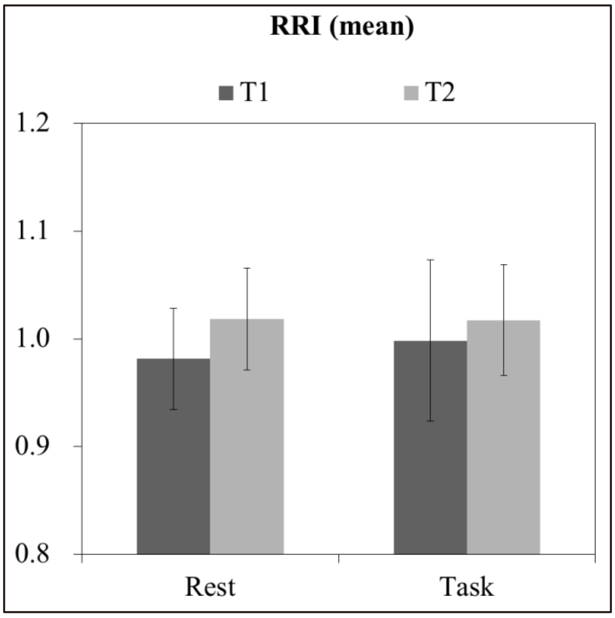
Source	SS	df	MS	F	p
Sample	0.009	1	0.009	0.132	0.718
Condition	0.010	1	0.010	0.142	0.707
Sample × Condition	0.030	1	0.030	0.444	0.508
Error	3.791	56	0.068		
Total	62.329	60			

According to Table 3-3 (A), the “sample” type and the test “condition” had no significant effects on the variation of the parameter RRI (mean); besides, the interactive effect between the “sample” type and the test “condition” on the variation of RRI (mean) was not significant, either. These results indicated that, whether the subjects were rubbed by a smooth and comfortable towel like T1 or by a rough and uncomfortable towel like T2, the average HR did not show a significant change trend. Figure 3-11 (A) shows the standardized values of RRI (mean) under “Rest” and “Task” conditions. When the subjects were rubbed with T1 under “Task” condition, the SD of RRI (mean) was a little greater. It suggests that the dynamic contact with a smooth and comfortable towel like T1 tends to enlarge the individual differences in average HR.

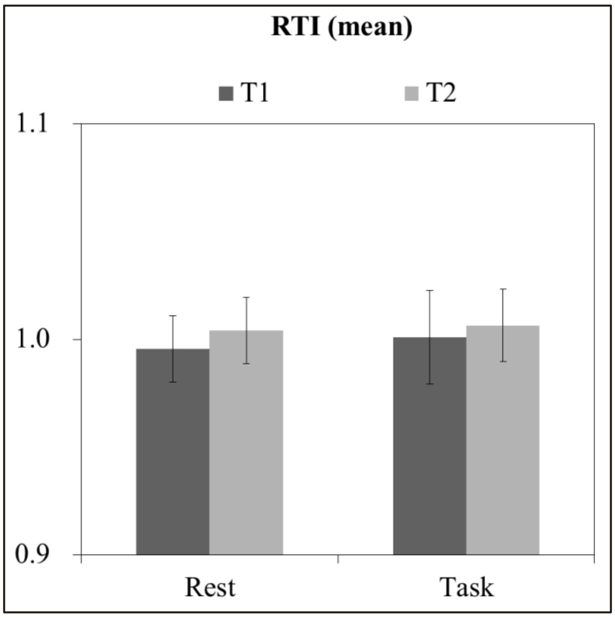
According to Table 3-3 (B), the variation of the parameter RTI (mean) was not significantly affected by the “sample” type, the test “condition” or the interaction between the “sample” type and the test “condition”. These results indicated that the dynamic contact with a towel, whether it was a smooth and comfortable one or a rough and uncomfortable one, failed to cause the average duration of ventricular depolarization and repolarization to show a significant change trend. Figure 3-11 (B) shows the standardized values of RTI (mean) under “Rest” and “Task” conditions. It is obvious that the change trends of RTI (mean) were very similar to the corresponding change trends of RRI (mean).

According to Table 3-3 (C), the “sample” type, the test “condition” and the interaction between the “sample” type and the test “condition” had no significant effects on the variation of the parameter HFnorm (RRI). These results indicated that neither the dynamic contact with a smooth and comfortable towel nor the dynamic contact with a rough and uncomfortable towel tended to lead the balance between sympathetic and parasympathetic innervation of HR to show a significant change trend. Figure 3-11 (C) shows the standardized values of HFnorm (RRI) under “Rest” and “Task” conditions. When the subjects were rubbed with T2 under “Task” condition, the SD of HFnorm (RRI) was a little larger. It suggests that the dynamic contact with a rough and uncomfortable towel like T2 tends to enlarge the individual differences in the balance between sympathetic and parasympathetic innervation of HR.

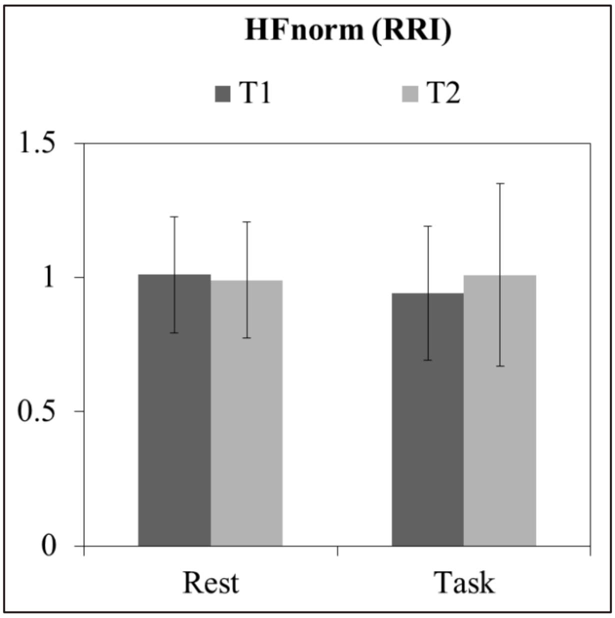
In summary, the average HR, the average duration of ventricular depolarization and repolarization and the balance between sympathetic and parasympathetic innervation of HR are not significantly affected by the experience of dynamic contact with a towel, whether it is a smooth and comfortable one or a rough and uncomfortable one.



(A) Average value of RRI



(B) Average value of RTI



(C) Normalized HF of RRI

Figure 3-11 Standardized values of the three parameters under “Rest” and “Task” conditions

3.3.2 Cardiac reactions to the removal of dynamic contact with towels

The two-way ANOVA was applied to examine the statistical significance of main effects of the “sample” type (T1 and T2) and the test “condition” (Rest and Re-rest) on the variation of each parameter. Table 3-4 shows the two-way ANOVA results.

According to Table 3-4 (A), the overall variation of RRI (mean) was significantly affected by the “sample” type ($p < 0.01$). Figure 3-12 shows the standardized values of RRI (mean) under “Rest” and “Re-rest” conditions. According to it, without sorting out test conditions, the values of RRI (mean) relevant to T2 as a whole were significantly greater than those relevant to T1 as a whole ($p < 0.01$). From “Rest” condition to “Re-rest” condition, both the values of RRI (mean) relevant T1 and those relevant to T2 showed an increasing trend; besides, the increment relevant to T2 tended to be a little larger. These results suggest that the removal of dynamic contact with a towel tends to cause the average HR to decease, and the overall decrement of average HR caused by the removal of dynamic contact with a rough and uncomfortable towel tends to be greater.

Table 3-4 Two-way ANOVA results relevant to the removal of dynamic contact with towels

(A) Dependent variable: RRI (mean)

**: p < 0.01; *: p < 0.05

Source	SS	df	MS	F	p	
Sample	0.026	1	0.026	10.410	0.002	**
Condition	0.008	1	0.008	3.221	0.078	
Sample × Condition	0.000	1	0.000	0.120	0.730	
Error	0.139	56	0.002			
Total	61.568	60				

(B) Dependent variable: RTI (mean)

**: p < 0.01; *: p < 0.05

Source	SS	df	MS	F	p	
Sample	0.002	1	0.002	5.080	0.028	*
Condition	0.002	1	0.002	7.117	0.010	**
Sample × Condition	0.000	1	0.000	0.143	0.707	
Error	0.018	56	0.000			
Total	60.755	60				

(C) Dependent variable: HFnorm (RRI)

**: p < 0.01; *: p < 0.05

Source	SS	df	MS	F	p
Sample	0.008	1	0.008	0.166	0.686
Condition	0.055	1	0.055	1.183	0.281
Sample × Condition	0.028	1	0.028	0.601	0.442
Error	2.582	56	0.046		
Total	59.108	60			

**: p < 0.01 *: p < 0.05

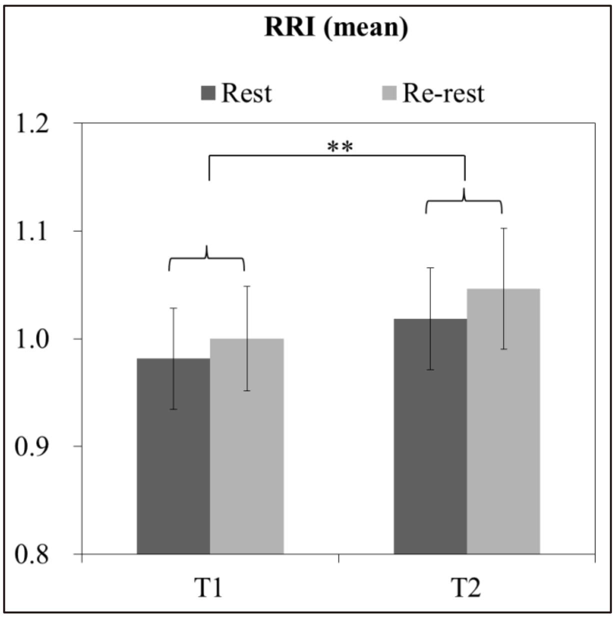
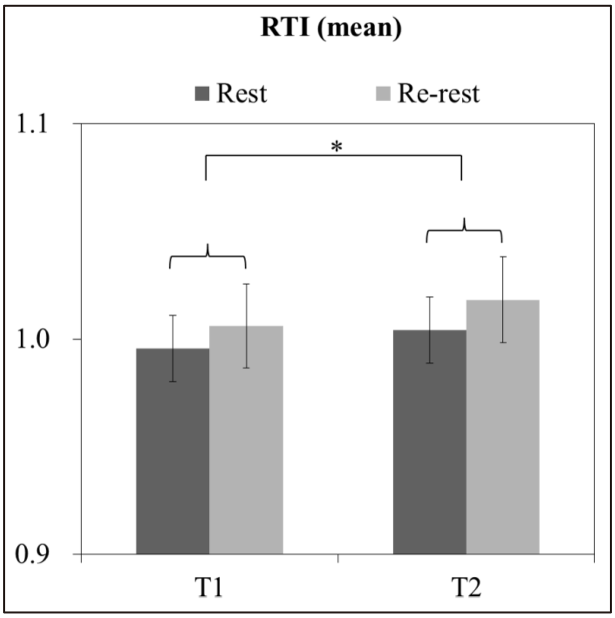


Figure 3-12 Standardized values of RRI (mean) under “Rest” and “Re-rest” conditions

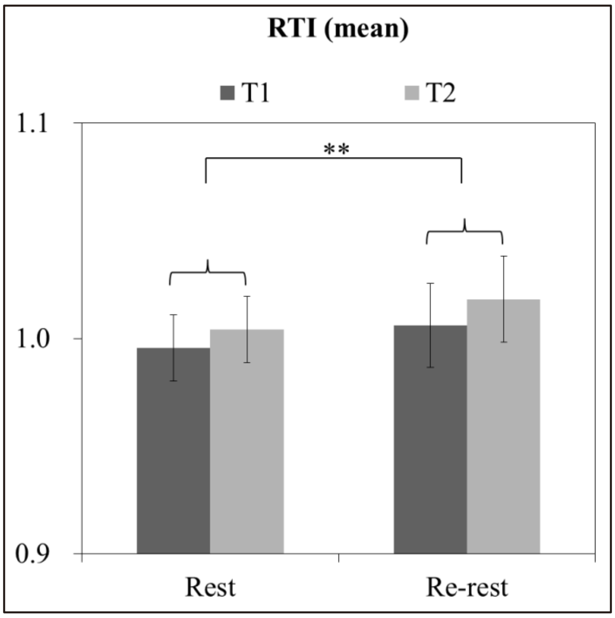
According to Table 3-4 (B), the “sample” type had an effect on the variation of RTI (mean) at a significance level of 0.05, and the test “condition” had an effect on the variation of RTI (mean) at a significance level of 0.01. Figure 3-13 shows the standardized values of RTI (mean) under “Rest” and “Re-rest” conditions. As shown in Figure 3-13 (A), without sorting out test conditions, the values of RTI (mean) relevant to T2 as a whole were significantly greater than those relevant to T1 as a whole ($p < 0.05$). From “Rest” condition to “Re-rest” condition, both the value of RTI (mean) relevant to T1 and that relevant to T2 showed an increasing trend, and the increment relevant to T2 tended to be larger. As shown in Figure 3-13 (B), without sorting out sample types, the values of RTI (mean) under “Re-rest” condition as a whole were significantly greater than those under “Rest” condition as a whole ($p < 0.01$). Under “Re-rest” condition, the difference between the value of RTI (mean) relevant to T2 and that relevant to T1 was even greater. These results suggest that the removal of dynamic contact with a towel tends to lead the average duration of ventricular depolarization and repolarization to increase; furthermore, the removal of dynamic contact with a rough and uncomfortable towel seems to lead to a larger increment in average duration of ventricular depolarization and repolarization.

**: $p < 0.01$ *: $p < 0.05$



(A) Between-sample

**: $p < 0.01$ *: $p < 0.05$



(B) Between-condition

Figure 3-13 Standardized values of RTI (mean) under “Rest” and “Re-rest” conditions

According to Table 3-4 (C), the "sample" type, the test "condition" as well as the interaction between the "sample" type and the test "condition" had no significant effects on the variation of the parameter HFnorm (RRI). These results indicated that, both the removal of dynamic contact with a smooth and comfortable towel like T1 and the removal of dynamic contact with a rough and uncomfortable towel like T2 failed to cause the balance between sympathetic and parasympathetic innervation of HR to show a significant change trend. Figure 3-14 shows the standardized values of HFnorm (RRI) under "Rest" and "Re-rest" conditions. According to it, the value of HFnorm (RRI) tended to decrease slightly from "Rest" condition to "Re-rest" condition. It suggests that the parasympathetic innervation of HR tends to decrease after the dynamic contact with a smooth and rough towel.

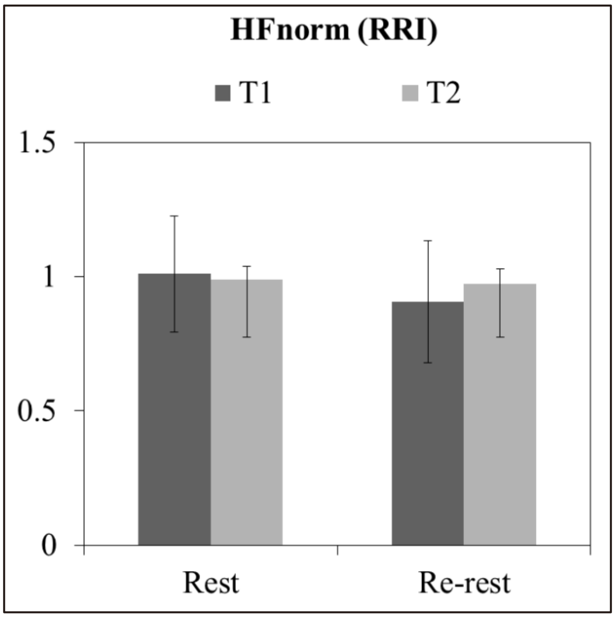


Figure 3-14 Standardized values of HFnorm (RRI) under "Rest" and "Re-rest" conditions

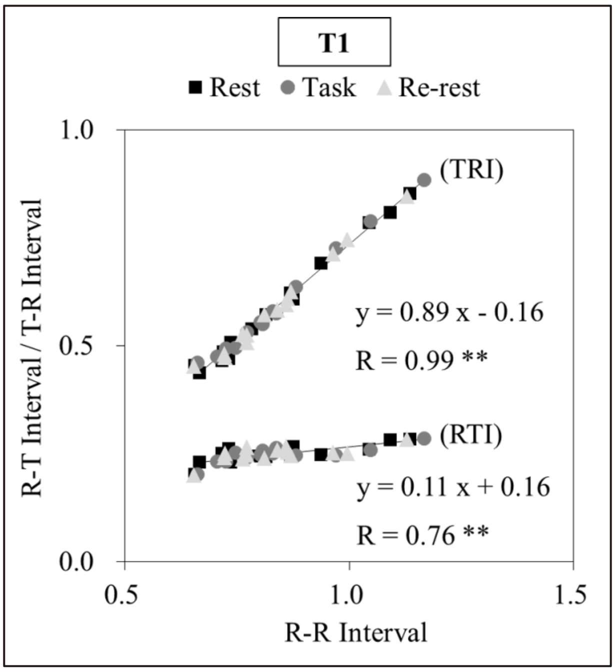
In summary, owing to the removal of dynamic contact with a relatively smooth and comfortable towel and/or a relatively rough and uncomfortable towel, the average HR tends to decrease and the average duration of ventricular depolarization and repolarization tends to increase. However, neither the removal of dynamic contact with a relatively smooth and comfortable towel nor the removal of dynamic contact with a relatively rough and uncomfortable towel tends to cause the balance between sympathetic and parasympathetic innervation of HR to change significantly.

3.4 Discussion

3.4.1 The relationship between RTI and RRI

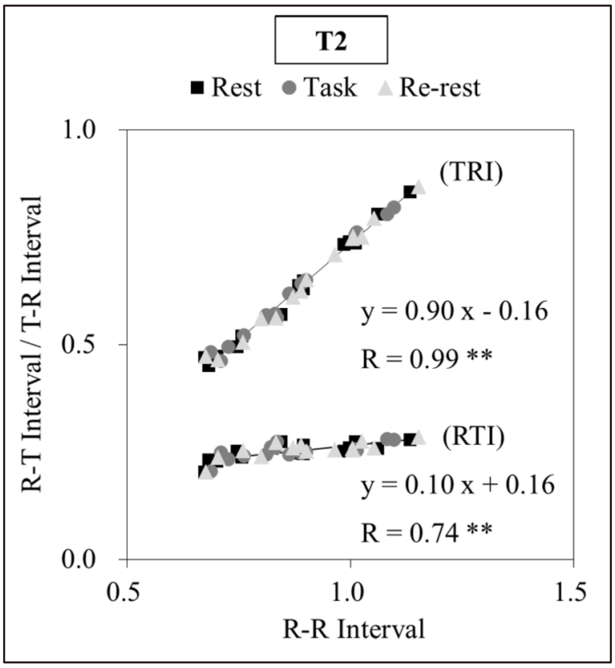
Each RRI (R-R interval) is comprised of an RTI (R-T interval) and a TRI (T-R interval). As introduced previously, RTI refers to the interval between the starting point of an R-wave and the ending point of the following T-wave traditionally; accordingly, TRI turns out to be the interval between the ending point of a T-wave and the starting point of the following R-wave. In this study, RTI was calculated as the interval between the peak point of an R-wave and the peak point of the following T-wave; therefore, TRI turned out to be the interval between the peak point of a T-wave and the peak point of the following R-wave. Mao *et al*. have examined the correlation between the traditionally calculated RTI and RRI as well as the correlation between the traditionally calculated TRI and RRI. According to their findings, the coefficient of the correlation between the traditionally calculated RTI and RRI was 0.76, and the coefficient of the correlation between the traditionally calculated TRI and RRI was 0.99 [36]. Figure 3-15 shows the correlation between RTI and RRI and that between TRI and RRI based on the calculation results in this study. According to it, the coefficient of the correlation between RTI and RRI was around 0.75 (T1: R = 0.76; T2: R = 0.74), and the coefficient of the correlation between TRI and RRI approached to 0.99 (T1: R = 0.99; T2: R = 0.99). Obviously, the correlation coefficients calculated in this study are consistent with the corresponding correlation coefficients calculated by Mao *et al.*. It suggests that the RTI calculated with the method introduced in this study can be taken as an alternative of the traditionally calculated RTI. That is to say, it is reasonable enough to take the interval between the peak point of an R-wave and the peak point of the following T-wave as an indicator of the duration of ventricular depolarization and repolarization. According to Figure 3-15, RTI increases linearly with the increase of RRI, but the increase rate is very slight. Owing to this characteristic, the individual differences in RTI turn out to be much smaller than the individual differences in RRI.

**: p < 0.01 *: p < 0.05



(A) Results relevant to T1

**: p < 0.01 *: p < 0.05



(B) Results relevant to T2

Figure 3-15 The correlation between RTI/TRI and RRI

3.4.2 Mechanisms for cardiac reactions to tactile smoothness

Without sorting out sample types, one-way ANOVA was applied to examine the statistical significance of the differences in each parameter between the six conditions. Table 3-5 shows the one-way ANOVA results. According to it, there were significant differences between some of the six conditions in RRI (mean) ($p < 0.05$) and RTI (mean) ($p < 0.05$). Figure 3-16 shows the corresponding least significant difference (LSD) post-hoc test results. According to Figure 3-16 (A), the value of RRI (mean) under the "Re-rest" condition relevant to T2 was significantly larger than that under each of the three conditions relevant to T1. According to Figure 3-16 (B), the value of RTI (mean) under the "Re-rest" condition relevant to T2 was significantly larger than that under the "Rest" condition relevant to T1 ($p < 0.01$) and that under the "Task" condition relevant to T1 ($p < 0.05$). Obviously, whether T1 or T2 was involved, the change trend of RRI (mean) and the corresponding change trend of RTI (mean) under the three successive conditions were not the same but similar. What is worth noting is that, the increase of RRI (mean) from "Rest" condition to "Re-rest" condition was not statistically significant, whereas the increase of RTI (mean) from "Rest" condition to "Re-rest" condition was statistically significant was a level of 0.0.5. It is supposed that, as a small part of RRI, RTI may be not so easy to be affected by some occasional changes, which may happen to RRI; as a result, RTI turns out to be more sensitive to expected changes than RRI. In general, the increase in RTI should be ascribed to the increase in RRI, and the increase in RRI indicates the decrease in HR. When the dynamic contact with a towel was removed, the average HR tended to become even lower than the HR before the dynamic contact with a towel occurred. It is supposed that the removal of dynamic contact with a towel tends to enhance the parasympathetic innervation of HR and make the average HR decrease.

In summary, both the removal of dynamic contact with T1 and the removal of dynamic contact with T2 tend to lead the average HR to decrease and lead the average duration of ventricular depolarization and repolarization to increase. The increase of average HR might be due to the increase of parasympathetic innervation of HR. In other words, the removal of dynamic contact with a towel tends to enhance parasympathetic nervous activity.

Table 3-5 One-way ANOVA results without sorting out sample types

(A) Dependent variable: RRI (mean)

**: $p < 0.01$; *: $p < 0.05$

Source	SS	df	MS	F	p	
Between conditions	0.037	5	0.007	2.458	0.040	*
Within conditions	0.254	84	0.003			
Total	0.292	89				

(B) Dependent variable: RTI (mean)

**: $p < 0.01$; *: $p < 0.05$

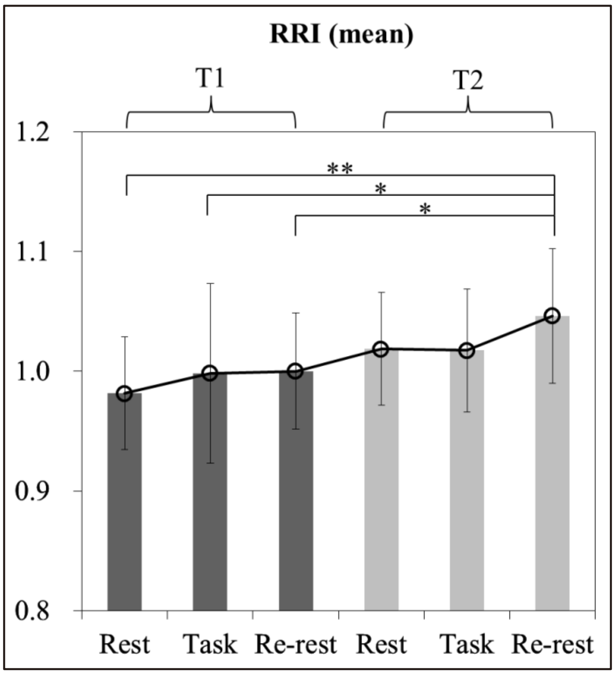
Source	SS	df	MS	F	p	
Between conditions	0.004	5	0.001	2.511	0.036	*
Within conditions	0.028	84	0.000			
Total	0.032	89				

(C) Dependent variable: HFnorm (RRI)

**: $p < 0.01$; *: $p < 0.05$

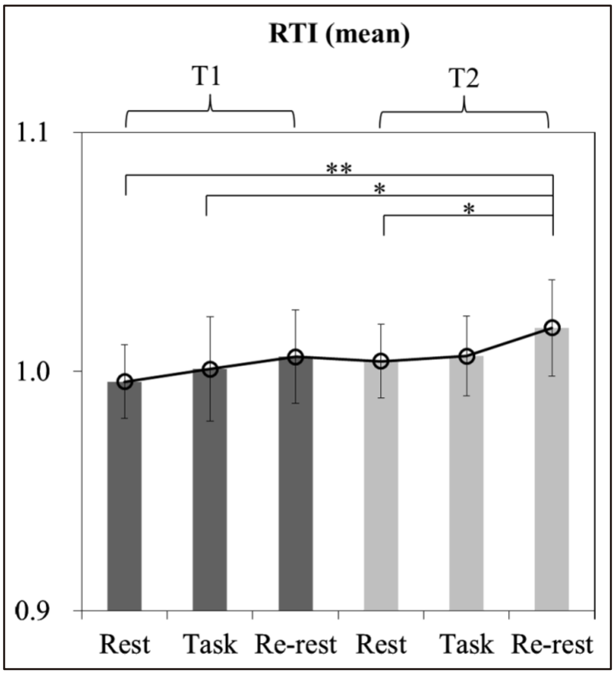
Source	SS	df	MS	F	p
Between conditions	0.126	5	0.025	0.419	0.835
Within conditions	5.065	84	0.060		
Total	5.191	89			

**: $p < 0.01$ *: $p < 0.05$



(A) Average value of RRI

**: $p < 0.01$ *: $p < 0.05$



(B) Average value of RTI

Figure 3-16 LSD post-hoc test results without sorting out sample types

3.5 Conclusions

In this study, with the respiratory rate identically controlled at 15 breaths per minute, the cardiac reactions caused by the experience and the removal of dynamic contact with towels different in tactile smoothness were observed, respectively. Based on the statistical analysis results, the following conclusions are drawn:

(1) Neither the experience of dynamic contact with a relatively smooth and comfortable towel nor the experience of dynamic contact with a relatively rough and uncomfortable towel tends to lead the average heart rate, the average duration of ventricular depolarization and repolarization or the balance between sympathetic and parasympathetic innervation of heart rate to increase or decrease significantly.

(2) The removal of dynamic contact with a towel, whether it is a relatively smooth and comfortable one or a relatively rough and uncomfortable one, tends to lead the average heart rate to decrease and lead the average duration of ventricular depolarization and repolarization to increase; furthermore, the decrement of average heart rate and the increment of average duration of ventricular depolarization and repolarization caused by the removal of dynamic contact with a rough and uncomfortable towel tend to be a little greater.

(3) R-T interval can be taken as an alternative of R-R interval to observe the changes in average heart rate; it is supposed that R-T interval may be relatively difficult to be affected by some occasional changes when compared with R-R interval.

(4) It seems difficult to differentiate a smooth and comfortable texture from a rough and uncomfortable texture only through observing heart rate variability, other measures such as observing the peripheral circulation should be combined to have a try.

Additional data

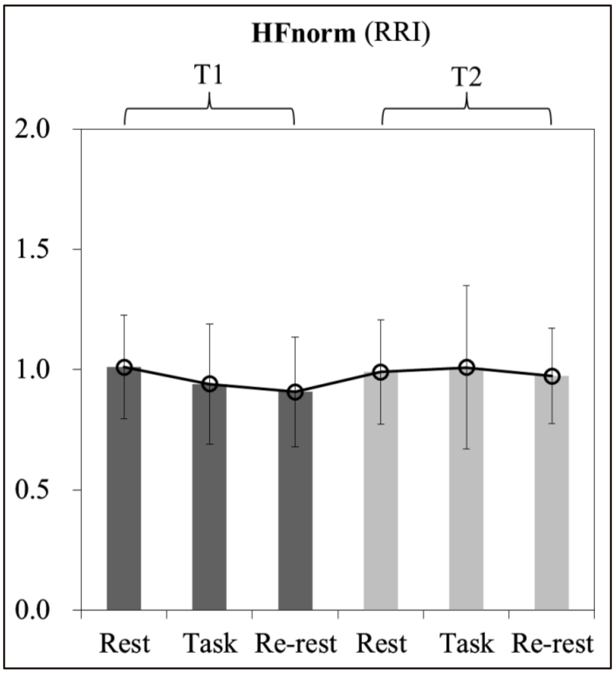


Figure 3-17 Standardized values of HFnorm (RRI) under different conditions

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Chapter 4

Study on cardiovascular and respiratory reactions to tactile softness

– based on ECG and PPG analysis –

Chapter 4: Study on cardiovascular and respiratory reactions to tactile softness: based on ECG and PPG analysis

4.1 Introduction

4.1.1 Mechanisms for the perception of hardness/softness

A few researchers have found that cutaneous information and kinesthetic information have different contributions to the perception of hardness/softness [1, 2]. In terms of compliant objects with rigid surfaces, both cutaneous information and kinesthetic information are necessary for the perception of hardness/softness; in terms of compliant objects with deformable surfaces, cutaneous information is necessary and sufficient for the perception of hardness/softness, and kinesthetic information assists in the perception of hardness/softness. In other words, when the hardness/softness of compliant objects with rigid surfaces are discriminated, the best discrimination can be achieved only by active touch due to the availability of both cutaneous and kinesthetic information; in contrast, under passive conditions, the absence of kinesthetic information results in considerable deterioration of discriminability. When the hardness/softness of compliant objects with deformable surfaces are discriminated, the subtle differences can be well discriminated by both active and passive touch; besides, under active conditions, kinesthetic information provides useful cues that allow the observers to discriminate differences in softness without being confounded by differences in applied velocity [3, 4]. These findings suggest that, whether the objects are rigid or deformable, active touch is always a better choice for hardness/softness discrimination. With regard to the neural coding mechanism for the perception of hardness/softness, it was found that the evoked neural responses of slowly adapting type I (SAI) afferents were nearly proportional to the perceived softness magnitude [5]. Therefore, it is hypothesized that SAI afferents population in the skin might encode the hardness/softness of the objects through detecting spatio-temporal variation of pressure on the skin.

4.1.2 Objective of this study

Pillows and cushions are commonly used as head or body supports in real life. When these kinds of products are used, the perception of softness plays a key role in determining the level of tactile comfort. We suppose that when materials different in tactile softness are evaluated by touch, different levels of physical and/or mental ease may lead the autonomic nervous system (ANS) to work in different ways. Based on this supposition, we intend to conduct a study to observe cardiovascular and respiratory reactions caused by touching materials different in tactile softness, in order to ascertain whether it is possible or not to find one or more cardiovascular and/or respiratory indicators that change with the levels of tactile softness.

Since active touch is thought to be more suitable for the perception of softness, "Tezawari" test method is to be applied to perceive tactile softness during the psychophysiological measurement. The electrocardiography (ECG) is to be recorded to study the variability of heart rate (HR), the photoplethysmography (PPG) is to be recorded to study the variability of blood pressure (BP), and the respiration (RSP) signal is to be recorded to study the variability of respiration. The variability of HR, the variability of BP and the variability of respiration are all closely related to the regulation of ANS. What is more, three types of materials definitely perceived to be different in tactile softness will be chosen as the samples.

4.2 Experimental details

4.2.1 Materials

4.2.1.1 Specifications

Several pillows and cushions that could be found in the laboratory were ranked according to the level of perceived compressional softness. In the end, a pillow perceived to be the softest, a cushion perceived to be the hardest, and a pillow whose compressional softness was perceived to be in the middle, were selected as the samples used in the physiological test. The three types of samples were labelled as “P1”, “P2” and “P3” according to the order in which they were determined to be used.

Figure 4-1 shows the general images of the three types of samples. P1 was a pillow made of 1.6 kg or so of OrsaEliocel foam (Length × Width × Height = 72 cm × 42 cm × 11 cm). P2 was a cushion covered with fabrics made of 85% polyester and 15% cotton and filled with 0.7 kg or so of small feathers (Length × Width × Height = 45 cm × 45 cm × 13 cm). P3 was a pillow covered with fabrics made of 100% polyester and filled with 1.0 kg or so of Urethane foam (Length × Width × Height = 40 cm × 60 cm × 13 cm).

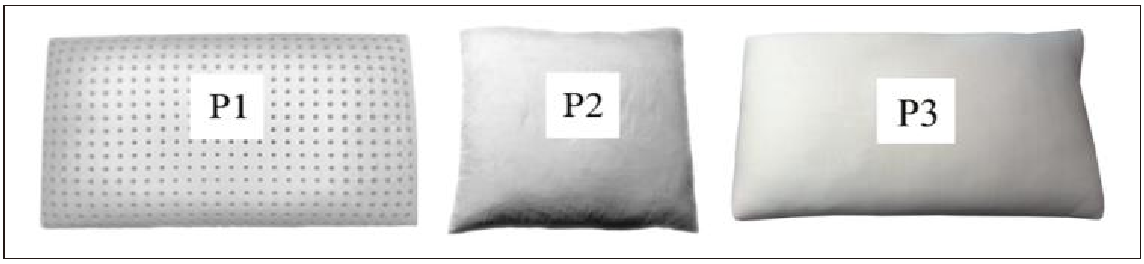


Figure 4-1 Samples used in the physiological test

4.2.1.2 Compression properties

The compression properties of the three types of samples were measured with Venustron II (AXIOM Co., Ltd., Tokyo, Japan) (as shown in Figure 4-2) under the environmental condition of "20℃ ± 2℃, 65% ± 4% RH". When compression properties of the three types of samples were measured, the maximum compression depth was set as 10 mm and the movement speed of the sensor was set as 1 mm/sec. The compression energy (WC) and the compression resilience (RC) of the three types of samples were calculated from pressure-depth curves (as shown in Figure 4-3) measured with Venustron II, respectively. WC is a physical indicator of compressional stiffness/softness. A greater value of WC signifies that greater pressure is needed to compress the surface to the maximum depth (i.e., 10 mm). Therefore, the larger the value of WC is, the stiffer the measured material may be. RC is a physical indicator of compressional elasticity. A greater value of RC signifies that the surface can recover from compression deformation at a higher rate within a given time. Therefore, the larger the value of RC is, the better the measured material's elasticity may be.

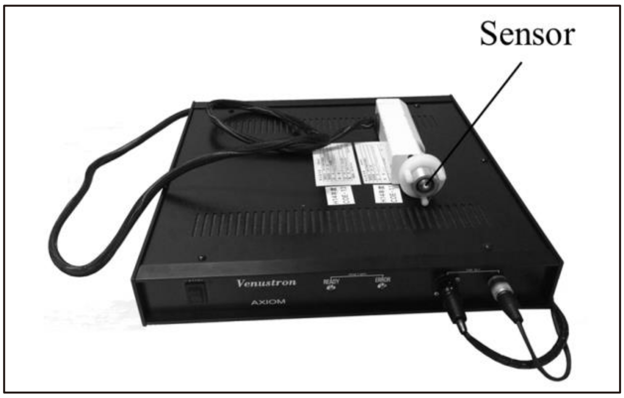
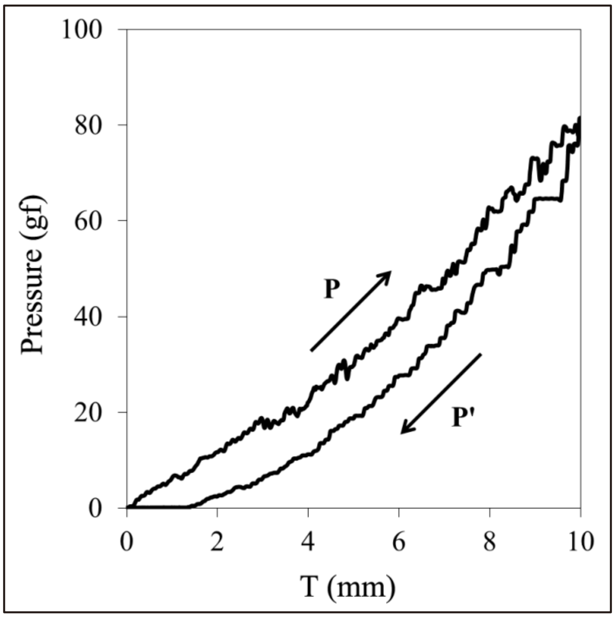


Figure 4-2 Venustron II used for compression property measurement



T: Depth; P: Compression curve; P': Recovery curve.

Figure 4-3 The pressure-depth curve measured with Venustron II

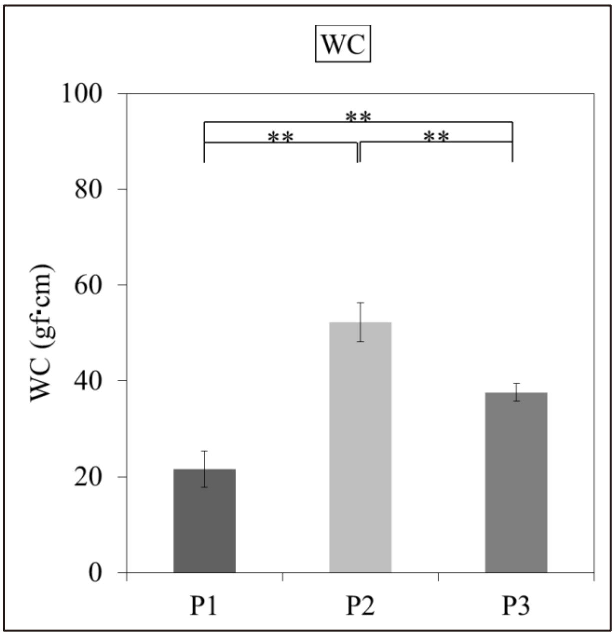
$$WC = \frac{\int_0^{10} P(T)dT}{10} \tag{1}$$

$$RC = \frac{\int_0^{10} P'(T)dT}{10WC} \times 100\% \tag{2}$$

Where, dT = 0.005 mm.

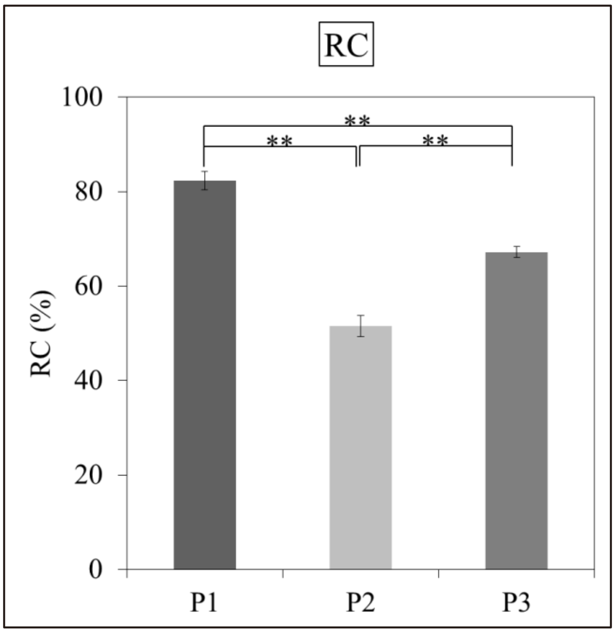
The one-way ANOVA and the Bonferroni's post-hoc test were conducted in succession to examine the statistical significance of between-sample differences in WC and RC. Figure 4-4 shows the calculation and significance test results relevant to WC and RC. According to Figure 4-4 (A), the WC of the three types of samples increased in the order of P1, P3 and P2. This result indicated that the compressional softness of P1 was the best, the compressional softness of P2 was the poorest, and the compressional softness of P3 was poorer than that of P1 but better than that of P2. According to Figure 4-4 (B), the RC of the three types of samples decreased in the order of P1, P3, P2. This result indicated that the compressional elasticity of P1 was the best, the compressional elasticity of P2 was the poorest, and the compressional elasticity of P3 was poorer than that of P1 but better than that of P2.

**: $p < 0.01$ *: $p < 0.05$



(A) Compression energy

**: $p < 0.01$ *: $p < 0.05$



(B) Compression resilience

Figure 4-4 Calculation and significance test results for compression properties

4.2.1.3 Sensory attributes

The sensory attributes of the three types of samples were investigated via a "Tezawari" test that was carried out under the environmental condition of "24℃ ± 1℃, 50% ± 4% RH" in a climate chamber. Eight pairs of terms, namely "Cool – Warm, Damp – Dry, Sticky – Slippery, Rough – Smooth, Incompressible – Compressible, Nonresilient – Resilient, Uncomfortable – Comfortable and Unpleasant – Pleasant", were involved in the "Tezawari" test. The rating scale was designed with the semantic differential (SD) method, which ranged from "-3" to "3". Herein, "-3, -2 and -1" meant the feeling indicated by the term on the left side could be "extremely, moderately and slightly" experienced in order; "3, 2 and 1" meant the feeling indicated by the term on the right side could be "extremely, moderately and slightly" experienced in order; "0" meant neither the feeling indicated by the term on the left side nor the feeling indicated by the term on the right side could be definitely experienced.

Figure 4-5 shows the sensory test results. The orders of four pairs of terms, namely "Incompressible – Compressible, Nonresilient – Resilient, Uncomfortable – Comfortable and Unpleasant – Pleasant", were generally consistent with the order of perceived compressional softness of the three types of samples. The evaluation results for "Incompressible – Compressible" revealed that P1 and P3 were perceived to be compressible whereas P2 was perceived to be a little incompressible. In general, the perceived compressibility (compressional softness) of the three types of samples decreased in the order of P1, P3 and P2. This order was consistent with the order of WC, the physical indicator of compressional softness. The evaluation results for "Nonresilient – Resilient" revealed that P1 and P3 were perceived to be resilient whereas P2 was perceived to be nonresilient. In general, the perceived resilience (compressional elasticity) of the three types of samples decreased in the order of P1, P3 and P2. This order was consistent with the order of RC, the physical indicator of compressional elasticity. The evaluation results for "Uncomfortable – Comfortable" and "Unpleasant – Pleasant" revealed that the tactile comfort of the three types of samples decreased in the order of P1, P3 and P2. Above all, based on the sensory test results, it is supposed that both perceived compressibility and perceived resilience might have contributed to the overall perception of compressional softness, and the perceived compressional softness might be the determining factor of the tactile comfort.

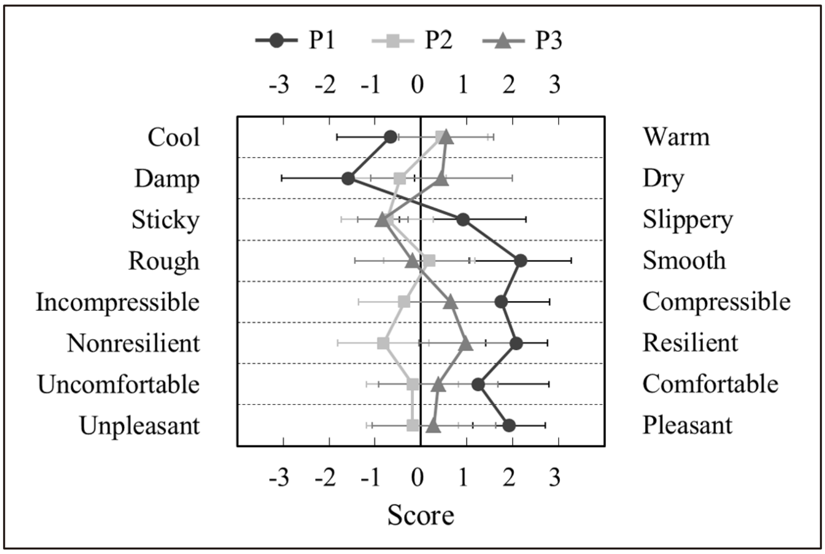


Figure 4-5 Sensory attributes of the samples

4.2.2 Subjects

Ten healthy university students (five males and five females) aged between twenty and thirty years old participated in the “Hadazawari” test and the physiological test. Table 4-1 shows the basic physical characteristics of the subjects. All of the subjects were required to refrain from doing intensive exercise, smoking and drinking coffee six hours before they were tested.

Table 4-1 Physical characteristics of the subjects

Gender	Number	Age (years)	Height (cm)	Weight (kg)	Hand temperature (℃)
Male	5	23.6 ± 2.2	170.6 ± 5.9	62.0 ± 6.2	33.3 ± 0.8
Female	5	24.4 ± 2.3	157.4 ± 6.6	47.0 ± 2.6	32.8 ± 1.1

4.2.3 Psychophysiological measurement

The physiological tests were conducted in a climate chamber under the environmental condition of "24℃ ± 1℃, 50% ± 4% RH". The MP 100 data acquisition system (BIOPAC Systems Inc., New York, USA) was used to record ECG, PPG and RSP signals. Figure 4-6 shows the general image of MP 100 data acquisition system. The ECG signal was detected by three ECG electrode leads (LEAD110S-R, BIOPAC Systems Inc., New York, USA). The PPG signal was detected by an earclip PPG transducer (TSD200C, BIOPAC Systems Inc., New York, USA). The RSP signal was detected by a fast response thermistor fixed under the left nostril (TSD101B, BIOPAC Systems Inc., New York, USA). Figure 4-7 shows the locations of ECG electrodes, the PPG transducer and the fast response thermistor.

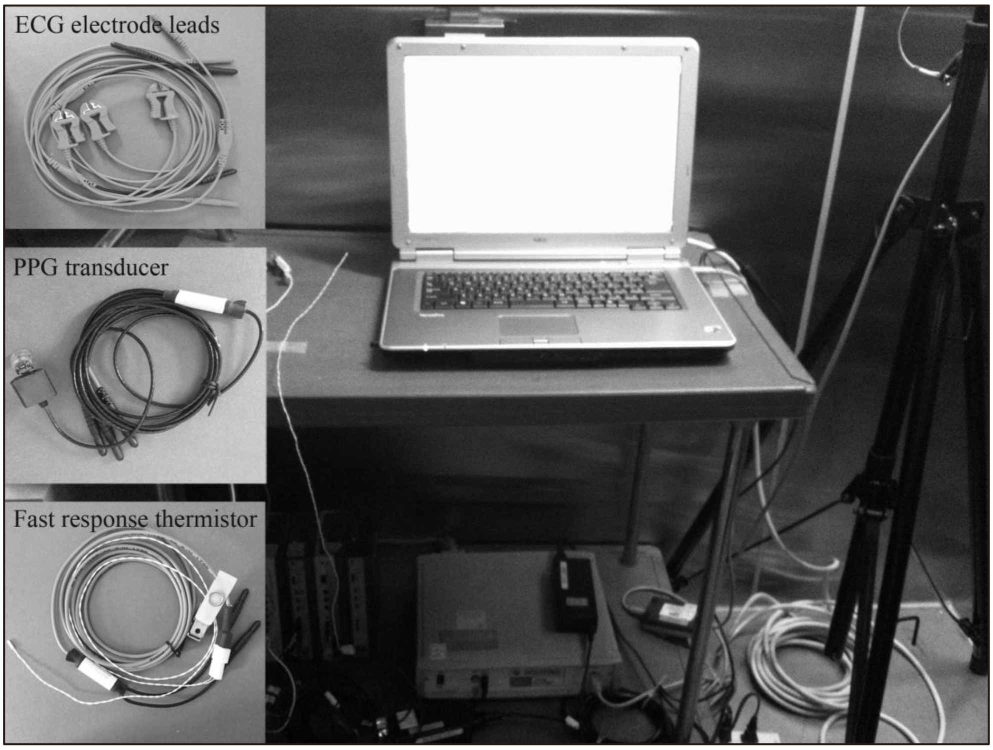


Figure 4-6 The MP 100 data acquisition system used for physiological measurement

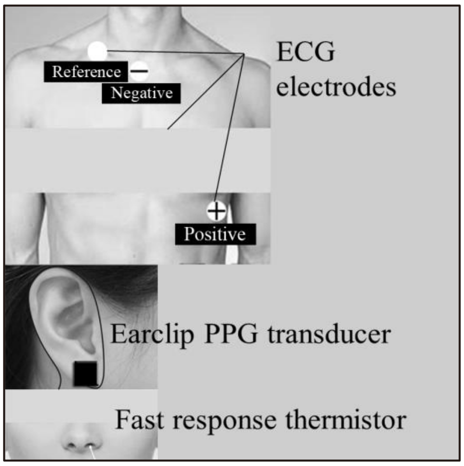


Figure 4-7 Locations of ECG, PPG and RSP signal detectors

Each subject was tested on three continuous days. The same sample was involved on the same day, and different samples were involved on different days. The sequence that P1, P2 and P3 were used on the three days was randomly determined. Figure 4-8 shows the procedure of physiological measurement. According to it, before the starting of the first physiological test, a subject had to change his/her top into a piece of short-sleeve cotton T-shirt and sink into the chair to have a rest. Meanwhile, the experimenter had to equip the subject with the MP 100 data acquisition system and explain the procedure of the physiological test to the subject. After the preparatory stage that lasted for about twenty minutes, a subject had to go through two six-minute physiological tests in succession, between which there were five to ten minutes to have a rest. Each physiological test was comprised of three successive conditions: “Rest” condition, “Task” condition and “Re-rest” condition. Under “Rest” and “Re-rest” conditions, a subject had to do nothing but keep being seated in the chair quietly. Under “Task” condition, a subject had to keep compressing the presented sample slowly and rhythmically. Throughout each physiological test, the subject was blindfolded with a pair of lightproof glasses, and ECG, PPG and RSP signals were recorded simultaneously at a sampling frequency of 2000 Hz.

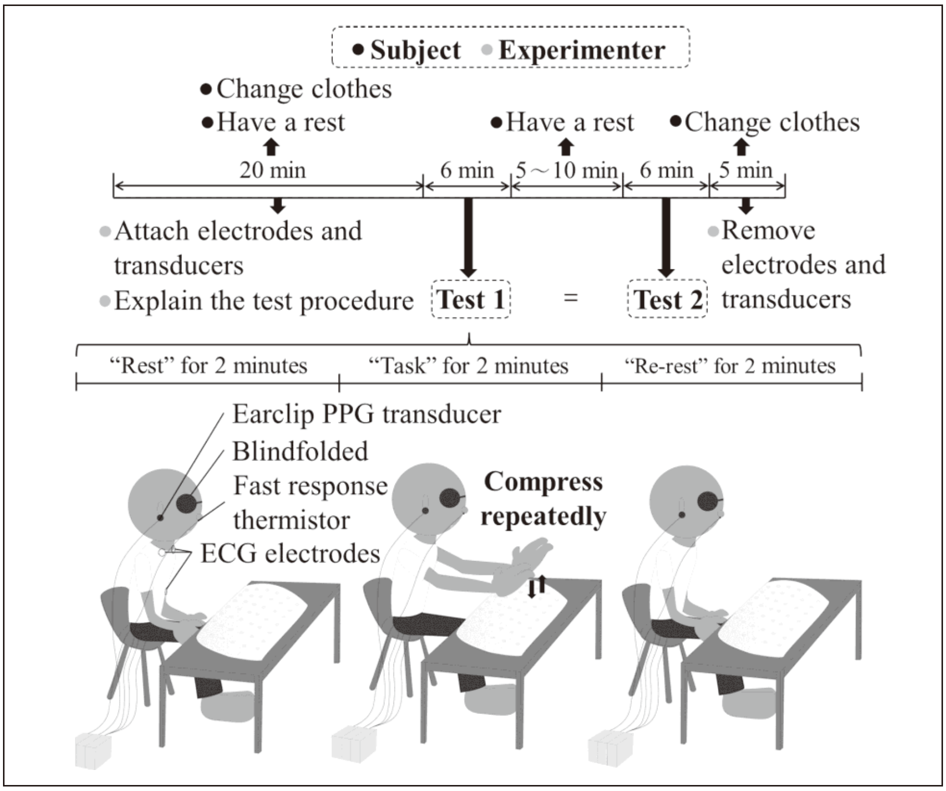


Figure 4-8 The procedure of physiological measurement

4.2.4 Data acquisition

Figure 4-9 shows the signals used for physiological data acquisition. The signals recorded in the first physiological test were preferentially read in for data acquisition. When any of these signals were abnormal, the signals recorded in the second physiological test were read in instead for data acquisition. The data of RRI (R-R interval: the interval between the peak points of two adjacent R-waves) and RTI (R-T interval: the interval between the peak point of an R-wave and the peak point of the following T-wave) were calculated from the ECG signal. The data of H_P (height of pulse wave: the amplitude difference between the maximum peak point and the minimum valley point of a pulse wave) were calculated from the PPG signal. The data of PWTT (pulse wave transmitting time: the interval between the peak point of an R-wave in ECG and the first valley point of the following pulse wave in PPG) were calculated from ECG and PPG signals. The data of T (duration of a breath: the interval between the peak points of two adjacent respiratory waves) were calculated from the RSP signal, and then they were converted into the corresponding data of RR (respiratory rate: the number of breaths within a minute) as per the equation "$RR_i = 1/T_i$".

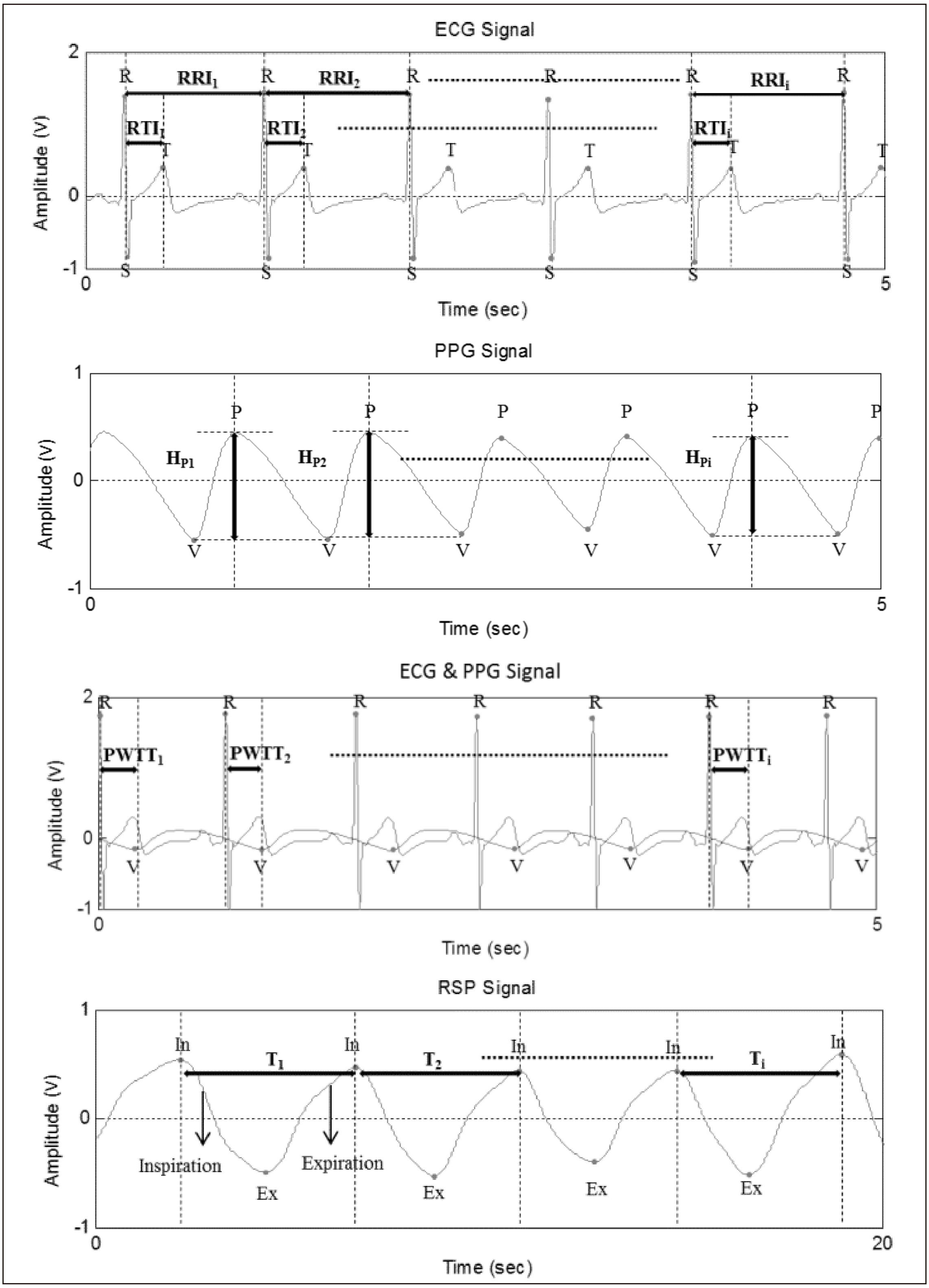


Figure 4-9 Signals used for physiological data acquisition

Regarding to each type of data mentioned above, the data from the 15th second to the 105th second were taken as the valid data under “Rest” condition, the data from the 135th second to the 225th second were taken as the valid data under “Task” condition, and the data from the 255th second to the 345th second were taken as the valid data under “Re-rest” condition. In time domain, the average value (Mean) and the coefficient of variation (CV) of RRI, RTI, H_P, PWTT and RR were calculated under different conditions. Besides, the root-mean-square (RMS) value of the amplitude of RSP signal was also calculated under different conditions. In frequency domain, the fast Fourier transform (FFT) was applied to estimate the power spectra of RRI and PWTT; then the value of low-frequency components' power (LF: 0.04 Hz - 0.15 Hz) and the value of high-frequency components' power (HF: 0.15 Hz - 0.4 Hz) relevant to RRI and PWTT were calculated under different conditions; ultimately, the value of normalized HF components' power (HFnorm) relevant to RRI and the value of HFnorm relevant to PWTT were calculated under different conditions as per the equation “HFnorm = HF / (LF + HF) × 100%)”. To avoid confusion, the LF, HF and HFnorm based on the power spectrum of RRI will be referred to as LF (RRI), HF (RRI) and HFnorm (RRI), and the LF, HF and HFnorm based on the power spectrum of PWTT will be referred to as LF (PWTT), HF (PWTT) and HFnorm (PWTT) in the following sections. Table 4-2 shows the symbols of the parameters mentioned above.

Table 4-2 Parameters in time domain and in frequency domain

(A) Time domain

Average (Mean)	Coefficient of variation (CV)	Root-mean-square (RMS)
RRI (mean)	RRI (cv)	
RTI (mean)	RTI (cv)	
H_P (mean)	H_P (cv)	
PWTT (mean)	PWTT (cv)	
RR (mean)	RR (cv)	RSP (rms)

(B) Frequency domain

Parameter	Description
HFnorm (RRI)	HFnorm calculated from the power spectrum of RRI
HFnorm (PWTT)	HFnorm calculated from the power spectrum of PWTT

4.3 Results

4.3.1 Cardiovascular and respiratory reactions to active contact with materials

The calculated values of the parameters shown in Table 4-2 were converted into Z-scores, and then the two-way ANOVA was applied to examine the statistical significance of main effects of the "sample" type (P1, P2 and P3) and the test "condition" (Rest, Task and Re-rest) on the variation of each parameter. Table 4-3 shows the two-way ANOVA results. According to it, the "sample" type and/or the test "condition" had significant effects on the variation of four types of parameters, namely RTI (cv), RR (cv), HFnorm (RRI) and HFnorm (PWTT).

According to Table 4-3 (D), the test "condition" had a significant effect on the variation of RTI (cv) ($p < 0.01$). Figure 4-10 (A) shows the corresponding least significant difference (LSD) post-hoc test results. Obviously, without sorting out sample types, the values of RTI (cv) under "Task" condition as a whole were significantly larger than those under "Rest" condition as a whole ($p < 0.01$) and those under "Re-rest" condition as a whole ($p < 0.01$). RTI signifies the duration of ventricular depolarization and repolarization [6, 7]. Therefore, the results mentioned above indicated that, owing to the active contact with the three types of samples, the variation of the ventricular depolarization and repolarization duration increased significantly; however, the increment in the variation of the ventricular depolarization and repolarization duration did not change with the samples.

According to Table 4-3 (J), the test "condition" had a significant effect on the variation of RR (cv) ($p < 0.01$). Figure 4-10 (B) shows the corresponding LSD post-hoc test results. According to it, without sorting out sample types, the values of RR (cv) under "Task" condition as a whole were larger than those under "Rest" condition as a whole at a significance level of 0.01 and larger than those under "Re-rest" condition at a significance level 0.05. RR (cv) corresponds to the variation of respiratory rate. The larger the value of RR (cv) is, the irregular the respiratory rhythm is. Therefore, the results mentioned above indicated that the active contact with the three types of samples disturbed the respiratory rhythm and led the uniformity of respiration to decrease. Moreover, the decrement in the uniformity of respiration did not change with the samples, either.

According to Table 4-3 (L), the “sample” type had a significant effect on the variation of HFnorm (RRI) (i.e., HFnorm calculated from the power spectrum of RRI) ($p < 0.05$). Figure 4-10 (C) shows the corresponding LSD post-hoc test results. Obviously, without sorting out test conditions, the values of HFnorm (RRI) relevant to P3 as a whole were significantly different from those relevant to P1 as a whole ($p < 0.05$) and those relevant to P2 ($p < 0.01$). Although the effect of the test “condition” on the variation of HFnorm (RRI) was not statistically significant, it seems that the value of HFnorm (RRI) under “Task” condition tended to be lower than that under “Rest” condition, and the decrement in HFnorm (RRI) from “Rest” condition to “Task” condition tended to change with the samples. As is well known, The HFnorm calculated from the power spectrum of RRI signifies the balance between sympathetic and parasympathetic innervation of HR [8]. The results mentioned above suggest that the active contact with the three types of samples tends to cause the sympathetic innervation of HR to increase and/or the parasympathetic innervation of HR to decrease.

According to Table 4-3 (M), the “sample” type had an effect on the variation of HFnorm (PWTT) (i.e., HFnorm calculated from the power spectrum of PWTT) at a significance level of 0.05, and the test “condition” had an effect on the variation of HFnorm (PWTT) at a significance level of 0.01. Since the interactive effect between the “sample” type and the test “condition” was significant ($p < 0.05$), the one-way ANOVA was further applied to examine the statistical significance of simple main effects of the “sample” type and the test “condition” on the variation of HFnorm (PWTT). Table 4-4 shows the one-way ANOVA results. According to Table 4-4 (A), the “sample” type had a significant effect on the variation of HFnorm (PWTT) under “Task” condition ($p < 0.05$). Figure 4-10 (D) shows the corresponding LSD post-hoc test results. According to it, the value of HFnorm (PWTT) under the

“Task” condition of compressing P2 was significantly larger than that under the “Task” condition of compressing P1 and that under the “Task” condition of compressing P3 ($p < 0.05$). According to Table 4.4 (B), as P1 was involved, the test “condition” had a significant effect on the variation of HFnorm (PWTT) ($p < 0.01$). Figure 4-10 (E) shows the corresponding LSD post-hoc test results. According to it, when P1 was involved, the value of HFnorm (PWTT) under “Task” condition was significantly lower than that under “Rest” condition and that under “Re-rest” condition ($p < 0.05$). In general, the results shown in Figure 4-10 (D) and Figure 4-10 (E) indicated that, the active contact with P1 and P3 (the samples of good softness) tended to lead the value of HFnorm (PWTT) to decrease, whereas the active contact with P2 (the sample of poor softness) failed to lead the value of HFnorm (PWTT) to show any noticeable change trend. As reported, the variations of PWTT in frequency domain correspond to the variations of BP in frequency domain [9-11]. Therefore, the results mentioned above suggest that the active contact with the three types of samples may cause BP to change in different ways in frequency domain.

In summary, among the four types of parameters discussed above, RTI (cv) and RR (cv) were magnified due to the active contact, but the increment from “Rest” condition to “Task” condition and the decrement from “Task” condition to “Re-rest” condition failed to show any significant between-sample differences. HFnorm (RRI) and HFnorm (PWTT) tended to decrease because of the active contact, and the decrement from “Rest” condition to “Task” condition and/or the increment from “Task” condition to “Re-rest” condition seemed to change with the samples. The significance test results showed that only the change trends of HFnorm (PWTT) turned out to be statistically significant. Considering that the three types of samples were mainly different in perceived compressional softness, the between-sample differences in change trends of HFnorm (PWTT) ought to be ascribed to the between-sample differences in perceived compressional softness. Consequently, it is supposed that HFnorm (PWTT) may be a promising parameter that can be used for tactile softness differentiation.

Table 4-3 Two-way ANOVA results for main effects of the “sample” type and the test “condition”

(A) Dependent variable: RRI (mean)

** p < 0.01; * p < 0.05

Source	SS	df	MS	F	p	
Sample	0.950	2	0.475	0.475	0.624	
Condition	0.133	2	0.066	0.066	0.936	
Sample × Condition	0.067	4	0.017	0.017	0.999	
Error	81.058	81	1.001			
Total	82.208	90				

(B) Dependent variable: RRI (cv)

** p < 0.01; * p < 0.05

Source	SS	df	MS	F	p	
Sample	3.423	2	1.712	1.193	0.309	
Condition	7.345	2	3.672	2.559	0.084	
Sample × Condition	2.263	4	0.566	0.394	0.812	
Error	116.260	81	1.435			
Total	129.291	90				

(C) Dependent variable: RTI (mean)

** p < 0.01; * p < 0.05

Source	SS	df	MS	F	p	
Sample	4.480	2	2.240	2.271	0.110	
Condition	0.013	2	0.007	0.007	0.993	
Sample × Condition	0.008	4	0.002	0.002	1.000	
Error	79.911	81	0.987			
Total	84.413	90				

(D) Dependent variable: RTI (cv)

** p < 0.01; * p < 0.05

Source	SS	df	MS	F	p	
Sample	1.451	2	0.725	0.120	0.888	
Condition	85.849	2	42.924	7.072	0.001	**
Sample × Condition	0.582	4	0.146	0.024	0.999	
Error	491.636	81	6.070			
Total	579.517	89	6.511			

(E) Dependent variable: H_P (mean)

** p < 0.01; * p < 0.05

Source	SS	df	MS	F	p
Sample	0.100	2	0.050	0.076	0.927
Condition	1.739	2	0.869	1.328	0.271
Sample × Condition	2.168	4	0.542	0.828	0.511
Error	53.045	81	0.655		
Total	57.051	90			

(F) Dependent variable: H_P (cv)

** p < 0.01; * p < 0.05

Source	SS	df	MS	F	p
Sample	4.524	2	2.262	2.321	0.105
Condition	4.118	2	2.059	2.113	0.128
Sample × Condition	2.857	4	0.714	0.733	0.572
Error	78.949	81	0.975		
Total	90.447	90			

(G) Dependent variable: PWTT (mean)

** p < 0.01; * p < 0.05

Source	SS	df	MS	F	p
Sample	0.892	2	0.446	0.406	0.668
Condition	3.251	2	1.625	1.480	0.234
Sample × Condition	0.294	4	0.073	0.067	0.992
Error	88.936	81	1.098		
Total	93.373	90			

(H) Dependent variable: PWTT (cv)

** p < 0.01; * p < 0.05

Source	SS	df	MS	F	p
Sample	4.514	2	2.257	1.706	0.188
Condition	1.174	2	0.587	0.444	0.643
Sample × Condition	0.345	4	0.086	0.065	0.992
Error	107.173	81	1.323		
Total	113.207	90			

(I) Dependent variable: RR (mean)

** p < 0.01; * p < 0.05

Source	SS	df	MS	F	p	
Sample	0.020	2	0.010	0.012	0.988	
Condition	3.010	2	1.505	1.787	0.174	
Sample × Condition	0.543	4	0.136	0.161	0.957	
Error	68.242	81	0.842			
Total	71.815	90				

(J) Dependent variable: RR (cv)

** p < 0.01, * p < 0.05

Source	SS	df	MS	F	p	
Sample	6.873	2	3.437	2.357	0.101	
Condition	20.581	2	10.290	7.059	0.001	**
Sample × Condition	1.876	4	0.469	0.322	0.863	
Error	118.077	81	1.458			
Total	147.407	89	1.656			

(K) Dependent variable: RSP (rms)

** p < 0.01, * p < 0.05

Source	SS	df	MS	F	p	
Sample	2.020	2	1.010	0.990	0.376	
Condition	0.668	2	0.334	0.327	0.722	
Sample × Condition	0.413	4	0.103	0.101	0.982	
Error	82.594	81	1.020			
Total	85.694	90				

(L) Dependent variable: HFnorm (RRI)

** p < 0.01, * p < 0.05

Source	SS	df	MS	F	p	
Sample	6.513	2	3.257	4.803	0.011	*
Condition	2.333	2	1.167	1.720	0.185	
Sample × Condition	2.532	4	0.633	0.933	0.449	
Error	54.927	81	0.678			
Total	66.306	89	0.745			

(M) Dependent variable: HFnorm (PWTT)

** p < 0.01, * p < 0.05

Source	SS	df	MS	F	p	
Sample	11.042	2	5.521	3.895	0.024	*
Condition	16.561	2	8.280	5.842	0.004	**
Sample × Condition	14.094	4	3.524	2.486	0.050	*
Error	114.804	81	1.417			
Total	156.500	89	1.758			

Table 4-4 One-way ANOVA results for simple main effects of the "sample" type and the test "condition" on the variation of HFnorm (PWTT)

(A) Between-sample

** p < 0.01, * p < 0.05

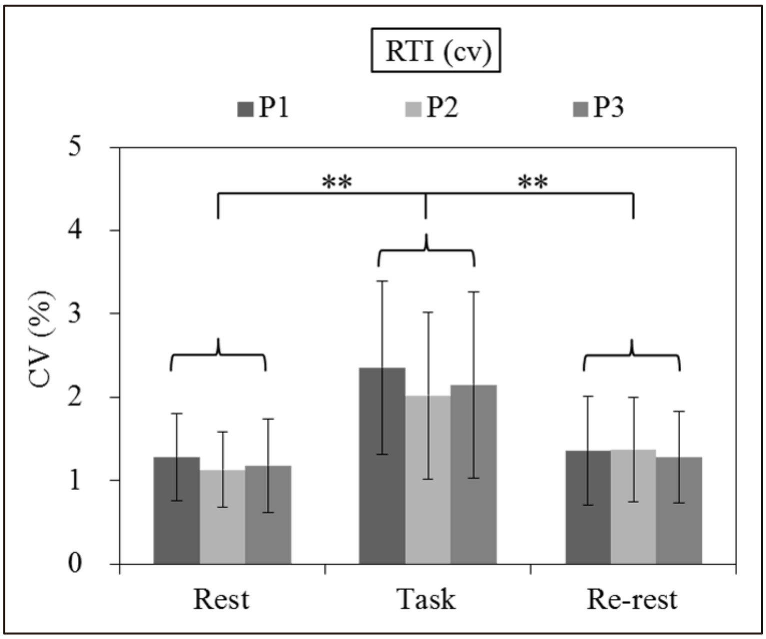
Condition	Source	SS	df	MS	F	p	
Rest	Between samples	2.963	2	1.481	1.536	0.233	
	Within samples	26.037	27	.964			
	Total	29.000	29				
Task	Between samples	21.315	2	10.657	5.194	0.012	*
	Within samples	55.405	27	2.052			
	Total	76.720	29				
Re-rest	Between samples	0.858	2	0.429	0.347	0.710	
	Within samples	33.361	27	1.236			
	Total	34.219	29				

(B) Between-condition

** p < 0.01, * p < 0.05

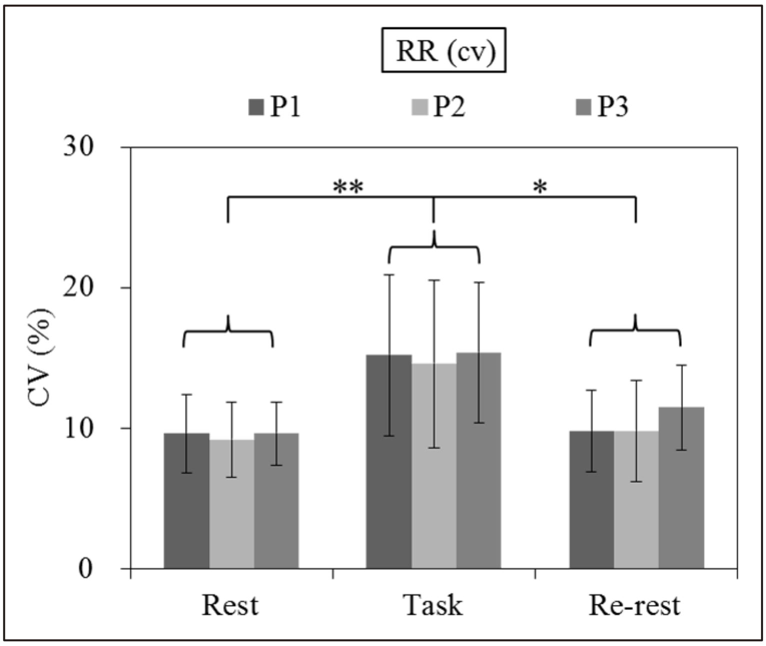
Sample	Source	SS	df	MS	F	p	
P1	Between conditions	19.707	2	9.853	7.979	0.002	**
	Within conditions	33.342	27	1.235			
	Total	53.049	29				
P2	Between conditions	0.095	2	0.047	0.098	0.907	
	Within conditions	13.053	27	.483			
	Total	13.148	29				
P3	Between conditions	9.381	2	4.691	2.444	0.106	
	Within conditions	51.815	27	1.919			
	Total	61.196	29				

**: $p < 0.01$ *: $p < 0.05$



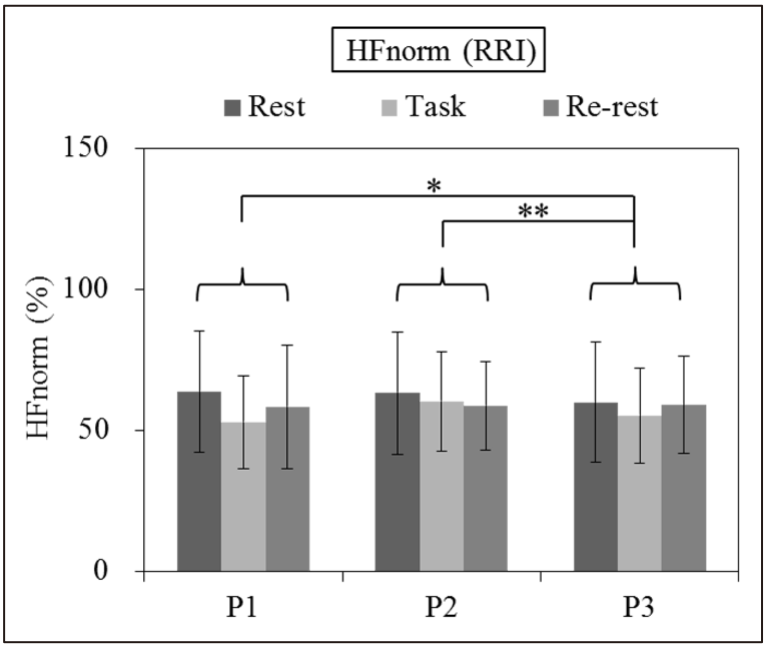
(A) LSD test results for the effect of the test "condition" on RTI (cv)

**: $p < 0.01$ *: $p < 0.05$



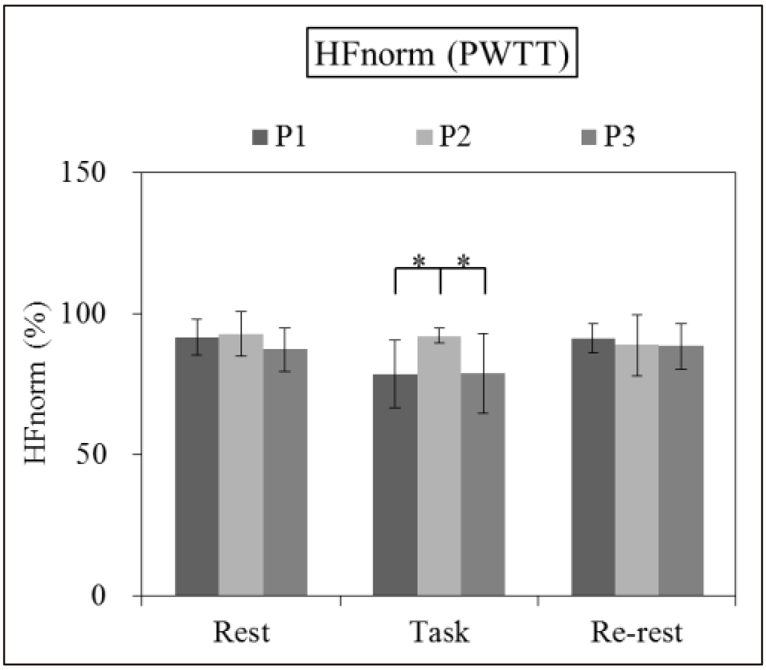
(B) LSD test results for the effect of the test "condition" on RR (cv)

**: p < 0.01 *: p < 0.05



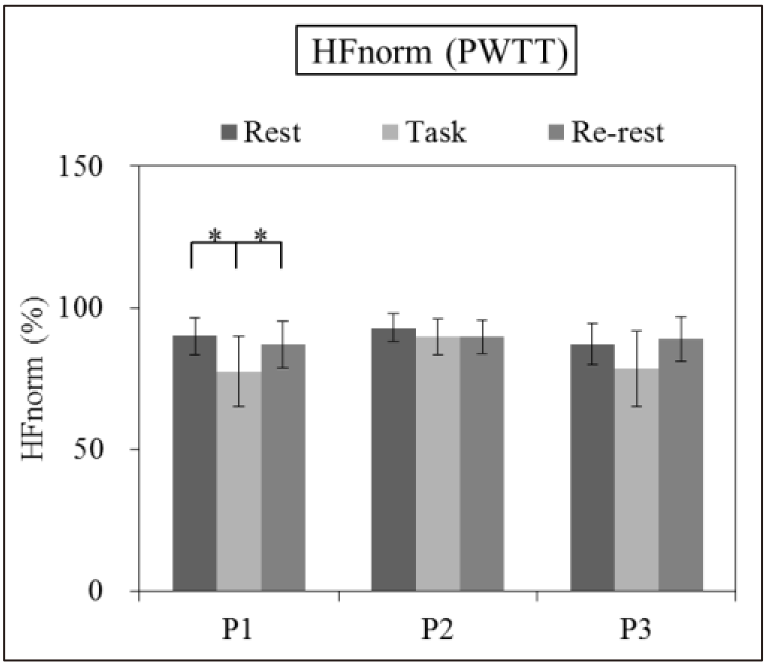
(C) LSD test results for the effect of the “sample” type on HFnorm (RRI)

**: p < 0.01 *: p < 0.05



(D) LSD test results for the simple main effect of the “sample” type on HFnorm (PWTT)

**: $p < 0.01$ *: $p < 0.05$



(E) LSD test results for the simple main effect of the test “condition” on HFnorm (PWTT)

Figure 4-10 Post-hoc test results for significant effects of the “sample” type and/or the test “condition”

4.3.2 The usability of HFnorm (PWTT) in tactile softness differentiation

The one-way ANOVA was applied to examine the statistical significance of between-sample differences in the decrement of HFnorm (PWTT) from “Rest” condition to “Task” condition and the increment of HFnorm (PWTT) from “Task” condition to “Re-rest” condition. Table 4-5 shows the one-way ANOVA results. It is obvious that there were significant between-sample differences in both change trends ($p < 0.05$). Figure 4-11 shows the corresponding LSD post-hoc test results. From “Rest” condition to “Task” condition, the decrement caused by compressing P1 was significantly larger than that caused by compressing P2 ($p < 0.05$); however, neither the decrement caused by compressing P1 nor the decrement caused by compressing P2 was significantly different from the decrement caused by compressing P3. From “Task” condition to “Re-rest” condition, there was no significant difference between the increment caused by stopping compressing P1 and that caused by stopping compressing P3; the increment caused by stopping compressing P2 was lower than that caused by stopping compressing P1 at a significance level of 0.01 and lower than that caused by stopping compressing P3 at a significance level of 0.05. To sum up, the results mentioned above indicated that, when P1 (the sample of best softness) and P2 (the sample of poorest softness) were compared, both the decrement caused by active contact and the increment caused by termination of active contact showed significant between-sample differences; when P2 (the sample of poorest softness) and P3 (the sample of better softness) were compared, only the increment caused by termination of active contact showed a significant between-sample difference. These results suggest that HFnorm (PWTT) may be a reliable parameter that can be used to differentiate materials of very good softness from those of poor softness, but its effectiveness in distinguishing between materials of different levels of good softness still needs to be verified through further studies.

Table 4-5 One-way ANOVA results for change trends of HFnorm (PWTT)

(A) From "Rest" condition to "Task" condition

**: $p < 0.01$; *: $p < 0.05$

Source	SS	df	MS	F	p	
Between samples	816.203	2	408.101	3.362	0.050	*
Within samples	3277.792	27	121.400			
Total	4093.994	29				

(B) From "Task" condition to "Re-rest" condition

**: $p < 0.01$; *: $p < 0.05$

Source	SS	df	MS	F	p	
Between samples	1456.358	2	728.179	5.087	0.013	*
Within samples	3864.852	27	143.143			
Total	5321.209	29				

**: p < 0.01 *: p < 0.05

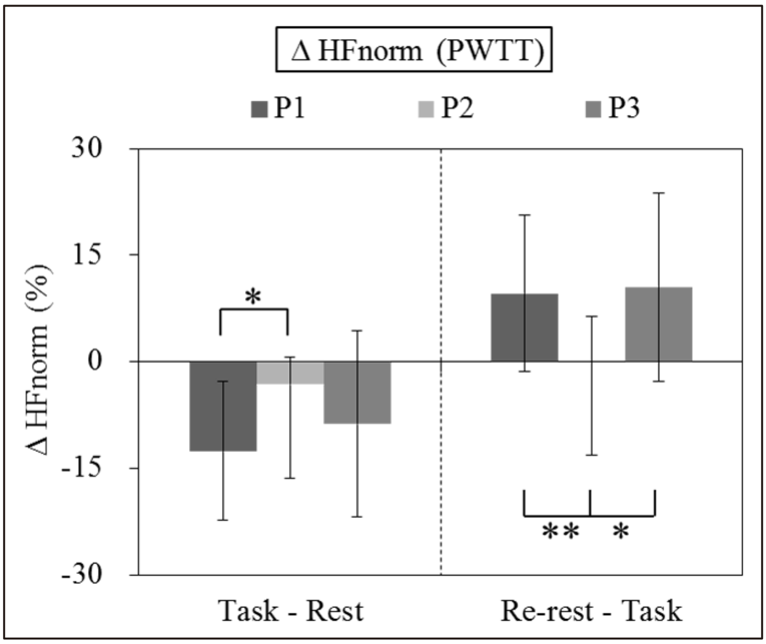


Figure 4-11 Post-hoc test results for change trends of HFnorm (PWTT)

4.4 Discussion

4.4.1 Mechanisms for HFnorm (PWTT) variations relevant to tactile softness

In fact, PWTT is the sum of PEP (pre-ejection period) and a-PWTT (pulse wave transmitting time in the artery). PEP is the period just before the blood is pumped into the aorta by the heart. a-PWTT is the time taken by the pulse wave to travel from the aorta to a peripheral artery [12]. a-PWTT is directly related to BP. When BP is high, the arterial walls are tense and hard, the pulse wave travels faster, and a-PWTT will be shortened. When BP is low, the arterial walls have less tension, the pulse wave travels slower, and a-PWTT will be lengthened [13]. Since the change in PEP over a short period is negligible in most cases, it is believed that PWTT corresponds to a-PWTT, and therefore correlates to BP [14, 15]. Although it is difficult to determine the actual value of BP through the actual value of PWTT, the variability of BP can be absolutely estimated through the variability of PWTT [16]. That is to say, the variations of PWTT in time and frequency domains correspond to the variations of BP in time and frequency domains.

Power spectral analysis is a traditional way to study the variability of HR and the variability of BP in frequency domain. Through power spectral analysis, the variations of HR and BP in frequency domain can be roughly divided into two groups, namely LF components (0.04 Hz - 0.15 Hz) and HF components (0.15 Hz - 0.4 Hz). A great many studies have revealed that, LF variations of HR are jointly mediated by the parasympathetic system and the sympathetic system, and they are very sensitive to sympathetic activators such as mental stress and exercise; HF variations of HR are mainly mediated by the parasympathetic system, and they are highly associated with the respiratory sinus arrhythmia (RSA) [17]. The mechanism for the variations of BP in frequency domain is still not very clear. It is hypothesized that LF variations of BP are predominantly mediated by sympathetic vasomotor tone and systemic vascular resistance, and HF variations of BP almost entirely result from the parasympathetic innervation of HR [18, 19]. Since the variations of PWTT in frequency domain correspond to the variations of BP in frequency domain, the hypothesis mentioned above can be used to account for the variations of PWTT in frequency domain.

HFnorm (PWTT) is a parameter indicating the proportion of HF variations in the overall variations of PWTT in frequency domain (i.e., the sum of LF variations and HF variations). The value of HFnorm (PWTT) depends on both of the value of LF (PWTT) and the value of HF (PWTT). Taking the results relevant to P1 and P2 for example, Figure 4-12 shows the average value of LF (PWTT) and the average value of HF (PWTT) calculated under different conditions. Obviously, the value of LF (PWTT) increased considerably while the value of HF (PWTT) decreased considerably because of the active contact with P1 (a sample of good softness). By comparison, the value of LF (PWTT) increased slightly while the value of HF (PWTT) decreased slightly due to the active contact with P2 (a sample of poor softness). These results indicated that both LF variations and HF variations of PWTT were associated with the active contact with materials different in tactile softness. It is supposed that LF variations of PWTT tend to increase more while HF variations of PWTT tend to decrease more due to the active contact with a softer material. Owing to the opposite change trends of LF and HF variations of PWTT, HFnorm (PWTT) that is determined by the expression "HF (PWTT) / (LF (PWTT) + HF (PWTT)) × 100%", turns out to be a parameter relatively sensitive to the differences in tactile softness. It is supposed that the physiological mechanism for the variations of HFnorm (PWTT) relevant to tactile softness may be like this: as a material of better softness is compressed, the ease of hand motion may be greater, the range of hand motion may be larger, and the frequency of hand motion may be lower and more regular; because of these changes in hand motion, the parasympathetic innervation of HR tends to decrease more, whereas the sympathetic vasomotor tone tends to increase even more; as a result, the portion of HF variations of PWTT in the overall variations of PWTT in frequency domain gets decreased. Provided that this hypothesis is believable, it is supposed that the parameter LF/HF (PWTT), which is determined by the expression "LF (PWTT) / HF (PWTT)" and has a similar physiological significance to the parameter HFnorm (PWTT), may be even more sensitive to the differences in tactile softness.

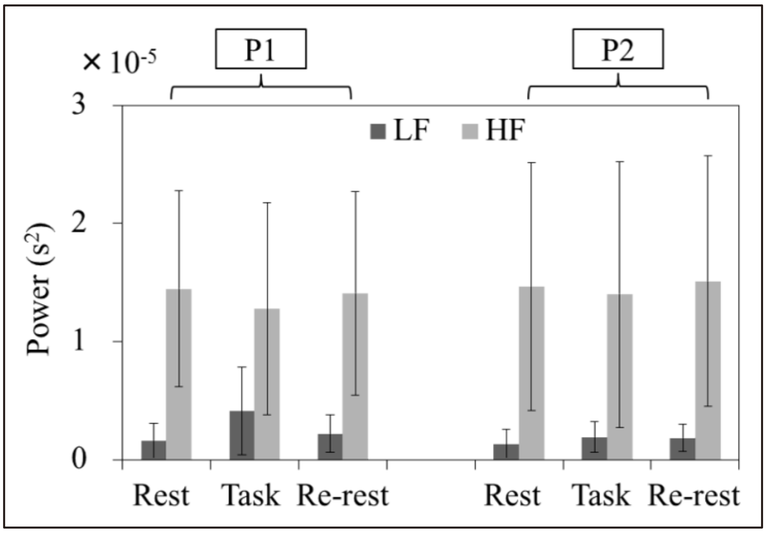


Figure 4-12 Average LF and HF variations of PWTT

4.4.2 The usability of LF/HF (PWTT) in tactile softness differentiation

The two-way ANOVA was conducted to examine the statistical significance of main effects of the "sample" type and the test "condition" on the variation of LF/HF (PWTT). Table 4-6 shows the two-way ANOVA results. It is obvious that both the "sample" type and the test "condition" had significance effects on the variation of LF/HF (PWTT) ($p < 0.01$). Since the interactive effect between the "sample" type and the test "condition" was significant ($p < 0.01$), the one-way ANOVA was further conducted to examine the statistical significance of simple main effects of the "sample" type and the test "condition" on the variation of LF/HF (PWTT). Table 4-7 shows the one-way ANOVA results. According to Table 4-7 (A), under "Task" condition, there were significant between-sample differences in LF/HF (PWTT) ($p < 0.01$). Figure 4-13 (A) shows the corresponding LSD post-hoc test results. According to it, the value of LF/HF (PWTT) under the "Task" condition of compressing P1 was larger than that under the "Task" condition of compressing P2 at a significance level of 0.01 and larger than that under the "Task" condition of compressing P3 at a significance level of 0.05. Meanwhile, the value of LF/HF (PWTT) under the "Task" condition of compressing P3 was larger than that under the "Task" condition of compressing P2 at a significance level of 0.10. These results indicated that LF/HF (PWTT) tended to decrease with the decrease in perceived compressional softness during the active contact. According to Table 4-7 (B), as P1 was involved, there were significant differences in LF/HF (PWTT) between different conditions ($p < 0.01$). Figure 4-13 (B) shows corresponding LSD post-hoc test results. According to it, the value of LF/HF (PWTT) increased significantly because of the active contact with P1 ($p < 0.01$) and decreased significantly after the active contact with P1 ($p < 0.01$). These results indicated that LF/HF (PWTT) tended to decrease due to the active contact with materials of very good softness and get recovered after the active contact with materials of very good softness. In summary, the results mentioned above suggest that the parameter LF/HF (PWTT) is sensitive to the differences in tactile softness at a higher significance level than the parameter HFnorm (PWTT). It proves that the hypothesis for LF and HF variations of PWTT relevant to tactile softness is reasonable in some ways.

Table 4-6 Two-way ANOVA results for main effects of the "sample" type and the test "condition" on the variation of LF/HF (PWTT)

** $p < 0.01$; * $p < 0.05$

Source	SS	df	MS	F	p	
Sample	0.244	2	0.122	5.915	0.004	**
Condition	0.314	2	0.157	7.603	0.001	**
Sample × Condition	0.390	4	0.097	4.717	0.002	**
Error	1.672	81	0.021			
Total	6.186	90				

Table 4-7 One-way ANOVA results for simple main effects of the "sample" type and the test "condition" on the variation of LF/HF (PWTT)

(A) Between-sample

** $p < 0.01$; * $p < 0.05$

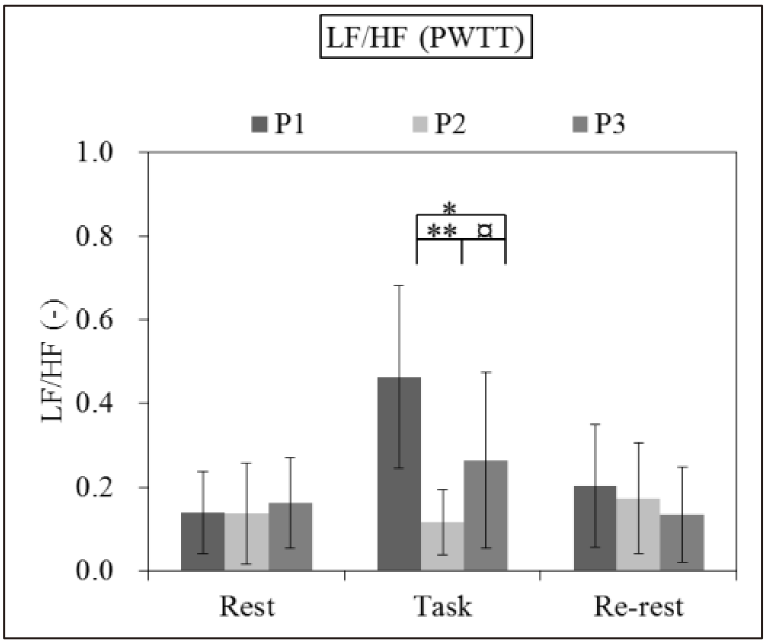
Condition	Source	SS	df	MS	F	p	
Rest	Between samples	0.004	2	0.002	0.164	0.849	
	Within samples	0.325	27	0.012			
	Total	0.329	29				
Task	Between samples	0.607	2	0.303	9.304	0.001	**
	Within samples	0.880	27	0.033			
	Total	1.487	29				
Re-rest	Between samples	0.023	2	0.012	0.669	0.520	
	Within samples	0.467	27	0.017			
	Total	0.490	29				

(B) Between-condition

** $p < 0.01$; * $p < 0.05$

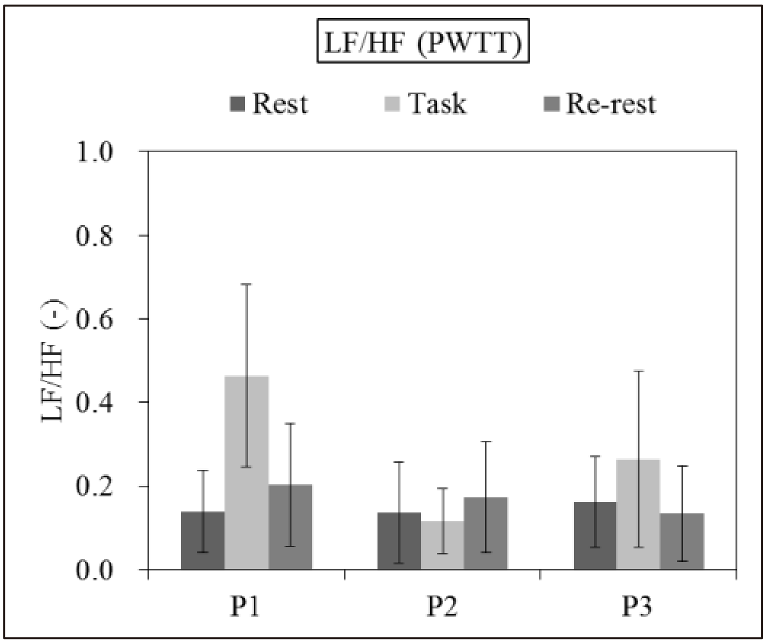
Sample	Source	SS	df	MS	F	p	
P1	Between conditions	0.595	2	0.298	11.387	0.000	**
	Within conditions	0.706	27	0.026			
	Total	1.301	29				
P2	Between conditions	0.016	2	0.008	0.628	.541	
	Within conditions	0.347	27	0.013			
	Total	0.363	29				
P3	Between conditions	0.092	2	0.046	2.010	0.154	
	Within conditions	0.620	27	0.023			
	Total	0.712	29				

** p < 0.01 * p < 0.05 ¤ p < 0.10



(A) LSD test results for simple main effects of the "sample" type

** p < 0.01 * p < 0.05 ¤ p < 0.10



(B) LSD test results for simple main effects of the test "condition"

Figure 4-13 Post-hoc test results for simple main effects of the "sample" type and the test "condition" on LF/HF (PWTT)

4.5 Conclusions

In this study, the cardiovascular and respiratory reactions to the active contact with three types of materials different in compressional softness were examined. Based on the statistical analysis results for several parameters calculated from ECG, PPG and RSP signals, the following conclusions are drawn:

(1) The variation of ventricular depolarization and repolarization duration tends to increase because of the active contact with deformable materials; however, the increment in the variation of ventricular depolarization and repolarization duration does not change with the levels of perceived compressional softness.

(2) The uniformity of respiration tends to decrease because of the active contact with deformable materials, but the decrement in the uniformity of respiration does not change with the levels of perceived compressional softness.

(3) The dominance of parasympathetic innervation of heart rate tends to decrease because of the active contact with deformable materials; besides, the decrement in the dominance of parasympathetic innervation of heart rate is likely to change with the levels of perceived compressional softness, but the change trends are not statistically significant.

(4) Low-frequency (LF) variations of PWTT tend to increase whereas high-frequency (HF) variations of PWTT tend to decrease because of the active contact with deformable materials; owing to the opposite change trends of LF and HF variations of PWTT, the parameter HFnorm (PWTT), which is determined by the expression "HF (PWTT) / (LF (PWTT) + HF (PWTT)) × 100%", and the parameter LF/HF (PWTT), which is determined by expression "LF (PWTT) / HF (PWTT)", prove to be very promising parameters that can be used to distinguish between materials different in perceived compressional softness.

(5) In frequency domain, the variations of PWTT are more sensitive to the differences in tactile softness than the variations of RRI during the active contact with deformable materials; it is supposed that the better sensitivity of the variations of PWTT in frequency domain should be attributed to the complex regulatory mechanism of PWTT, which involves both cardiac and vascular functions.

Additional data

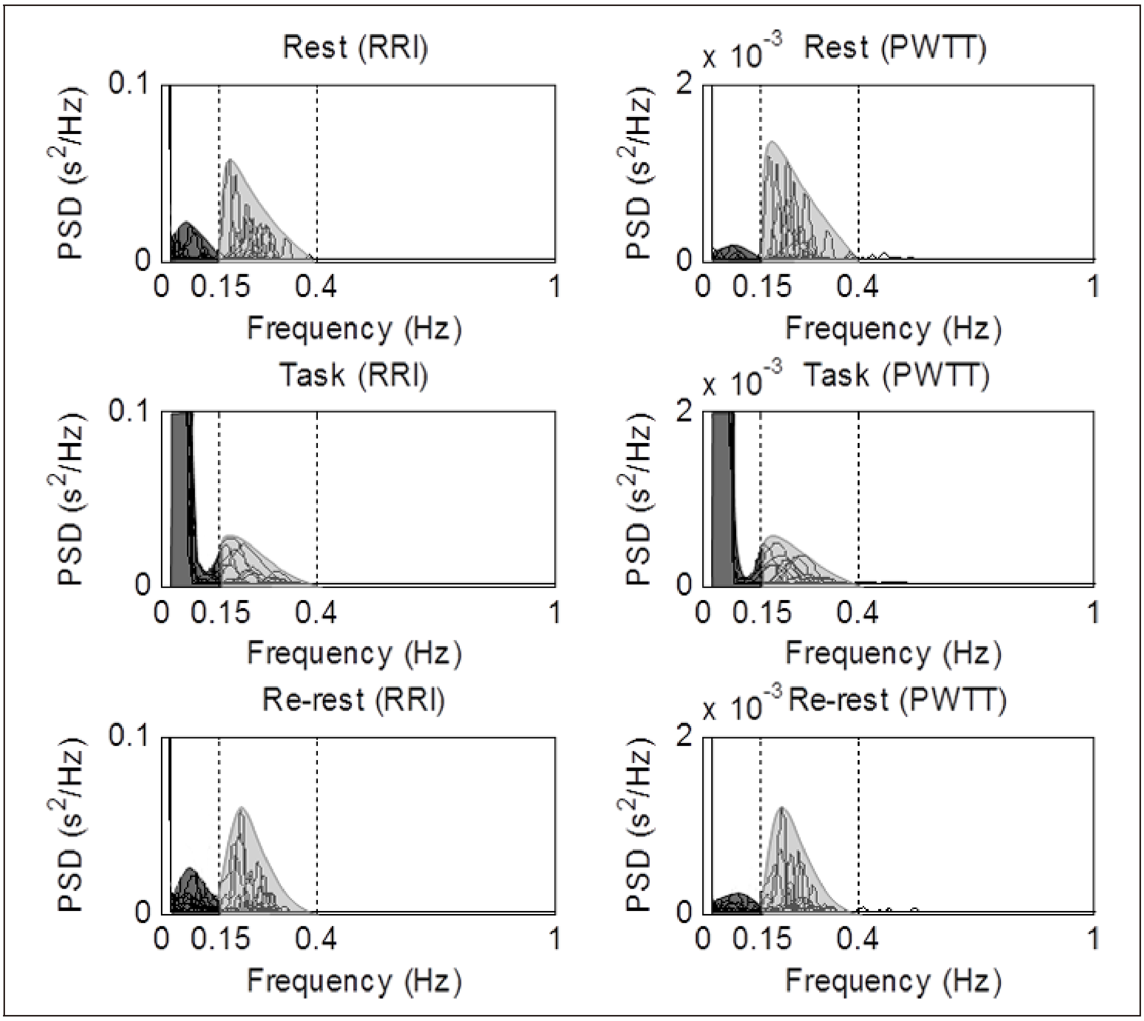
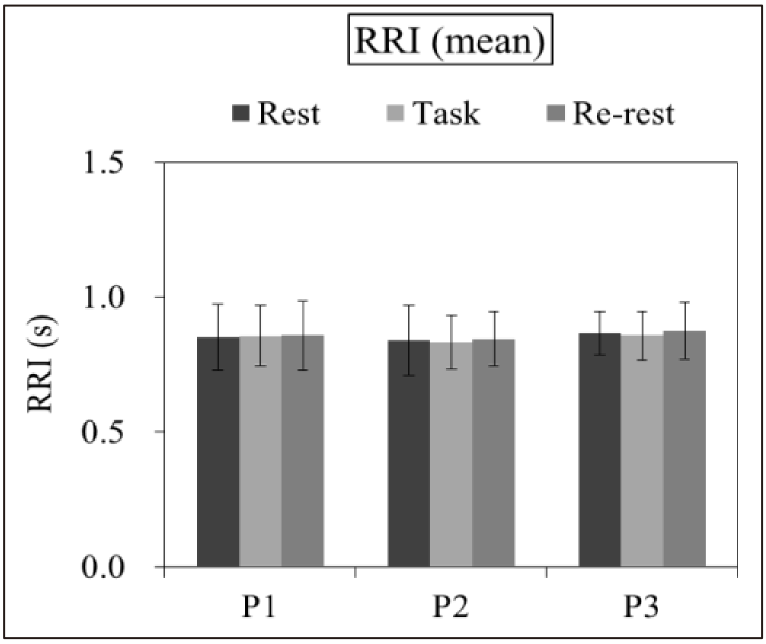
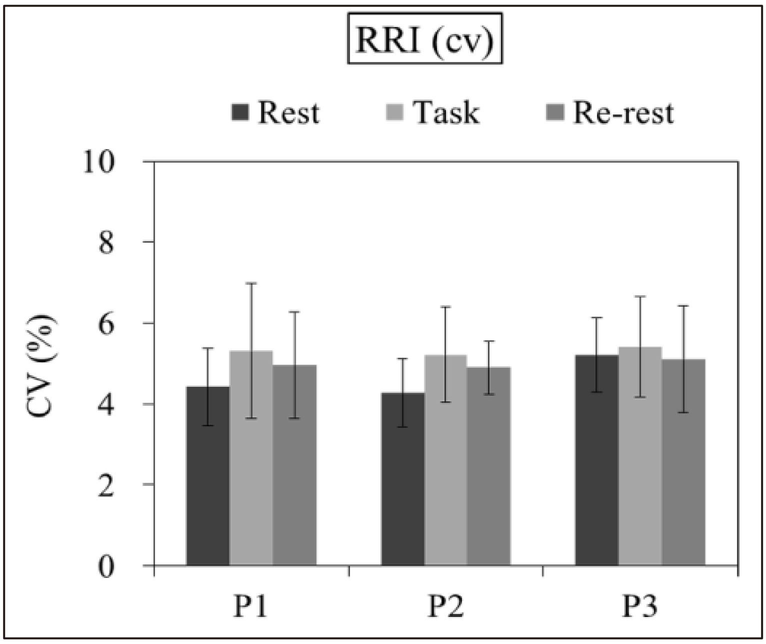


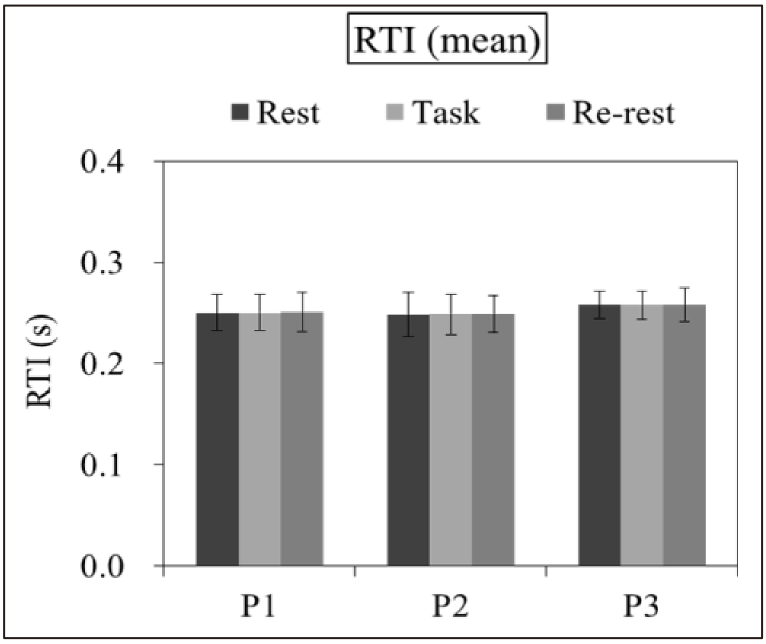
Figure 4-14 Power spectra of RRI and PWTT



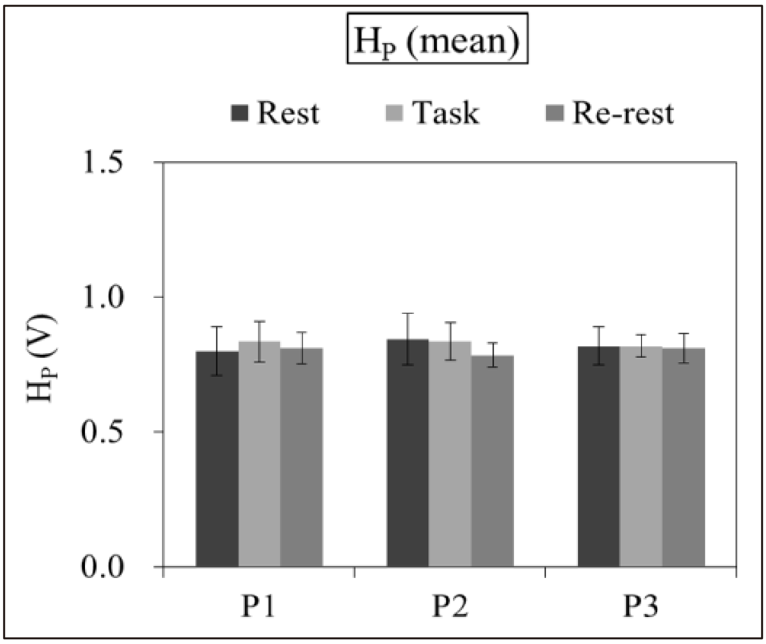
(A) Average value of RRI



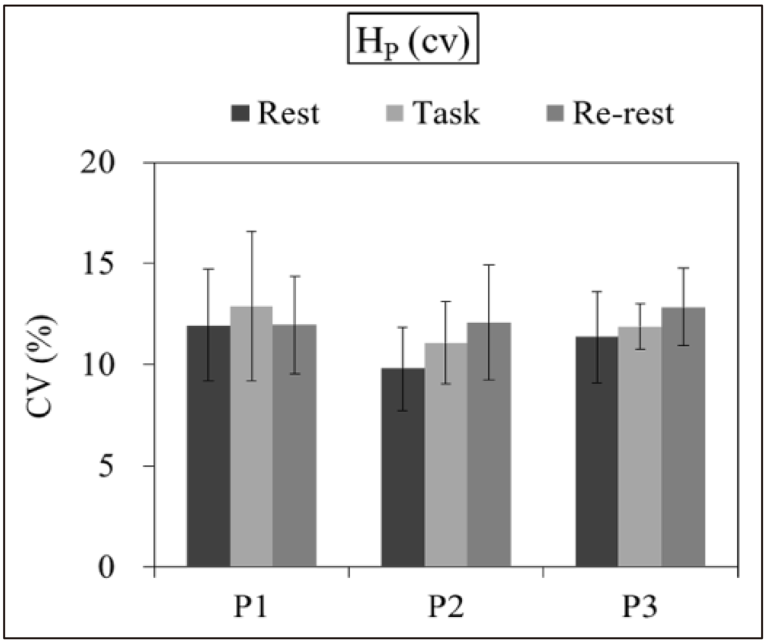
(B) CV of RRI



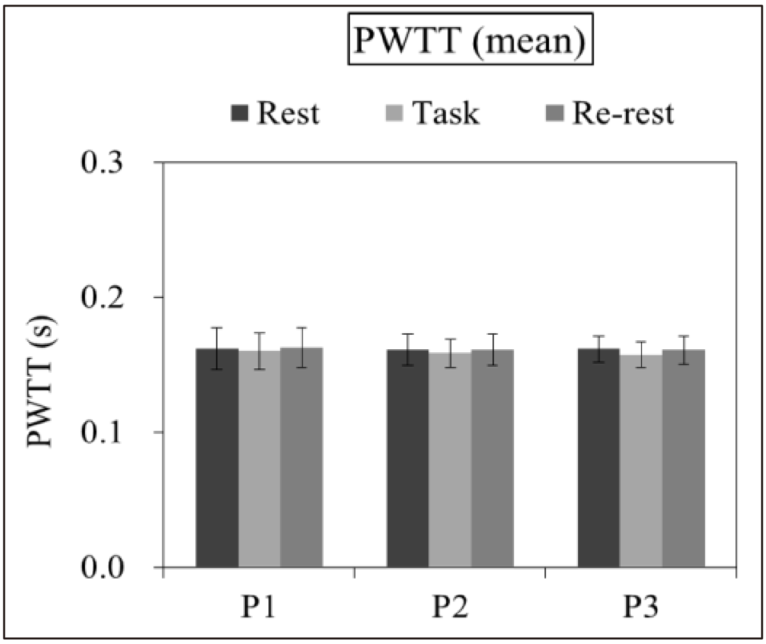
(C) Average value of RTI



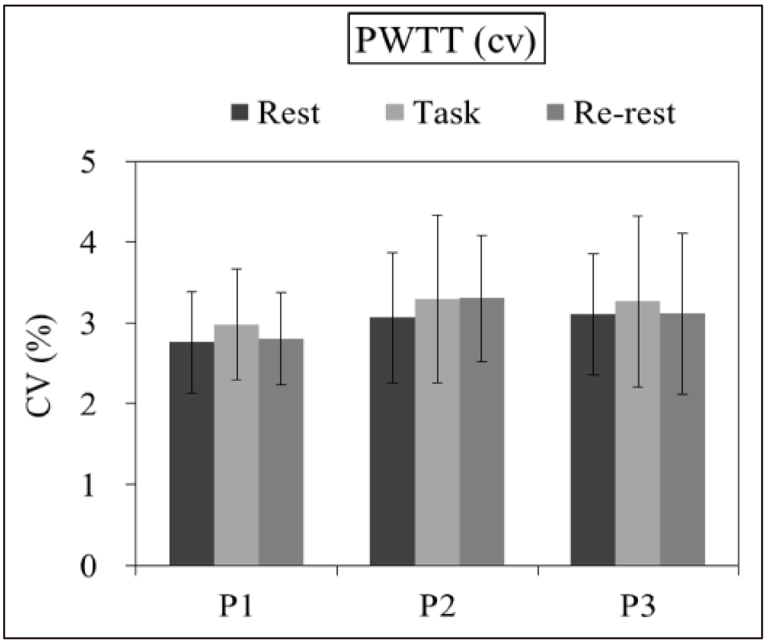
(D) Average value of H_P



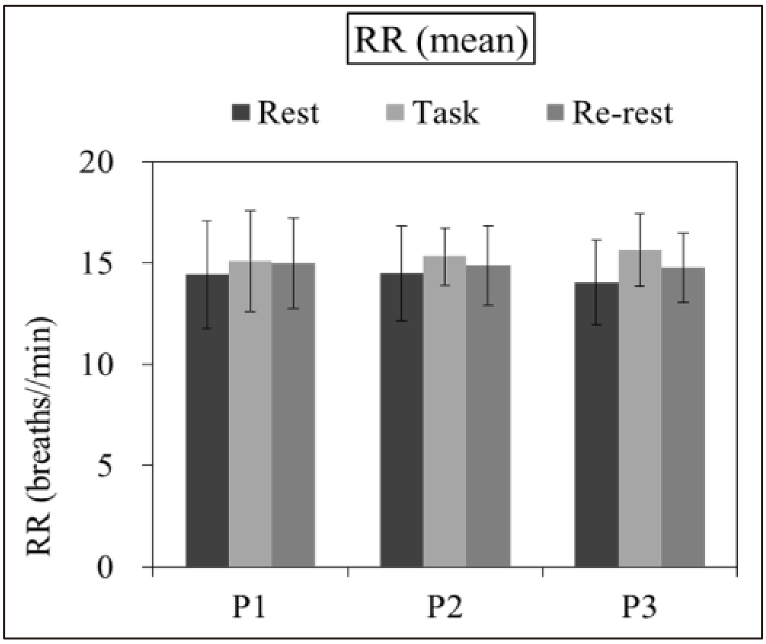
(E) CV of H_P



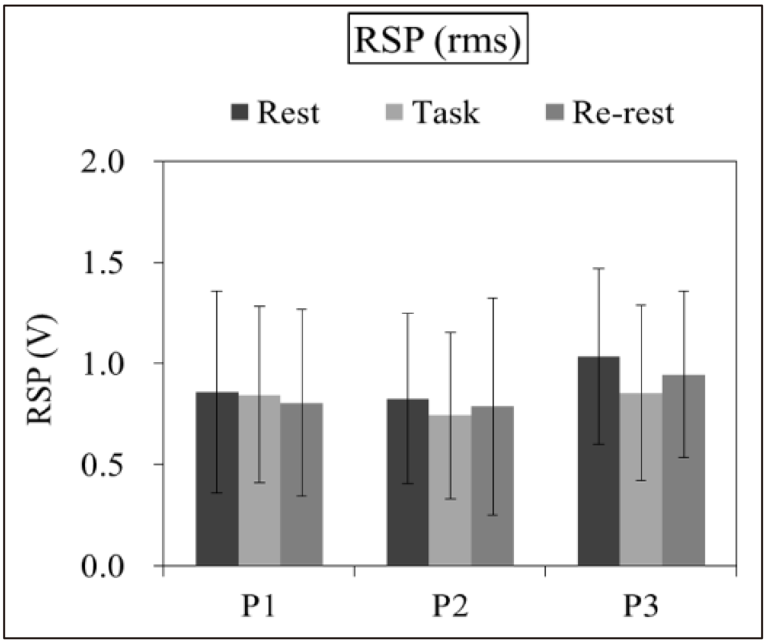
(F) Average value of PWTT



(G) CV of PWTT



(H) Average value of RR



(I) RMS of RSP

Figure 4-15 Calculated values of the parameters not discussed under the subsection 4.3.1

**: p < 0.01 *: p < 0.05

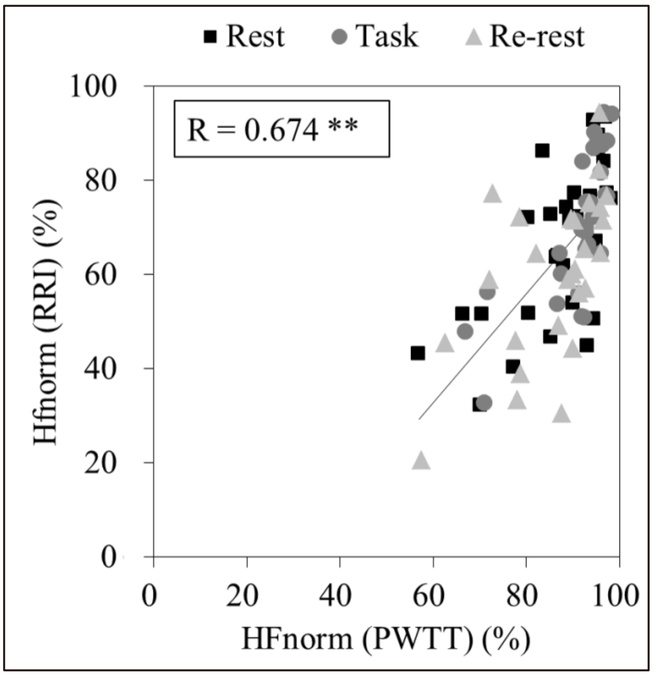


Figure 4-16 The relationship between HFnorm (RRI) and HFnorm (PWTT)

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Chapter 5

General conclusions

Chapter 5: General conclusions

Tactile comfort is playing a more and more important role in determining consumer preferences for textile products. Therefore, it is necessary to find some effective methods of evaluating tactile comfort or tactile sensations mostly contributing to tactile comfort. Physiological parameters can indicate the physical and/or mental conditions of the human body. If it is possible to find some physiological parameters that change with the levels of tactile comfort/tactile sensations, it will be very helpful to the development of comfortable and healthy textile products.

According to what has been found by a few researchers, the fundamental sensations contributing to tactile comfort is recognized as smoothness and softness. The perception of smoothness and the perception of softness involve different perceptual mechanisms. Therefore, when textile materials are touched in different ways, either the perception of smoothness or the perception of softness may play a major role in determining the status of tactile comfort. In terms of the perception of smoothness, the relative sliding movement between the skin and the material is necessary, whereas the incentive is negligible. Therefore, both passive forearm touch ("Hadazawari") and active hand touch ("Tezawari") are suitable for smoothness discrimination. In terms of the perception of softness, the kinesthetic information (i.e., the pressure distribution detected by mechanicoreceptors) is necessary, and the kinesthetic information will help to enhance the accuracy of softness discrimination. Therefore, active hand touch ("Tezawari") is a better choice for softness discrimination.

In order to ascertain whether it is possible to differentiate between materials different in tactile smoothness and tactile softness through observing the changes of physiological parameters, three preliminary studies based on psychophysiological measurement techniques were carried out.

In the first study, the coolness and moistness discrimination differences between active hand touch ("Tezawari") and passive forearm touch ("Hadazawari") were investigated by taking three types of single jersey fabrics as the samples. According to the comparative analysis results, the following conclusions are drawn: (a) when discriminated via passive forearm touch, the coolness and moistness differences between materials are perceived to be more intense and persistent; (b) whether active hand touch or passive forearm touch is involved, when materials definitely different in perceived coolness are compared in pairs, the presentation order has a significant effect on the perceived intensity of coolness; (c) within a given time, the perceived intensity of moistness correlates very well with the perceived intensity of coolness. These findings suggest that: (a) when used as a sensory test method, passive forearm touch is a better choice for coolness and moistness discrimination; (b) when applied in a psychophysiological measurement experiment for the perception of other sensations rather than coolness and moistness, coolness and moistness differences between materials should be better controlled to get expected results.

In the second study, with the respiratory rate identically controlled at 15 breaths per minute, the cardiac reactions caused by the experience and the removal of dynamic contact with towels different in tactile smoothness were observed, respectively. According to the statistical analysis results, the following conclusions are drawn: (a) neither the experience of dynamic contact with a relatively smooth and comfortable texture nor the experience of dynamic contact with a relatively rough and uncomfortable texture tends to lead the average heart rate, the average duration of ventricular depolarization and repolarization or the balance between sympathetic and parasympathetic innervation of heart rate to change significantly; (b) both the removal of dynamic contact with a relatively smooth and comfortable texture and the removal of dynamic contact with a relatively rough and uncomfortable texture tend to lead to a decrease in average heart rate and an increase in average duration of ventricular depolarization; (c) the average R-T interval increases with the increase of average R-R interval, and the R-T interval may be relatively difficult to be affected by occasional changes when compared with the R-R interval. These results suggest that: (a) average R-T interval may be taken as an alternative of average R-R interval to observe the changes in average heart rate; (b) it seems difficult to differentiate between textures different in tactile smoothness only through observing heart rate variability, and other measures such as peripheral circulation measurement should be combined to have a try.

In the third study, the cardiovascular and respiratory reactions caused by active contact with two pillows and a cushion that are different in compressional softness were examined. According to the statistical analysis results, the following conclusions are drawn: (a) the variation of ventricular depolarization and repolarization duration tends to increase because of the active contact with deformable materials, but the increment does not change with the levels of perceived softness; (b) the uniformity of respiration tends to decrease because of the active contact with deformable materials, but the decrement does not change with the levels of perceived softness; (c) the parasympathetic innervation of heart rate tends to decrease because of the active contact with deformable materials, and the decrement is likely to change with the levels of perceived softness; (d) low-frequency (LF) variations of PWTT (pulse wave transmit time) tend to increase whereas high-frequency (HF) variations of PWTT tend to decrease because of the active contact with deformable materials; (e) the parameter HFnorm (PWTT), which is determined by the expression "HF (PWTT) / (LF (PWTT) + HF (PWTT)) × 100%", and the parameter LF/HF (PWTT), which is determined by expression "LF (PWTT) / HF (PWTT)", prove to be promising parameters that can be used to differentiate between deformable materials different in tactile softness. These results suggest that the variations of PWTT (an indicator of blood pressure) in frequency domain tends to be more sensitive to the differences in tactile softness than the variations of R-R interval.

As the ultimate goal, we expect to establish a psychophysiological evaluation system for tactile comfort of textile products. However, since few studies relevant to the topic in this thesis have ever been done by other researchers, we need to start with some preliminary qualitative experiments to found a theoretical basis for the establishment of the psychophysiological evaluation system. In general, the psychophysiological measurement techniques are based on the psychological and physiological responses of the human body. If too many materials are involved in the psychophysiological tests, the subjects may be burdened physically and/or in mind. As a result, it will be difficult for us to get representative signals or information through psychophysiological measurement. In this thesis, the three studies were designed for the purpose of ascertaining if there are any cardiac, vascular and/or respiratory parameters that change with the status of tactile comfort. In order to ensure the precision of perception or recognition of the subjects, only two or three types of representative materials were selected to conduct the psychophysiological tests. In the end, the research results convince us that it is very promising to correlate tactile comfort of textile products with some physiological parameters that are associated with the regulation of autonomic nervous system. What we need to do next is to verify the findings of the three studies by applying them to more materials.

Publications

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   Effectiveness of the "Tezawari" and "Hadazawari" sensory test methods in the evaluation of fine-textured knitted fabrics Part I: coolness and moistness discrimination
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   Study on cardiovascular and respiratory responses relevant to tactile softness evaluation – based on ECG and PPG analysis –
   International Journal of Affective Engineering (Special Issue), Vol.13, No.4, pp.269-277 (Published in 2014)

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   Preliminary study on physiological responses related to dynamic contact with towels: based on ECG analysis
   Textile Bioengineering and Informatics Symposium Proceedings 2014, ISSN:19423438, pp.779-787 (Published in 2014)

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   The 6th International Conference on Advanced Fiber / Textile Materials, Ueda, Japan
   December 8th, 2011

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   The 8th China International Silk Conference, Suzhou, China
   September 9th, 2013