信州大学審査学位論文

Study on measurement and evaluation methods on the sense of touch of thick clothing products

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CONTENTS

FIGURES

TABLES

CHAPTER 1

Preface

1. Preface

1.1. Background

Texture is the uniformity and variation of the surface of an object, which can mean the actual or implied features of surfaces. The texture of a surface can be described in many ways, such as *smooth*, *rough*, *shiny*, or *dull.* Obviously, texture is a complex synthetic sensation that covers many aspects of the sensory features of a surface, including visual, auditory, and various tactile perceptions. In normal situations, people often see a garment or fabric when they touch or wear it, and hear the sound of the contact and friction between the skin and the fabric or between different parts of the clothing material. All the information gained from the visual, tactile, and auditory signals provides us with the overall perception of the surface texture [1].

Fabric handle, which describes the way a fabric feels when touched by a human hand, is an important aspect of fabric texture [2]. Fabric handle properties have been extensively studied in the areas of subjective sensory descriptors, psychophysics, fabric mechanics, and objective and subjective assessment methods. Fabric handle is a complex synthetic sensation that consists of many dimensions, which are obtained through the active manipulation of a human hand. However, there is a fundamental difference between the perception of touch by wearing a garment and by handling a fabric. When wearing a garment, touch is passive, where the wearer does not move intentionally to get information about the clothing; information is essentially imposed on the skin. In the process of handling a fabric, touch is active, where the observer is palpating with hands intentionally to obtain objective information about the fabric [3-5].

The subjective perception of texture of clothing by a wearer or user is determined by psychological processes, which in turn are evoked by various physical stimuli such as visual stimuli, thermal stimuli, pressure stimuli, tactile stimuli, etc. Also, the actions of the autonomic nervous system to adjust heart beat, blood flow, and perspiration rate are physiologically modulated by these physical stimuli and their psychological responses. Therefore, it is necessary that the evaluation of clothing comfort be considered in terms of physical stimuli, psychological responses, and physiological responses.

These physical stimuli are determined by a number of physical processes that are dependent on the relevant fabric physical properties and structural features. Therefore, it seems desirable and logical to develop methods to predict the fabric handle objectively. Considerable research work has been carried out to measure fabric properties and predict some aspects of tactile sensation performance through various approaches.

Evaluation of thin fabric handle through fabric objective measurement, which has been developed on the basis of the work of Kawabata and his co-workers, has widely been recognized and used around the world. On the basis of fundamental work on fabric mechanical properties and thin fabric handle, they developed the KES-F system. This system is composed of four testers: KES-FB1 tensile and shear tester, KES-FB2 bend tester, KES-FB3 compression tester, and KES-FB2 surface-friction and geometric roughness tester. The fabric handle evaluation terms of: *NUMERI* (smoothness), *SHARI* (crispness), *KOSHI* (stiffness), *HARI* (spread or anti-drape), *FUKURAMI* (fullness and softness), and *SOFUTOSA* (softness) are predicted by his equations from subjective perception and objective measurements in the form of linear and mixed linear-log functions [6]. However, previous studies for the objective evaluation of fabric handle are mainly focusing on thin textile materials and products such as woven fabrics, knit fabrics, nonwoven fabrics, etc. Therefore, in this thesis, I discuss the evaluation of texture for thick textile products.

1.2. Purpose and Structure of Thesis

I have written this thesis with two major goals in mind. The first goal is to clarity how the deterioration or changing of the texture of thick fabrics, which touched the skin directly, influences psychological and physiological response. As mentioned above, the subjective perception of the texture of clothing by a wearer or user is determined by psychological and physiological processes, which are evoked by various physical stimuli. Many works have been carried out to estimate the psychological response using sensory tests and to measure the physical response using textile test standards as well as the KES method. However, there are few studies on the physiological response to texture deterioration.

In Chapter 2, I discuss about the physiological and psychological responses to the deterioration of the texture of pile cloth through washing. The texture deterioration of a towel is intense as compared to other type of cloths, because it is washed more frequently. In the case of babies and disabled people, towels are used passively and it is considered that passive touch has more influence on the physiological response. Therefore, multiple washed pile cloths samples were prepared for this research and sensory tests were passively carried out to investigate the psychological response. In order to figure out the influence on the physiological response, indexes of the activity of the autonomic nervous system were measured.

In Chapter 3, I discuss the influence of sweat absorbent liners on helmet comfort. The sweat absorbent liner (SAL) plays the roles of giving the helmet fit and absorbing sweat. Helmet comfort changes due to sweating during work or exercise. When wearing a helmet, the touch is also passive. However, hand evaluation plays an important role in the expectation for helmet comfort both when helmet makers design a helmet and when users purchase a helmet. Therefore, the effects of the physical properties of the SAL on helmet comfort were investigated and forehead feel was statistically compared with hand feel.

The second goal is the development of a new hand evaluation measurement system, which reflects the human sense. The KES-F system is a very useful system to evaluate the fabric handle objectively, but it is difficult to measure the mechanical properties of thick materials such as sheepskin and thick-pile fabric. The new hand evaluation measurement system is composed of a three-dimensional Cartesian manipulator and a three-axis force sensor module to imitate the human palpate motions and sense, and is dealt with in Chapter 4.

In Chapter 4, the hand evaluation measurement system is verified by the evaluation of sheepskin's fabric hand. Sheepskins are evaluated in Japan using unique evaluation terms such as *DANRYOKU* (perceived elasticity), *KEGOMI* (richness and fullness of hair), *KESABAKI* (smoothness and softness of hair), etc. Therefore, it is necessary to measure the fabric hand properties of sheepskin mechanically. For this study, I focused on *DANRYOKU* and *KEGOMI* and figured out the relationship between the tactile sensation and the mechanical properties of sheepskin.

CHAPTER 2

Physiological and Psychological Responses to the Deterioration of the Texture of Pile Cloths through Washing

2. Physiological and Psychological Responses to the Deterioration of the Texture of Pile Cloths through Washing

2.1. Introduction

Japan's medical treatment of preemies is the top level in the world, and Japan has the lowest mortality rate for preemies in the world. However, various medical treatments and environments that exist in neonatal intensive care units (NICU) overload and add stress to the preemie. It has been pointed out that this causes some problems in the development of *Kansei* (the senses), where this is the integrated ability of creativity, cognition, and expression. The stress can be reduced by emulating the environment of the inside of the mother's womb as much as possible. As part of developmental care, keeping the preemie's posture like it would be in the mother's womb is an effective way. In hospitals, including Nagano Children's Hospital, this positioning is performed using a pile cloth that is called a "positioning mat". However, it is believed that repeated washing of the positioning mat deteriorates the texture and causes stress for the preemie. Also, the positioning mat is used passively and it is considered that passive touch has more influence on the physiological response.

The subjective perception of the texture of cloth by a wearer or user is determined by psychological and physiological processes, which are evoked by various physical stimuli. Many works have been carried out to estimate the psychological response using sensory tests and to measure the physical properties using textile test standards as well as the KES method. However, there are few studies on the physiological response to texture deterioration.

Therefore, multiple washed pile cloths, the top side of positioning mats, were prepared for this research and sensory tests were passively carried out to investigate the psychological response. In order to figure out the influence on the physiological response, indexes of the activity of the autonomic nervous system when samples touched the human body were measured.

2.2. Experiment

2.2.1. Samples

Table 2-1 shows the name of the samples and washing frequency. The sample cloths were composed of plain knit fabric blending of 80% cotton and 20% polyester and 100% cotton pile yarns, which were driven in the loop of knit fabric and sheared at 2mm (c.f. Table 2-2). These samples were prepared to measure the change in the fabric's texture according to the washing frequency. All the samples were washed once to eliminate any chemicals, oil, etc. that had adhered to the material during the manufacturing process. The samples were exposed in a standard condition (temperature: 20±2°C; relative humidity: 65±4%) for 24 hours or more before the experiments and the measurement environment was kept at the same condition.

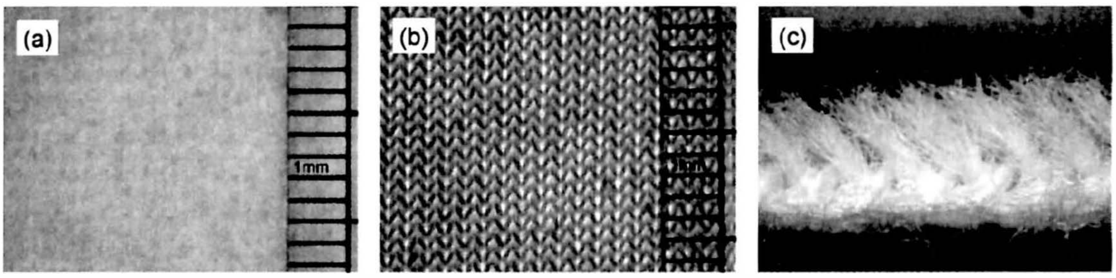


Figure 2-1 Pictures of sample: (a) Front, (b) Back, and (c) Pile

Table 2-1 Sample names

L 0	Sample washed with dirt from the manufacturing process
L 1	L 0 sample washed once
L10	L 0 sample washed 10 times
L30	L 0 sample washed 30 times
L50	L 0 sample washed 50 times

Table 2-2 Sample detail

	Structure	Composition	Loop density (Wale / Course)	Pile length
Knit	Plain	Cotton 80% Polyester 20%	11/cm / 14/cm	
Pile	Shearing	Cotton 100%		2mm

2.2.2. Physical Property Tests

2.2.2.1. Air Permeability

The air permeability test was carried out according to JIS L 1018:1999. The size of the specimens was 10cm×10cm. After the samples were installed in the cylinder of the examination machine (Air permeability machine; TOYOSEKI), the inhalation pump was adjusted so that the inclination type barometer showed the pressure of the water column to be 1.27cm with the rheostat, and the amount ($cc/cm^2/s$) of air that passed was calculated from the pressure at the air orifice, which was 11mm in diameter, that was registered on the vertical type barometer at that time. After having measured three pieces respectively, the mean value of the test piece was shown.

2.2.2.2. Moisture Regain

The moisture regain was tested according to JIS L 1018:1999. Three specimens of each sample, which were 10cm×10cm were prepared. The mass (g) of the specimens, which were left for 12 hours or more in the standard state were measured before they were dried. After that, these specimens were left in a heat chamber at 105±2°C and the constant mass was being measured to determine an absolute dry mass.

2.2.2.3. Water Absorption

Water absorption was tested according to JIS L 1097. Five specimens of 20cm× 2.5cm in size were prepared in the vertical direction and horizontal direction of the sample respectively. Position was adjusted so that the bottom of the specimens was immersed in water and the specimens were left for ten minutes. After ten minutes had passed, the water absorption height was measured to be up to 1mm.

2.2.2.4. Surface Property

The mean of friction coefficient (MIU) and the geometric roughness (SMD) were measured. A tension of 20 gf/cm was applied to the specimen and it was secured to a smooth metal sample stand. The contact load was 50 gf and the specimen was moved at the speed of 0.1 cm/s. KES-FB4 surface tester (KATO Tech) was used for this test.

2.2.2.5. Warm/Cool Touch

The q-max was measured for the warm/cool touch. The specimen was put on the sample stand (3cm×3cm) and the hot plate set to 10°C above the room temperature. The contact pressure was 10 gf/cm^2. Styrene foam was used for the sample stand. A KES-F7 Thermo Labo (KATO Tech) was used for the measurement.

2.2.3. Physiological Measurements

The physiological and psychological responses were measured to understand the influence of changes in the fabric texture through increased washing frequency on the human mind and body. The subjects were 13 healthy male and female university students (α-amylase activation test was done on four subjects).

Figure 2-2 shows the measurement flow. After the subjects had become accustomed enough to the experimental environment where they were made to sit, the measurement began. Saliva was collected before beginning measurements of their electrocardiogram, blood flow, and respiration. After beginning these measurements, a state of rest was taken for 120 seconds, and the sample was placed in contact for 120 seconds. The method of contact with the sample was a passive touch on the inside of the forearm. In order to maintain constant pressure, it was hung from the subject's arm like when carrying a bag. Silicon rubber was added on the sample to keep the load constant. The samples were presented to subjects at random and sample names were not given to them to minimize any potential bias. After the electrocardiogram, blood-flow, and respiration were measured for 120 seconds, saliva was collected again from those who had been in contact with the sample. After the saliva was collected, the sample contact was stopped and a sensory test was carried out.

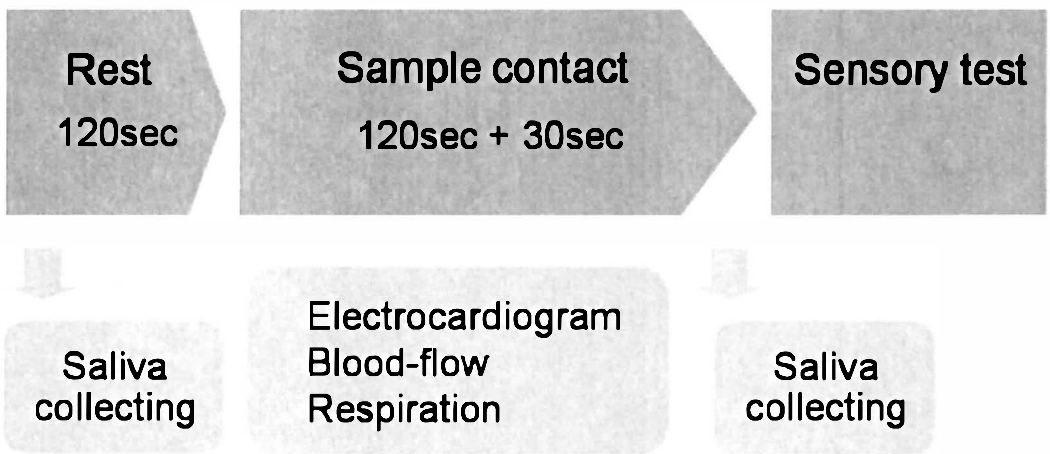


Figure 2-2 Measurement flow

2.2.3.1. Electrocardiogram (ECG)

The electrocardiogram (ECG) was obtained using bipolar chest leads (left collarbone or superior margin of the sternum and xiphoid process) with a ground lead (under the left eighth rib) and the analog ECG was converted to the digital ECG via an amplifier (ECG100C: BIOPAC Systems). The sampling frequency was 2000 Hz, and the signal was filtered through a low-pass filter of 5 Hz and a high-pass filter of 40 Hz for the analysis of ECG. The R-wave was detected from the ECG wave. The R-R intervals (The interval between one R wave and the next R wave) were restructured in the time series data. The frequency of R-R intervals was analyzed by fast Fourier transform (FFT), and the power spectrum of the low-frequency region (LF: 0.05-0.15Hz) and high-frequency region (HF: 0.15-0.5Hz) was obtained. The low-frequency (LF) component reflects both sympathetic nerve activity and parasympathetic activity. The high-frequency (HF) component is a quantitative marker of parasympathetic activity. Therefore, the LF/HF ratio is considered to reflect the sympathetic modulations and HF/(HF+LF) ratio is used as a parasympathetic activity index. It can be presumed to reflect the state of physiological stress on the body.

The average of heartbeat (beat per minute, BPM) was calculated in two sections during contact with the cloth and during rest. The ratio of the heartbeats was calculated to figure out the change of the number of heartbeats before and after contact. The coefficient of the variation of R-R intervals (CVRR: Standard deviation/Mean×100 (%)) were calculated from the R-R interval of ECG wave in the data of the two sections during contact with the cloth and during rest.

2.2.3.2. Peripheral Blood Flow

The quantity of blood-flow under the skin of the index fingertip was measured. The autonomic nervous activity influences changes in the amount of blood-flow in the peripheral parts. A laser-Doppler flow meter (LDF100C: BIOPAC Systems) was used to measure the amount of blood-flow. The ratio of the average amount of blood-flow during contact with the cloth and during rest was calculated.

2.2.3.3. Respiration Depth

An increase in the respiration rate is assumed to be the result of excitation of the autonomic nerve system. The temperature change curve of exhalation and inhalation was considered as the respiration cycle. A thermal resistor (amplifier for skin, A/D converter, SKT100C: BIOPAC Systems) was installed in the nose. The sampling frequency was 200Hz. The power spectrum which was obtained from the respiration curve was calculated by processing with FFT and this was integrated between 0.1Hz before and after the peak in the respiration cycle (during two seconds). In this test, the peaks appeared at 0.25Hz because respiration was controlled. Therefore, the integral interval was 0.15Hz to 0.35Hz.

2.2.3.4. α-amylase Activation in Saliva

The density of the hormone in saliva is difficult to measure because it showed very a low order with the nM (nmol/L). However, there are a lot of merits as compared with blood and urine. Saliva can be collected without giving the subject any psychological or physical pain, and it doesn't require any special preprocessing. Therefore, the α-amylase in the saliva, which is the one of the digestive enzymes, has been focused on as a marker material to establish the technology that quantitatively evaluates the biological reaction to stress [7].

In this test, saliva was gathered using a amylase sensor (α-AMY: YAMAHA MOTOR) before the rest period and after the cloth contact and the activation value of α-amylase was measured. The index was the ratio of the amylase activation value during contact with the cloth to the value during rest.

2.2.3.5. Psychological Response

A sensory test using a semantic differential (SD) method was carried out to investigate the psychological response. Subjects evaluated the fabric handle using a 5-point scale of -2 to +2 in their mother tongue. Table 2-3 shows the evaluation terms and rating scale.

Table 2-3 Sensory test terms and rating scale

- 2	- 1	0	+ 1	+ 2
Rough	Slightly	Neither	Slightly	Fine (Smooth)
Hard	Slightly	Neither	Slightly	Soft
Uncomfortable	Slightly	Neither	Slightly	Comfortable
Cool	Slightly	Neither	Slightly	Warm
Feels bad on the skin	Slightly	Neither	Slightly	Feels good on the skin
Uneasy feeling	Slightly	Neither	Slightly	Soothing feeling

2.3. Results

All test result values are shown in Table 2-8 and their significant differences were compared each other in one-way ANOVA using Scheffe's method.

2.3.1. Physical Property

2.3.1.1. Air Permeability

Figure 2-3 shows the result of the air-permeability test and Table 2-4 shows the result of multiple comparisons. The quantity of airflow decreased after one wash and then increased according to an increase in the washing frequency. It seemed that the air permeability decrease of the single wash sample occurred due to the deformation of piles. After that, the air permeability was improved because of the damage and deterioration of piles by multi-washes.

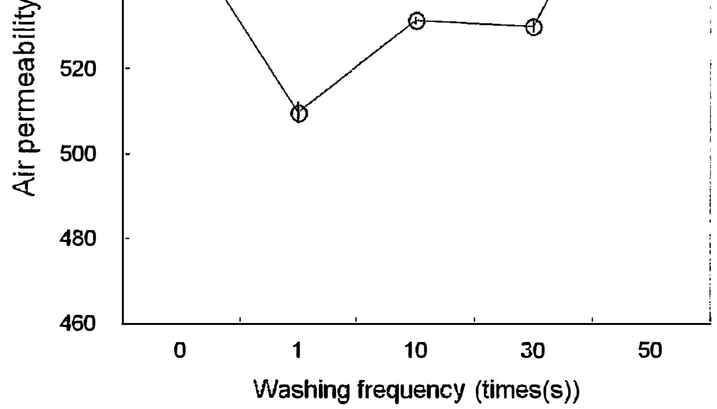


Figure 2-3 Air permeability

Table 2-4 Multiple comparisons of air permeability (: P<0.01, *: P<0.05)**

	L0	L1	L10	L30	L50
L0		**			*
L1					**
L10					**
L30					**
L50					

2.3.1.2. Moisture Regain

Figure 2-4 shows the result of the moisture regain test. Moisture regain was gradually decreasing with increasing wash frequency. However, as a result of multiple comparisons, there were no significant differences between them.

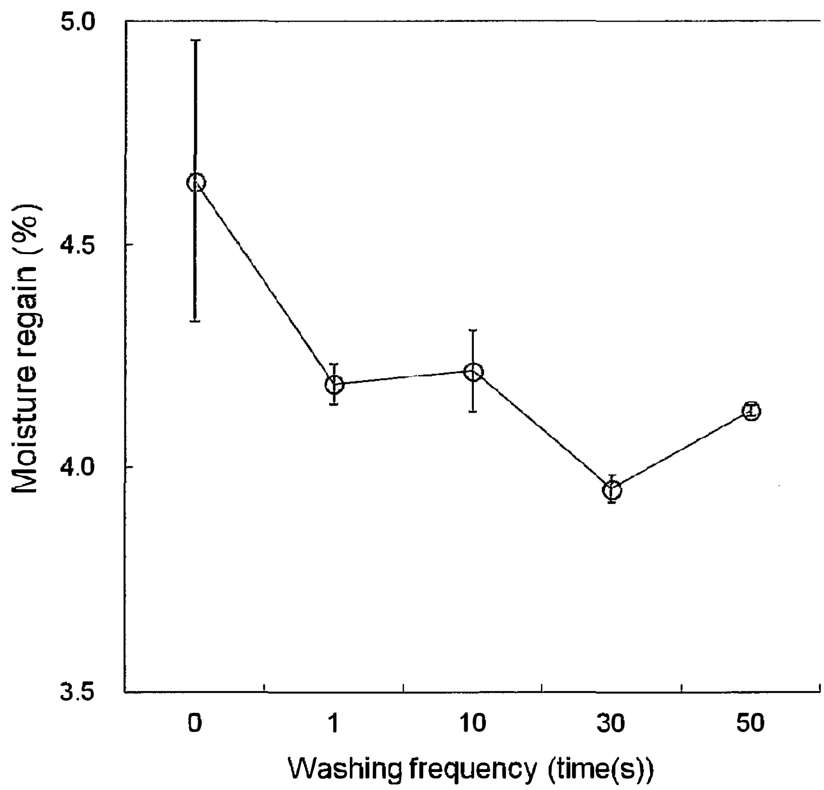


Figure 2-4 Moisture regain

2.3.1.3. Water Absorption

Figure 2-5 shows the result of the water absorption test and Table 2-5 shows the result of multiple comparisons. The water absorption in the wale direction was higher than in the course direction. Both water absorptions increased until 10 times washing, and there were also significant differences between them. It was considered that the removal of the oil elements, which were attached during the manufacturing process, influenced this increasing. After 10 times washing, water absorption decreased because of the damage and deterioration of piles with multiple-washes.

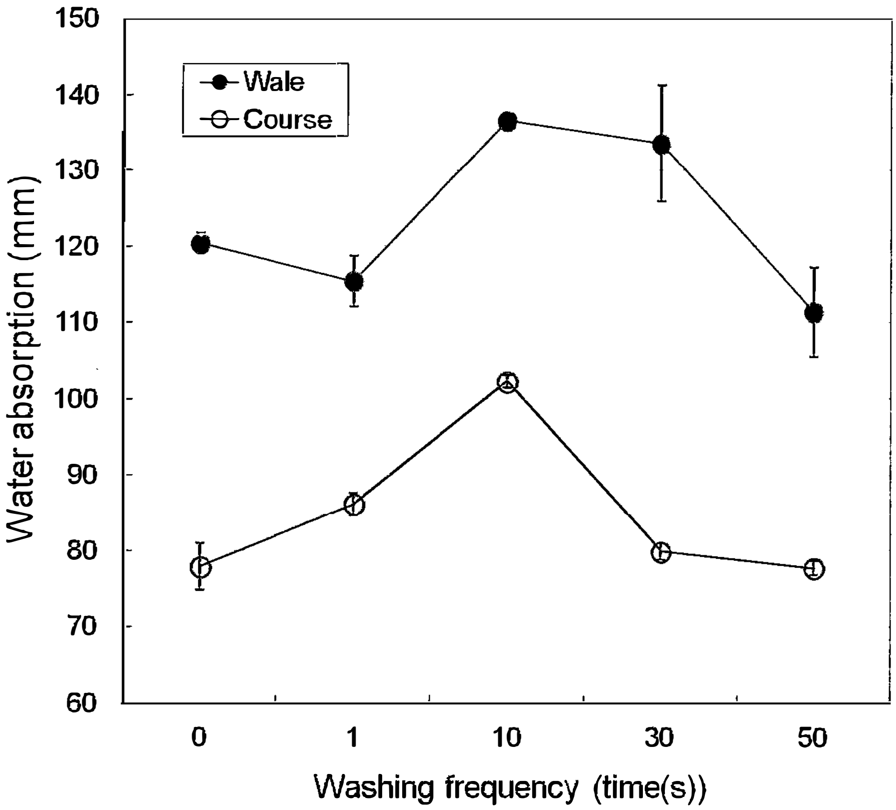


Figure 2-5 Water absorption

Table 2-5 Multiple comparisons of water absorption (upper triangle: wale direction, lower triangle: course direction; **: P<0.01, *: P<0.05)

Wale / Course	L0	L1	L10	L30	L50
L0			**	**	
L1			**	**	
L10	**	**			**
L30			**		**
L50			**		

2.3.1.4. Surface Property

① Mean of Friction Coefficient (MIU)

Figure 2-6 shows the result of the mean of friction coefficient test. L10 showed the highest MIU value. However, there were no significant differences between them.

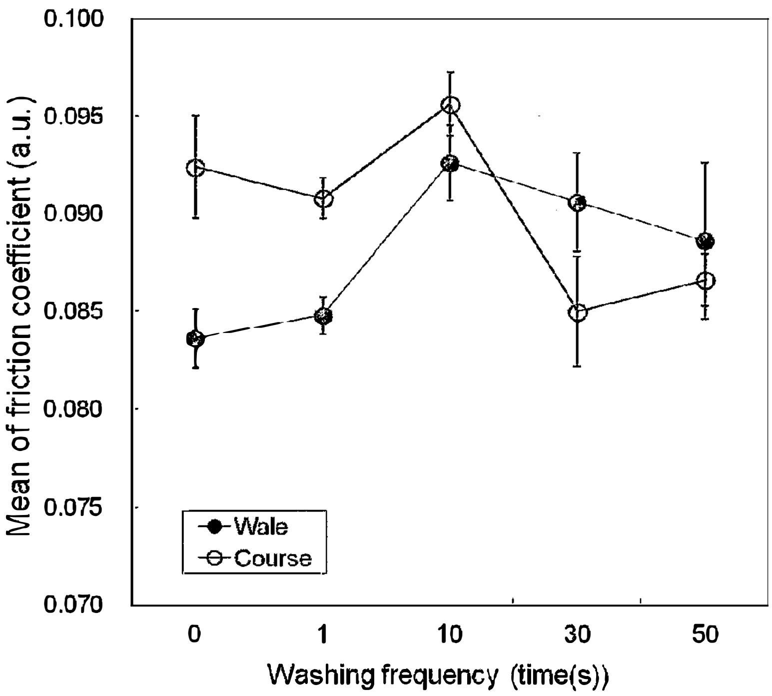


Figure 2-6 Mean of friction coefficient (MIU)

② **Geometric Roughness (SMD)**

Figure 2-7 shows the result of the geometric roughness test and Table 2-6 shows the result of multiple comparisons. SMD value dropped after a single wash, and then it increased in the wale direction with multiple washes. In the course direction, L30 showed the highest value.

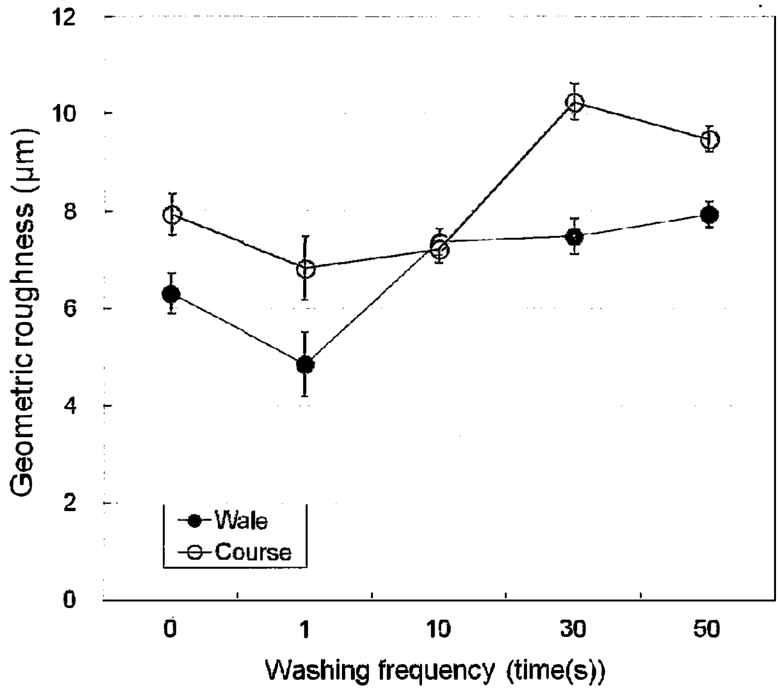


Figure 2-7 Geometric roughness (SMD)

Table 2-6 Multiple comparisons of geometric roughness (upper triangle: wale direction, lower triangle: course direction; **: P<0.01, *: P<0.05)

Course \ Wale	L0	L1	L10	L30	L50
L0					
L1			**	**	**
L10					
L30		**	**		
L50		*			

③ Warm/Cool Touch (q-max)

Figure 2-8 shows the result of the warm/cool touch test and Table 2-7 shows the result of multiple comparisons. The maximum heat flux, q-max, represents a chilly sensation. L1 showed the highest value and q-max value decreased with increasing the wash frequency. It was considered that heat flux went down because the contact area of the solid copper plate to the piles of the samples was decreased by the multiple washes.

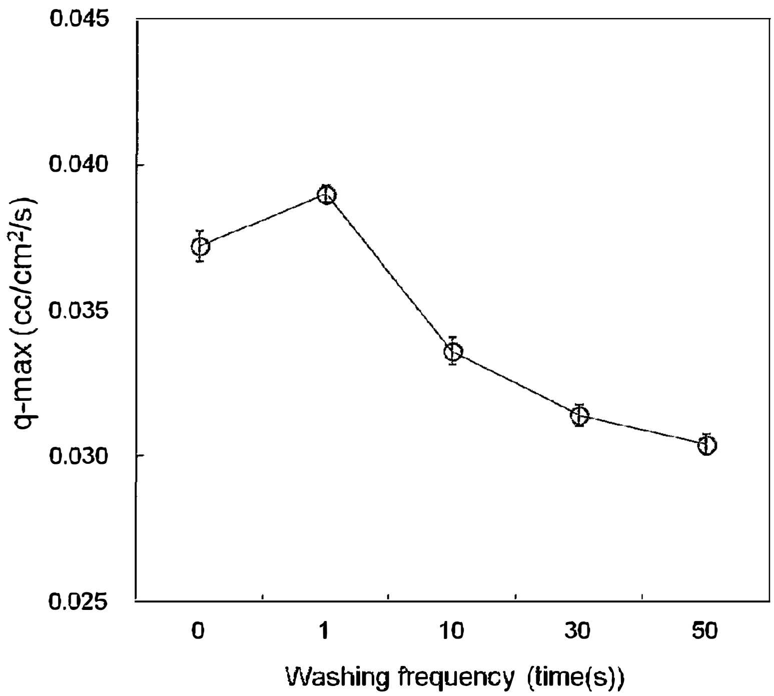


Figure 2-8 Maximum heat flux (q-max)

Table 2-7 Multiple comparisons of maximum heat flux (: P<0.01, *: P<0.05)**

	L0	L1	L10	L30	L50
L0			**	**	**
L1			**	**	**
L10				*	**
L30					
L50					

2.3.2. Physiological Response

2.3.2.1. Electrocardiogram

① Sympathetic Nerve Activity Index, LF/HF

Figure 2-9 shows the result of the LF/HF ratio. The LF/HF value decreased until 10 times washing and then increased rapidly after 30 times washing and L50 showed the highest value. The sympathetic nerve activity became dominant after 30 times washing. It was shown that the deteriorated pile cloths due to multiple washings gave humans stress. However, as a result of multiple comparisons in one-way ANOVA using Scheffe's method, there were no significant differences between them.

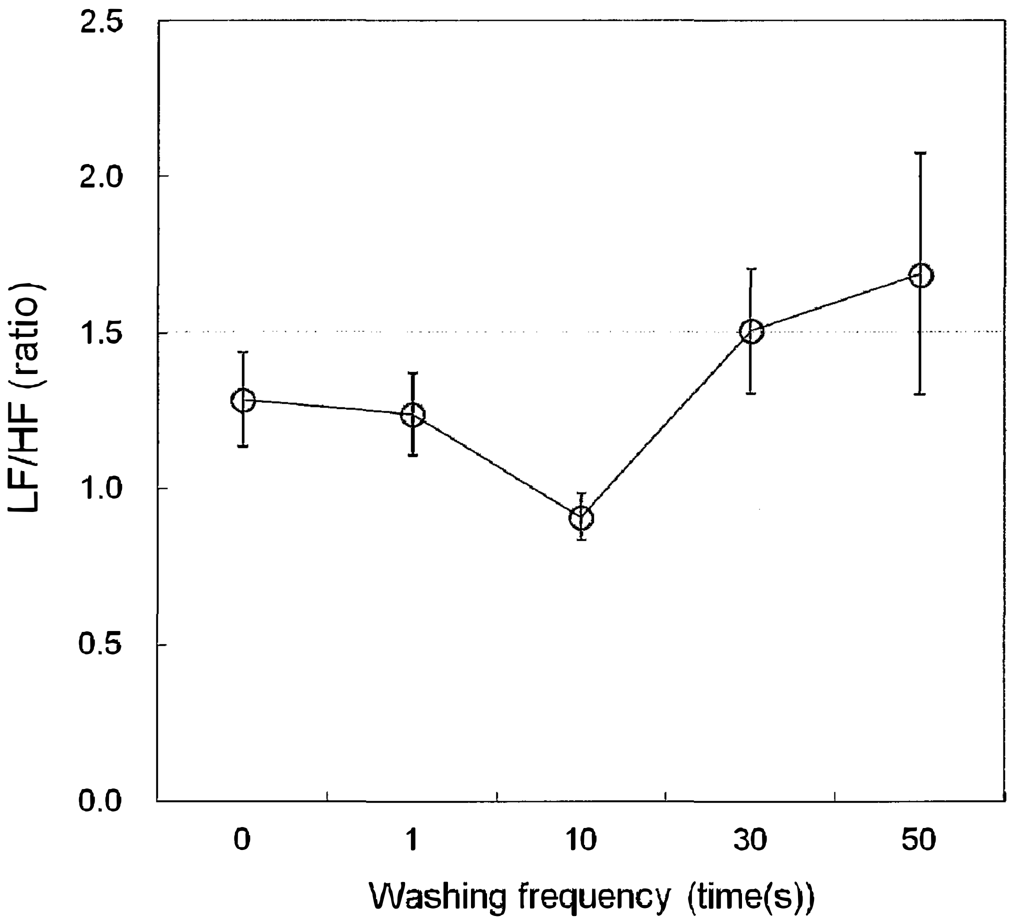


Figure 2-9 Sympathetic nerve activity index (LF/HF ratio)

② **Parasympathetic Nerve Activity Index, HF/(HF＋LF)**

Figure 2-10 shows the result of the HF/(HF+LF) ratio. It became a low value from the 30th wash rapidly but it had a tendency to increase up until the 10th. It was shown that the sympathetic nerve activity was dominant from the 30th wash but the parasympathetic activity was dominant from the 10th wash. However, as a result of multiple comparisons, there were no significant differences between them.

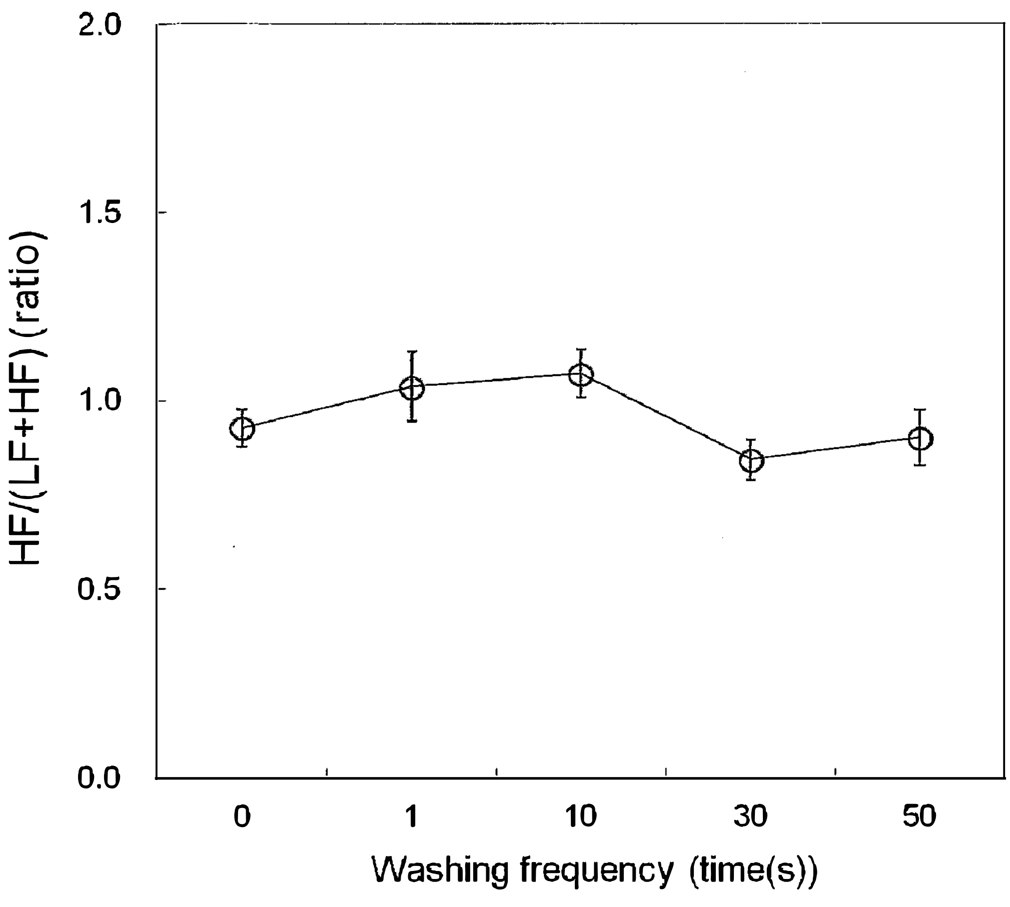


Figure 2-10 Parasympathetic nerve activity index (HF/(HF+LF) ratio)

③ **Heart Beat (BPM)**

Figure 2-11 shows the result of the heart beat. There is no relationship between heart beat and washing frequency. It was considered that the texture deterioration of pile cloth had no influence on changes in heart beat.

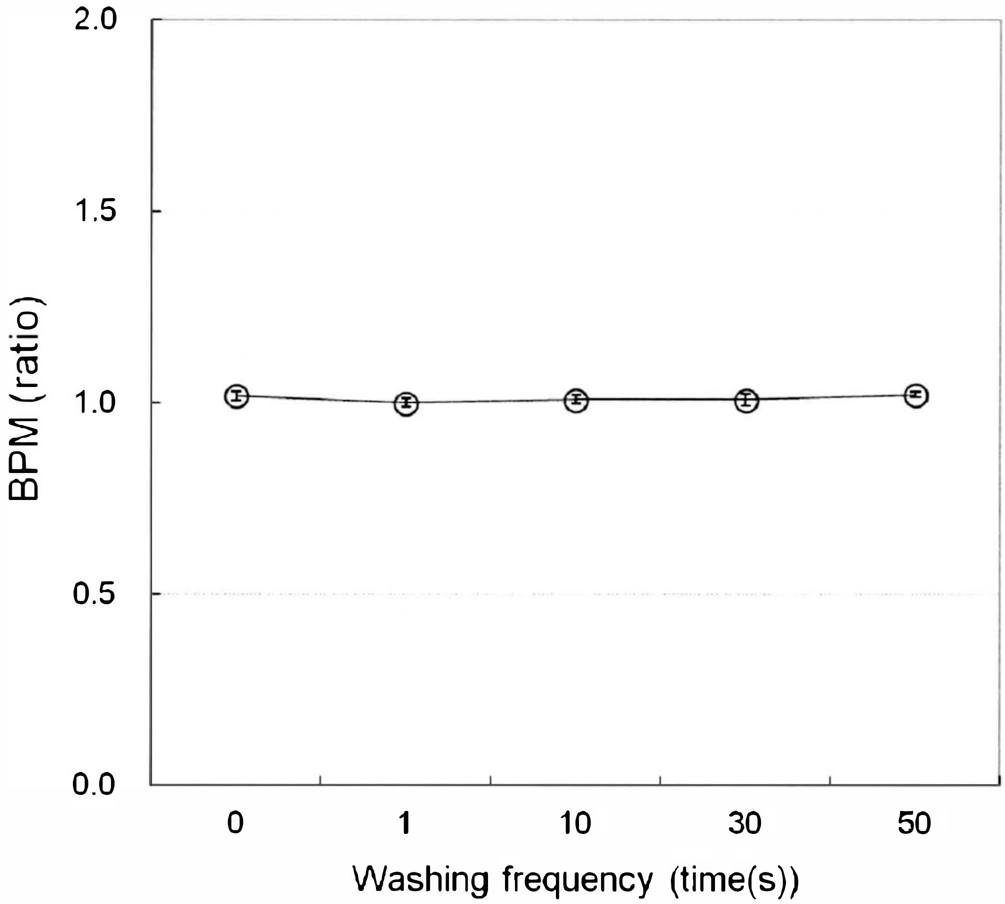


Figure 2-11 Heart beat

④ **Variation Coefficient of R-R Intervals (CVRR)**

Figure 2-12 shows the result of the variation coefficient of R-R intervals. L1 showed the highest value. However, there was no significant difference between samples.

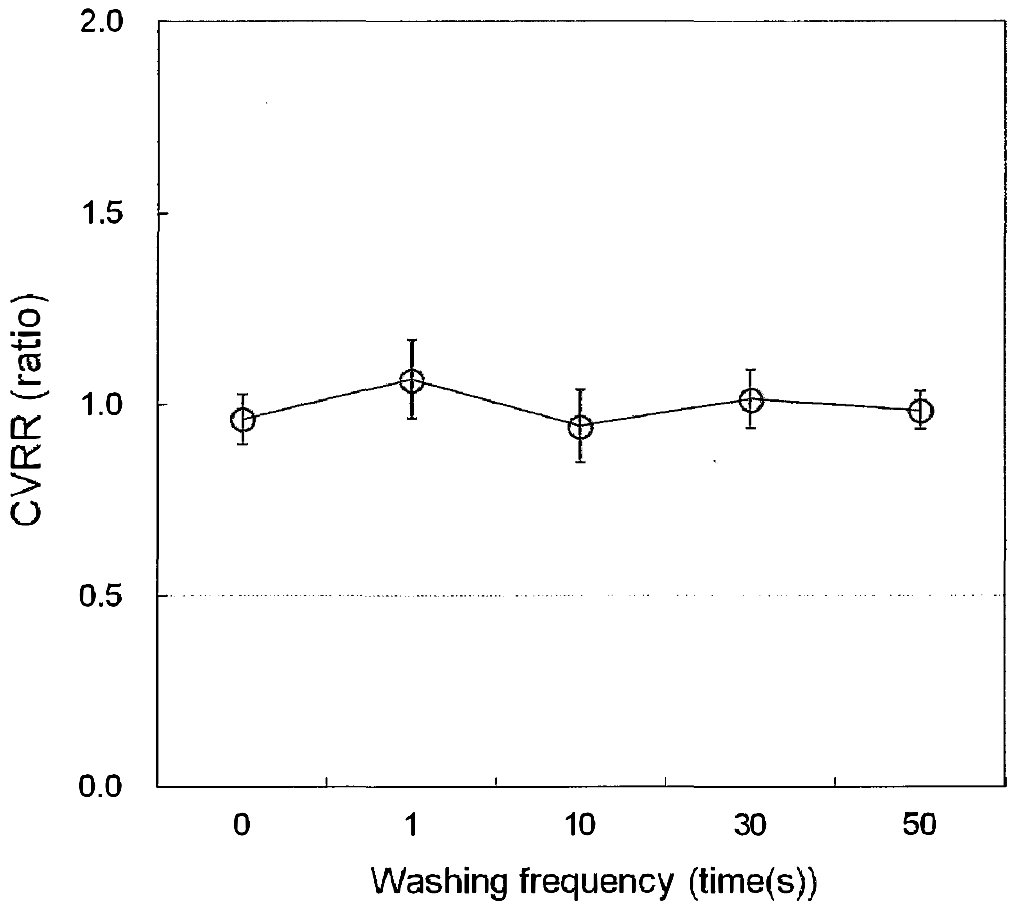


Figure 2-12 Variation coefficient of R-R intervals (CVRR)

2.3.2.2. Peripheral Blood-Flow

Figure 2-13 shows the result of the peripheral blood flow. L1 showed the highest value. There was no significant difference corresponding to the washing frequency.

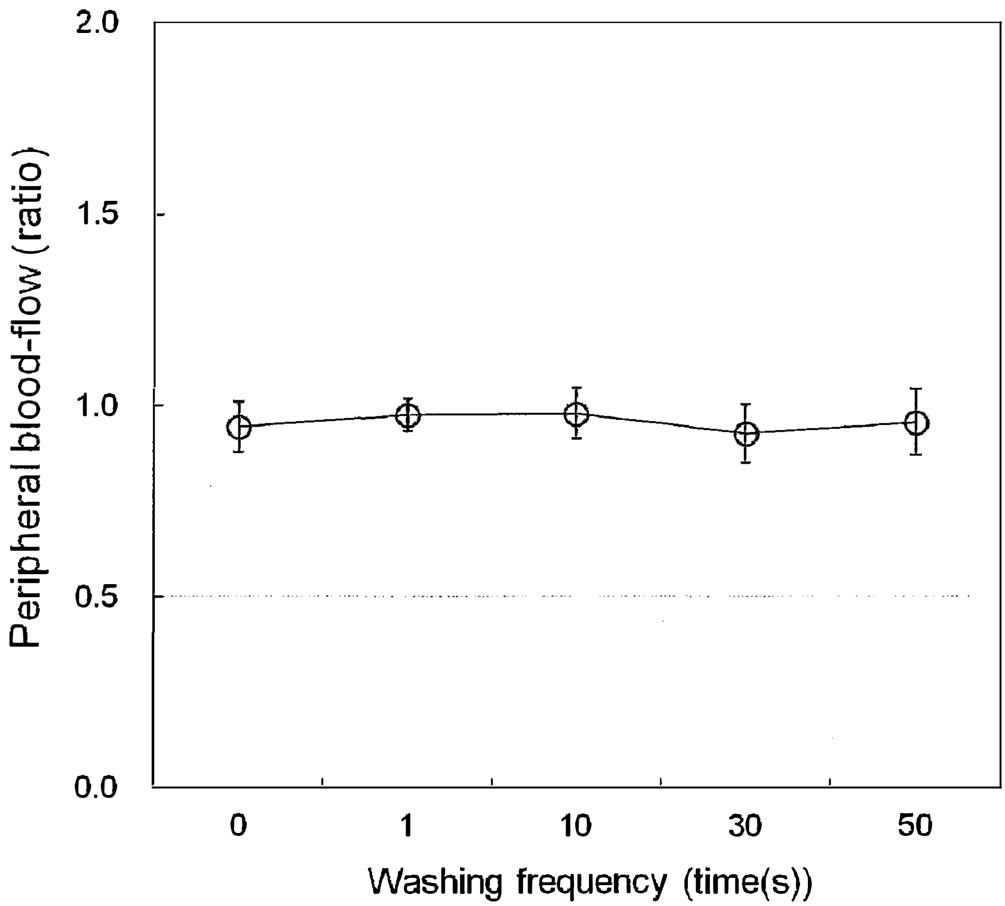


Figure 2-13 Peripheral blood flow

2.3.2.3. Respiration Depth

Figure 2-14 shows the result of the respiration depth. There was no influence from the washing frequency, even though L1 showed the highest ratio value. However, as a result of multiple comparisons, there were no significant differences between them.

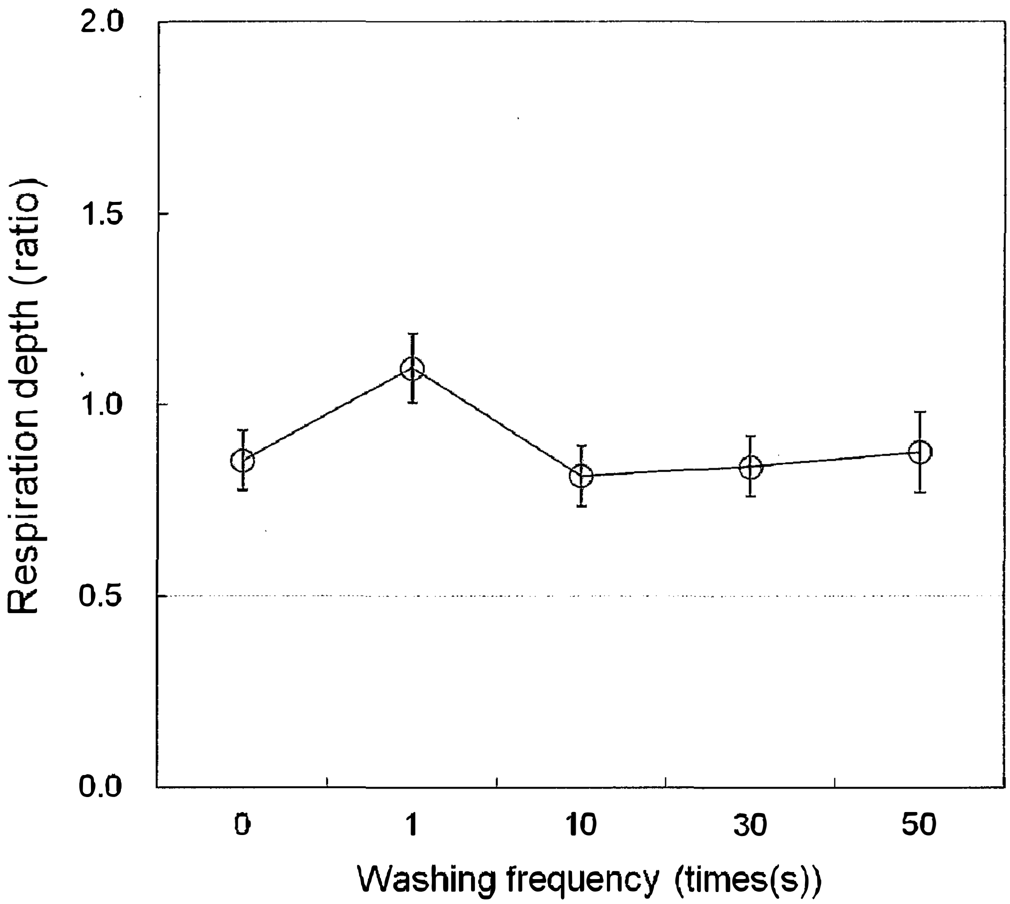


Figure 2-14 Respiration depth

2.3.2.4. α-amylase Activation in Saliva

Figure 2-15 shows the result of α-amylase activation in saliva. The α-amylase activation value decreased until 10 times washing, and then it showed an increase to L0 level or higher. This α-amylase activation value gave a similar tendency of autonomic nervous activity such as LF/HF. However, as a result of multiple comparisons, there were no significant differences between them.

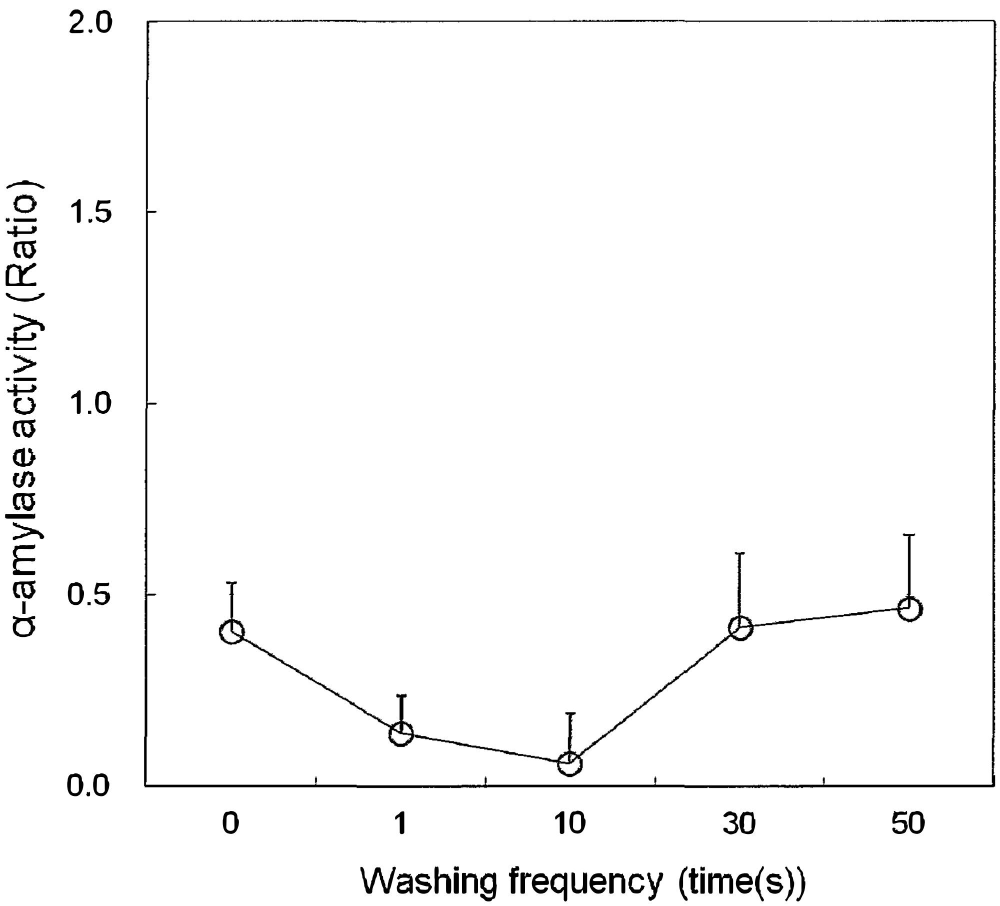


Figure 2-15 α-amylase activation in saliva

Table 2-8 Experiment results

Measurement / Evaluation			Unit	L0	L1	L10	L30	L50
JIS	Air permeability		cc/cm²/sec	552	510	531	530	583
	Moisture regain		%	4.6	4.2	4.2	4.0	4.1
	Water absorption –W*		mm	120	115	137	134	111
	Water absorption –C*		mm	78	86	102	80	78
KES	Surface property	MIU-W	a.u.	0.084	0.085	0.093	0.091	0.089
		MIU-C	a.u.	0.092	0.091	0.096	0.085	0.087
		SMD-W	μm	6.3	4.9	7.4	7.5	7.9
		SMD-C	μm	7.9	6.8	7.2	10.3	9.5
	Warm/cool touch	q-max	W/m²	0.037	0.039	0.034	0.031	0.030
Physiological response	Electrocardiogram	LF/HF	(ratio)	1.29	1.24	0.91	1.51	1.69
		HF/(LF+HF)	(ratio)	0.93	1.04	1.07	0.84	0.90
		BPM	(ratio)	1.02	1.00	1.01	1.01	1.02
		CVRR	(ratio)	0.96	1.06	0.94	1.01	0.98
	Respiration		(ratio)	0.85	1.10	0.81	0.84	0.88
	Blood-flow		(ratio)	0.94	0.98	0.98	0.93	0.96
	Saliva	α-amylase	(ratio)	0.40	0.14	0.06	0.41	0.47
Psychological response	Sensory test	Fineness	point	1.2	0.7	1.0	-0.2	-0.8
		Softness	point	1.3	0.6	0.1	-0.8	-0.6
		Comfort	point	1.1	0.5	0.7	0.1	0.4
		Warmth	point	0.4	0.5	0.8	-0.2	0.4
		Feel on the skin	point	1.1	0.6	1.0	0.1	-0.2
		Soothing feeling	point	1.1	0.7	0.7	0.1	0.3

* W: Wale direction, C: Course direction

2.3.3. Psychological Response

2.3.3.1. Fineness (fine/smooth - rough)

Figure 2-16 shows the profile of "Fineness" and Table 2-9 shows the result of multiple comparisons in one-way ANOVA using Scheffe's method. The feeling of fineness was decreasing with increasing washing frequency. After 30 times washing, samples were evaluated as being slightly rough. As a result of multiple comparisons, there were no significant differences among L0, L1, and L10. L10, L30, and L50 were significantly different from each other.

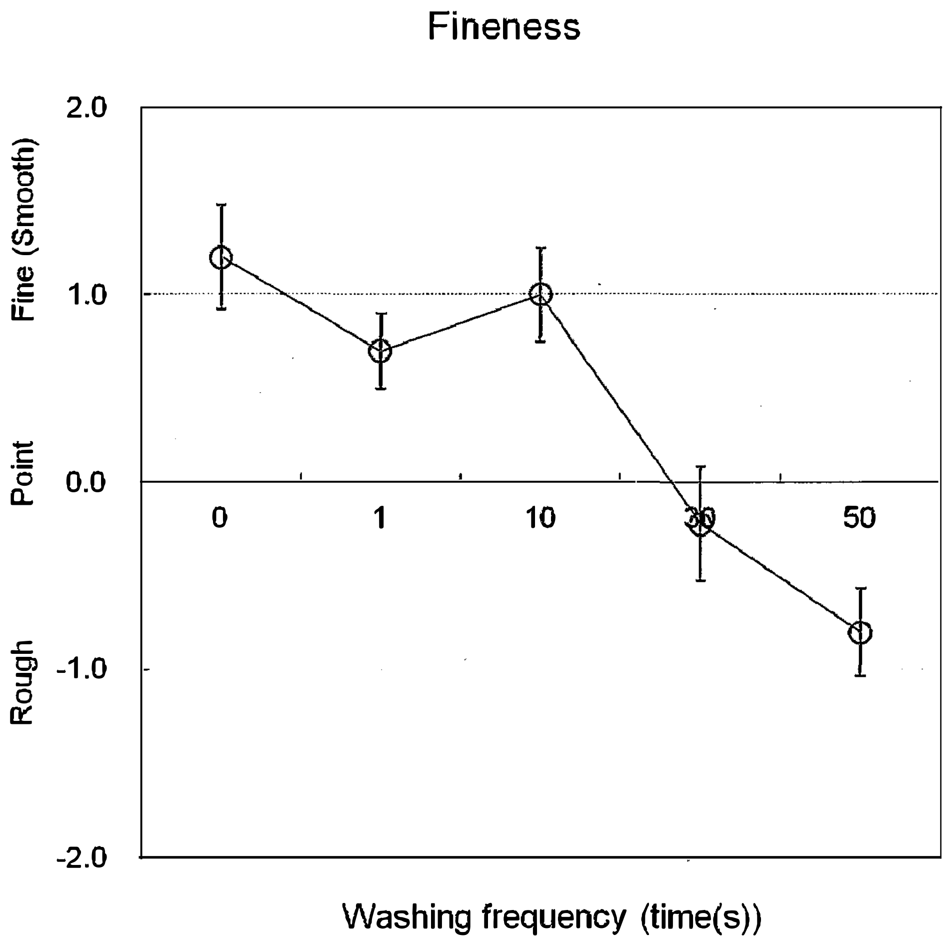


Figure 2-16 Profile of evaluation term: Fineness

Table 2-9 Multiple comparisons of "Fineness" (: P<0.01, *: P<0.05)**

	L0	L1	L10	L30	L50
L0				*	**
L1					**
L10					**
L30					
L50					

2.3.3.2. Softness (soft - hard)

Figure 2-17 shows the profile of "Softness" and Table 2-10 shows the result of multiple comparisons. The feeling of softness was decreasing with increasing washing frequency, although L50 was slightly recovered. After 30 times washing, samples were evaluated as being hard. As results of multiple comparisons, there was no significant difference between L0 and L1. L10, L30, and L50 were significantly different from each other.

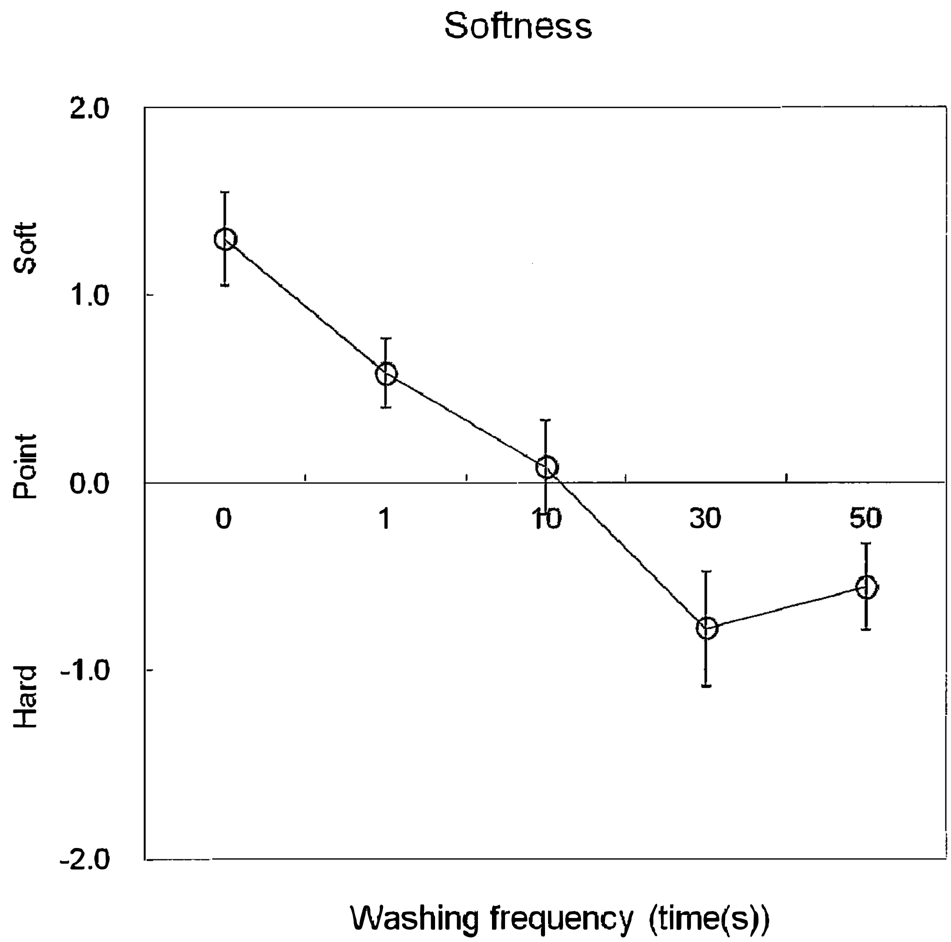


Figure 2-17 Profile of evaluation term: Softness

Table 2-10 Multiple comparisons of "Softness" (: P<0.01, *: P<0.05)**

	L0	L1	L10	L30	L50
L0			*	**	**
L1				*	
L10					
L30					
L50					

2.3.3.3. Comfort (comfortable - uncomfortable)

Figure 2-18 shows the profile of "Comfort" and Table 2-11 shows the result of multiple comparisons. The comfortable feeling decreased with increasing washing frequency and L30 showed the lowest value. However, there was no sample which was evaluated as being uncomfortable. As a result of multiple comparisons in one-way ANOVA using Scheffe's method, there was significant difference only between L0 and L30.

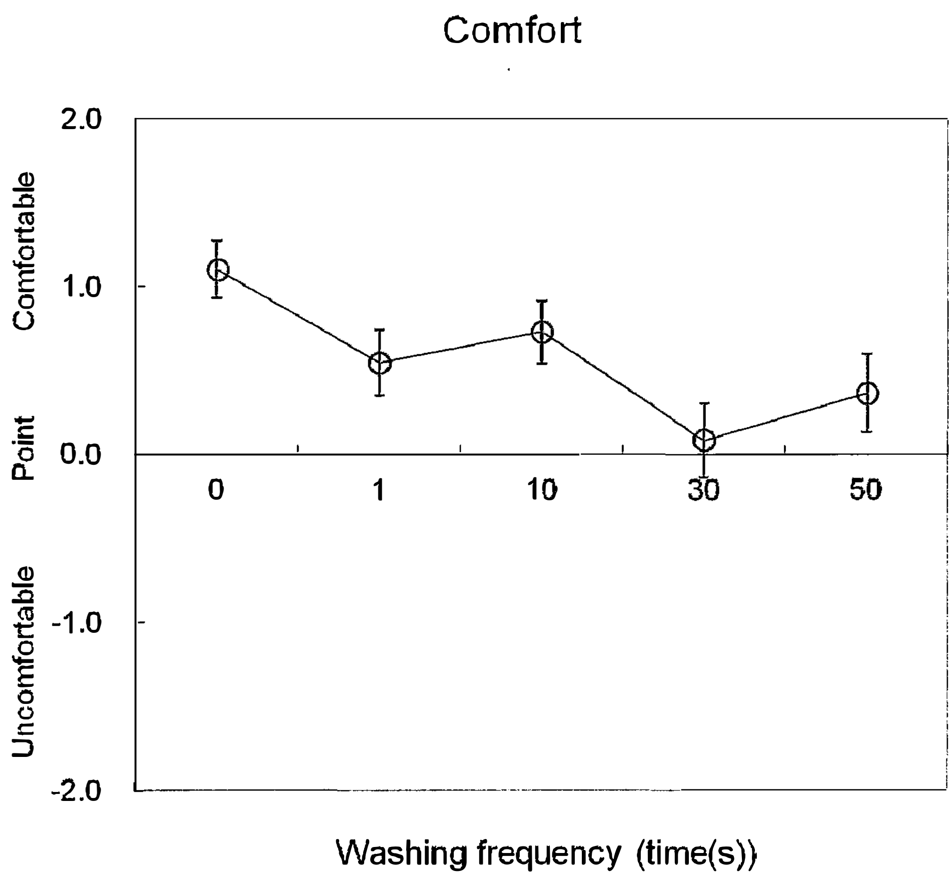


Figure 2-18 Profile of evaluation term: Comfort

Table 2-11 Multiple comparisons of "Comfort" (: P<0.01, *: P<0.05)**

	L0	L1	L10	L30	L50
L0				*	
L1					
L10					
L30					
L50					

2.3.3.4. Warmth (warm - cool)

Figure 2-19 shows the profile of "Warmth" and Table 2-12 shows the result of multiple comparisons in one-way ANOVA using Scheffe's method. L30 showed the lowest value and L50 value was recovered. As a result of multiple comparisons, however, there was significant difference only between L10 and L30.

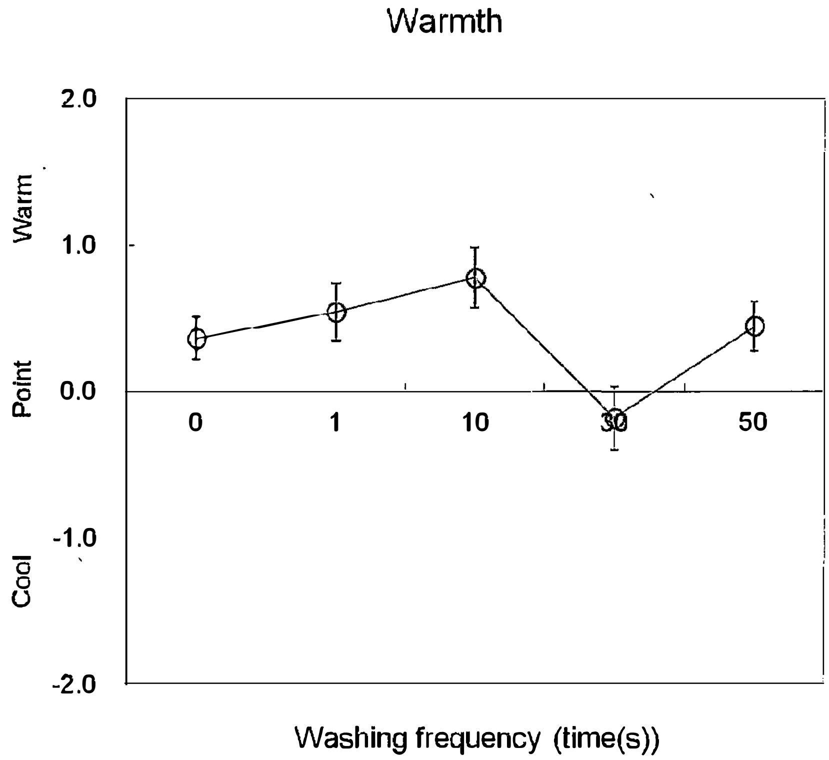


Figure 2-19 Profile of evaluation term: Warmth

Table 2-12 Multiple comparisons of "Warmth" (: P<0.01, *: P<0.05)**

	L0	L1	L10	L30	L50
L0					
L1					
L10				*	
L30					
L50					

2.3.3.5. Feeling on the Skin (good - bad)

Figure 2-20 shows the profile of "Feeling on the Skin" and Table 2-13 shows the result of multiple comparisons in one-way ANOVA using Scheffe's method. L10 showed a higher value than L1, and after that the feeling on the skin value was decreasing with increasing washing frequency. As results of multiple comparisons, L0 and L10 were significantly different from L50.

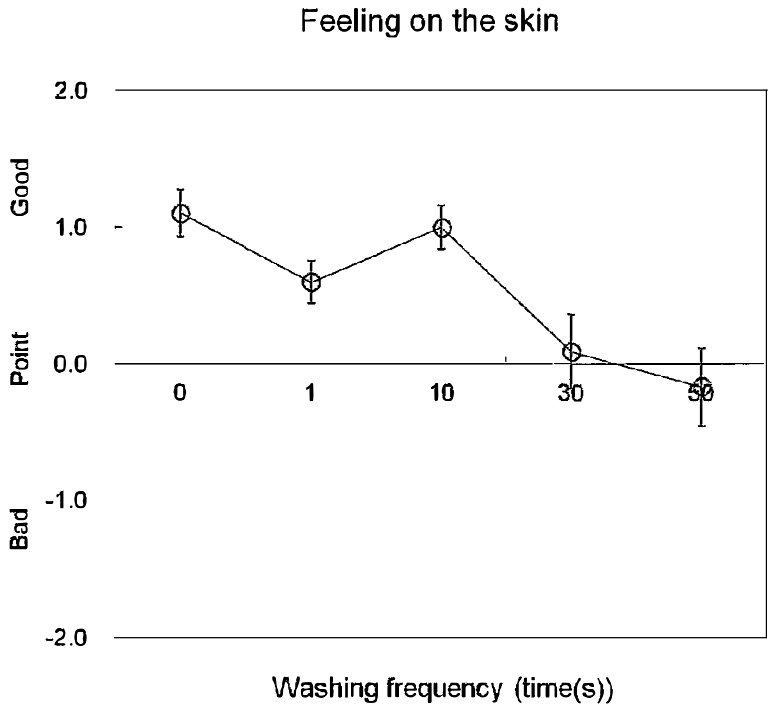


Figure 2-20 Profile of evaluation term: Feeling on the skin

Table 2-13 Multiple comparisons of "Feeling on the skin" (: P<0.01, *: P<0.05)**

	L0	L1	L10	L30	L50
L0					*
L1					
L10					*
L30					
L50					

2.3.3.6. Soothing Feeling (soothing feeling - no soothing feeling)

Figure 2-21 shows the profile of "Soothing Feeling" and Table 2-14 shows the result of multiple comparisons. Soothing feeling values decreased with increasing washing frequency, although L50 value was slightly recovered. However, there was no sample which was evaluated as having no soothing feeling. As the result of multiple comparisons, L0 had a significant difference from L30.

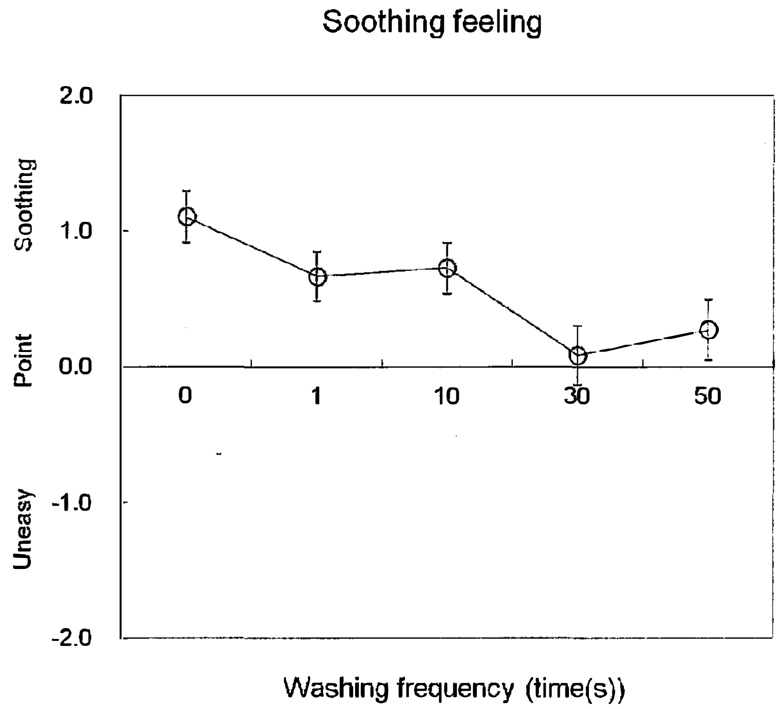


Figure 2-21 Profile of evaluation term: Soothing feeling

Table 2-14 Multiple comparisons of "Soothing feeling" (: P<0.01, *: P<0.05)**

	L0	L1	L10	L30	L50
L0				*	
L1					
L10					
L30					
L50					

2.4. Discussion

Table 2-15 shows the results of correlation analysis.

Table 2-15 Correlation coefficient matrix

Group	Correlation coefficient	Air permeability	Moisture regain	Water absorption-w	Water absorption-c	MIU-w	MIU-c	SMD-w	SMD-c	q-max	LF/HF	HF/(LF+HF)	BPM	CVRR	Respiration	Blood-flow	Amylase	Fineness	Softness	Comfort	Warmth	Feel on the skin	Soothing feeling
JIS	Air permeability	1.00																					
	Moisture regain	0.17	1.00																				
	Water absorption-w	-0.43	-0.24	1.00																			
	Water absorption-c	-0.46	-0.10	0.60	1.00																		
KES	MIU-w	0.01	-0.65	0.70	0.57	1.00																	
	MIU-c	-0.29	0.60	0.26	0.73	-0.04	1.00																
	SMD-w	0.66	-0.14	0.33	-0.01	0.72	-0.32	1.00															
	SMD-c	0.49	-0.49	0.06	-0.59	0.32	-0.86	0.70	1.00														
	q-max	-0.58	0.59	-0.23	0.10	-0.73	0.54	-0.95	-0.80	1.00													
Physiological Response	LF/HF	0.60	-0.12	-0.55	-0.87	-0.17	-0.91	0.33	0.79	-0.50	1.00												
	HF/(LF+HF)	-0.48	0.21	0.11	0.82	0.04	0.85	-0.46	-0.92	0.54	-0.84	1.00											
	BPM	0.97	0.33	-0.34	-0.48	-0.06	-0.21	0.63	0.47	-0.51	0.52	-0.51	1.00										
	CVRR	-0.51	-0.41	-0.30	-0.31	-0.38	-0.48	-0.63	-0.00	0.36	0.29	-0.06	-0.61	1.00									
	Respiration	0.49	0.06	0.57	0.10	0.57	0.02	0.05	0.40	0.66	0.01	0.36	0.50	0.06	1.00								
	Blood-flow	-0.27	0.07	-0.12	0.72	0.07	0.08	-0.35	-0.82	0.38	-0.62	0.94	-0.36	0.01	0.42	1.00							
	Amylase	0.70	0.02	-0.37	-0.90	-0.23	-0.75	0.43	0.81	-0.47	0.88	-0.94	0.72	-0.05	-0.32	-0.82	1.00						
Physiological Response	Fineness	-0.52	0.70	0.29	0.48	-0.31	0.86	-0.57	-0.80	0.78	-0.85	0.64	-0.37	-0.22	0.10	0.36	-0.61	1.00					
	Softness	-0.21	0.91	-0.23	0.03	-0.74	0.67	-0.59	-0.73	0.87	-0.48	0.43	-0.07	-0.09	0.29	0.26	-0.25	0.84	1.00				
	Comfort	0.06	0.96	-0.11	0.18	-0.50	0.80	-0.36	-0.68	0.62	-0.55	0.46	0.19	-0.47	-0.04	0.31	-0.25	0.81	0.91	1.00			
	Warmth	-0.01	0.35	-0.16	0.65	-0.01	0.80	-0.23	-0.81	0.35	-0.62	0.88	-0.06	-0.29	0.20	0.93	-0.68	0.45	0.42	0.57	1.00		
	Feel on the skin	-0.40	0.74	0.32	0.50	-0.25	0.90	-0.45	-0.77	0.69	-0.85	0.62	-0.25	-0.37	-0.04	0.36	-0.57	0.99	0.83	0.86	0.50	1.00	
	Soothing feeling	-0.12	0.93	-0.10	0.22	-0.56	0.82	-0.52	-0.76	0.75	-0.61	0.53	0.01	-0.33	0.10	0.36	-0.14	0.88	0.96	0.98	0.56	0.90	1.00

2.4.1. Relation between Physiological Response and Physical Property

LF/HF and HF/(HF+LF) obtained from electrocardiogram, and the activation value of α-amylase in the saliva correlated strongly with water absorption in the course direction, MIU in the course direction, and SMD in the course direction. There is the threshold, where physical performance decreased due to the deterioration and damage of pile cloth, between the 10th and 30th wash. After 10th wash, it was confirmed that the piles of sample were falling out, and the surface of samples became uneven and irregular. After the 30th wash, however, the surface of samples became even and slightly regular, even though the piles were still falling out due to multiple washing (c.f. Figure 2-22). Therefore, it was considered that the autonomic nerve system response could be estimated by the measurement of physical properties such as surface property and water absorption.

CVRR showed weak correlation with material properties, although it was strongly correlated with respiration depth.

Respiration depth showed negative correlation with SMD in the wale direction. It was considered that this physical property was appropriate for the parameter to estimate the autonomic nerve system response, because they showed weak correlation with other autonomic nerve system indexes.

The blood flow correlated strongly with water absorption in the course direction and SMD in the course direction.

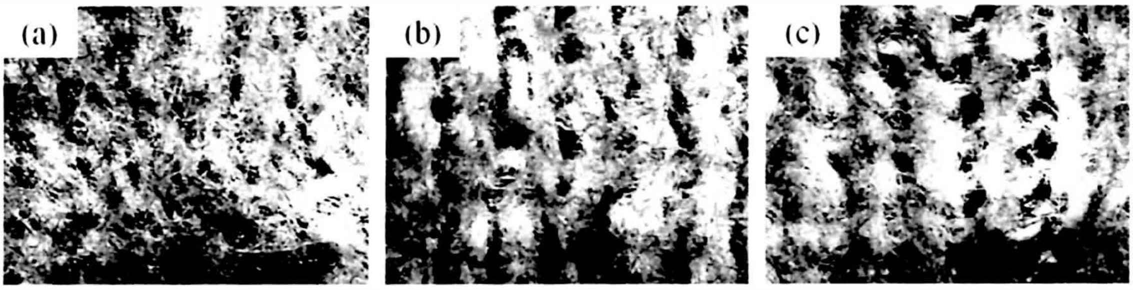


Figure 2-22 Surface images of sample: (a) L10, (b) L30, and (c) L50

2.4.2. Relation between Psychological Response and Physical Property

The evaluation term, "Fineness", correlated strongly with MIU in the course direction and q-max, and it had negative correlation with SMD in the course direction.

The evaluation term, "Softness", correlated strongly with moisture regain and q-max, and it had negative correlation with MIU in the wale direction and SMD in the course direction.

The evaluation term, "Comfort", correlated strongly with moisture regain and MIU in the course direction.

The evaluation term, "Warmth", correlated strongly with MIU in the course direction and correlated negatively with SMD in the course direction.

The evaluation term, "Feel on the skin", correlated strongly with moisture regain and MIU in the course direction, and it had negative correlation with SMD in the course direction.

The evaluation term, "Soothing feeling", correlated strongly with moisture regain, MIU in course direction, and q-max, and it had negative correlation with SMD in the course direction.

MIU in the course direction correlated positively with the sensory test terms. High

MIU value means that the texture of pile cloth is not smooth. The absence of pile gave humans a rough feeling, even though the surface of samples became a little even, but KES-FB4 surface tester could not reflect this human tactile sense. It was considered that whereas roughness was evaluated under a specific load in the sensory test, the friction measurement module (friction detector and weighing) floated on the surface of the piles, since the load of this module was lower than the specific load and it was not able to adjust to this test. Therefore, MIU could not represent the deterioration of towel cloth by washing.

In the other hand, SMD in the course direction correlated negatively with the sensory test term. This value means the geometric roughness of specimen surface. The q-max correlated negatively with the sensory test terms, but the correlation with the sensory test term, "Warmth", was very weak.

2.4.3. Relation between Physiological Response and Psychological Response

LF/HF correlated negatively with the sensory test terms. Among these terms, "Fineness" and "Feeling on the skin" showed strong correlation. It was considered that if the texture of pile cloth became rough due to multiple washing, the rough texture gave human stress and this stress induced the parasympathetic nervous system dominance.

HF/(HF+LF) correlated positively with the sensory test terms. Among these terms, "Warmth" showed strong correlation. Also, "Warmth" had a strong correlation with peripheral blood flow. Both physiological indexes indicate a sympathetic nerve activity. It was considered that the pile cloth, which felt warm, could be expected to provide a relaxation effect.

2.5. Conclusion

In this chapter, we investigated how the texture deterioration of pile cloth by multiple washing influenced human sensation. Therefore, it was necessary to measure the physical properties of multiple washed pile cloths using the JIS and KES test methods to figure out their physical deterioration. Indexes of autonomic nervous system activity were measured from ECG, respiration, peripheral blood flow, etc., and sensory tests were carried out to evaluate the contact feeling when deteriorated cloths were touched to human skin. And physical property parameters, indexes of autonomic nerve system activity, and sensory test terms were compared using statistical methods to figure out the relationship among them.

As the results of physical property tests, it was confirmed that there was a threshold of washing frequency at which the texture of pile cloth deteriorated rapidly: when washed between 10 and 30 times in this study. This physical behavior corresponded approximately to physiological and psychological responses. Furthermore, the texture of deteriorated pile cloth caused sympathetic nerve dominance. In other words, the texture of pile cloth deteriorates after the threshold of washing frequency and the deteriorated texture gives humans stress.

As the results of correlation analyses, SMD and water absorption correlated strongly with LF/HF and HF/(HF+LF). Therefore, it was considered that the autonomic nervous system response could be estimated by the measurement of physical properties such as surface property and water absorption. Among these physical property parameters, SMD in particular corresponded to both physiological and psychological responses.

However, MIU did not represent the deterioration of pile cloth, because the static load of the MIU measurement module was not able to adjust for specific loads when humans evaluated the texture of pile fabrics. Therefore, it is necessary to develop a tester which reflects the human palpate motion and tactile sense.

CHAPTER 3

The Influence of Sweat Absorbent Liners on Helmet Comfort and Comparison with Fabric Hand

3. The Influence of Sweat Absorbent Liners on Helmet Comfort and Comparison with Fabric Hand

3.1. Introduction

Since the main role of a safety helmet is to protect the head against occupational hazards, most countries require that a safety helmet be worn through laws and regulations. Wearing a safety helmet is now mandatory and has been enforced for workers through supervision of these laws and regulations. However, workers are likely to remove their helmets during uncomfortably hot weather if they experience discomfort, such as heat stress, while wearing them [8, 9]. Therefore, it is necessary for safety helmets to not only offer protection, but also comfort.

3.1.1. Previous Helmet Comfort Studies

In 1989, Nagata proposed the following requirements for a hat or cap to be worn during the summer: (1) good reflection of heat rays from the surface, i.e., white or light in color with a flat and smooth surface; (2) low heat transfer coefficient for the shell material; (3) ventilation or sufficient dome space to prevent increases in temperature and humidity between the helmet and head [10].

In 1988, Abeysekera and Shahnavaz investigated the benefits of ventilated helmets in both laboratory and field settings. In the field study, ventilation helmets were found to be less hot and cause less perspiration than unmodified helmets. However, during laboratory tests, they found no significant differences in the subjects' heart rates and skin temperatures based on whether they wore the ventilated or unventilated helmets. In fact, the unmodified helmets were found to be preferred by the users, presumably, because of the added protection they offer [8].

In 1976, Fonseca investigated the effects of ventilation slits in helmets on evaporative heat transfer. He determined that the total head coverage area needed to be reduced from 67% to 47% to significantly increase evaporative heat transfer. In addition to this, the benefits of ventilation were negated when a large air space existed between the helmet shell and the head [11].

In 2001, Davis et al. evaluated subjects' physiological and psychophysical responses to a standard helmet, a passive-ventilation helmet, and an active-ventilation helmet in a high-temperature environment. They found that none of the tested helmets added significant burden based on physiological variables, but that dome space temperature varied significantly among the helmets tested. The active-ventilation helmet in particular maintained a significantly lower dome space temperature than either the standard helmet or the passive-ventilation helmet. However, despite having the lowest dome space temperature, it was not preferred due to its excessive weight and uncomfortable fit. Psychophysical results showed that ventilation contributed to greater helmet comfort, and that weight and fit were important factors in helmet design [12].

As this survey shows, hygrothermal properties must be an important factor in helmet comfort. However, ventilation holes (or slits) in the safety helmet are not considered to be a necessary or sufficient condition for enhancing helmet comfort when safety helmets are selected by users.

3.1.2. Purpose

We investigated the effects of the physical properties of sweat absorbent liners (SAL) on helmet comfort and compared forehead feel with hand feel. Because helmet fit is one of the major factors of helmet comfort, it is much related to how the head band with SAL attached comes in contact with the forehead (c.f. Figure 3-1). In addition to this, the hand feel plays an important role in expectations for helmet comfort both when helmet makers design a helmet and when users purchase a helmet.

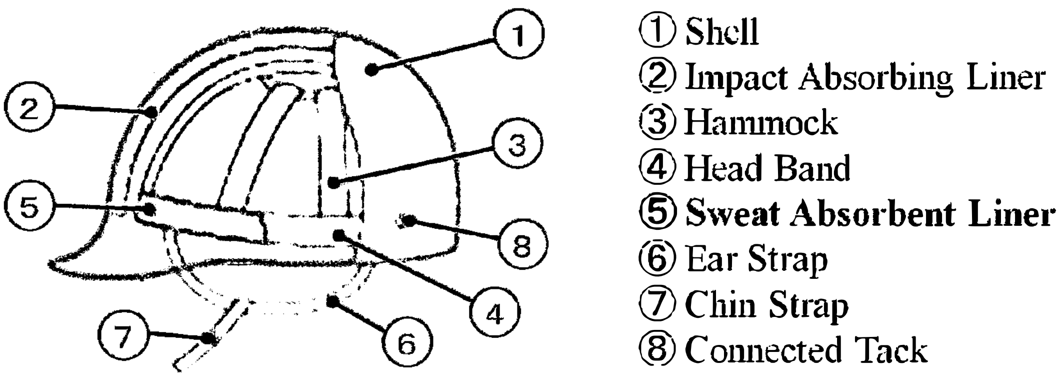


Figure 3-1 Structure of safety helmet

3.2. Samples

Seven SAL fabric samples, shown in Figure 3-2, were prepared for this research. All samples were made from polyester, though each used different fabrication methods. Table 3-1 shows the details of the samples. Sample #1, #2, and #4 are air-mesh fabrics and they are resilient. Their thicknesses are respectively 1.8mm, 2.3mm, and 2.1mm. Sample #3 is a nonwoven fabric and thickness is 0.8mm. Sample #5 and #6 are warp-knit fabrics and thicknesses of both are 1.1mm. Sample #7 is warp-knitted velour fabric and thickness is 1.5mm. The thicknesses of all samples are measured at a pressure of 0.049kPa. The sample size was 20cm×20cm and each sample was subjected to three different conditions: dry, wet 2g ($0.005g_{water}/cm^2$), and wet 10g ($0.025g_{water}/cm^2$).

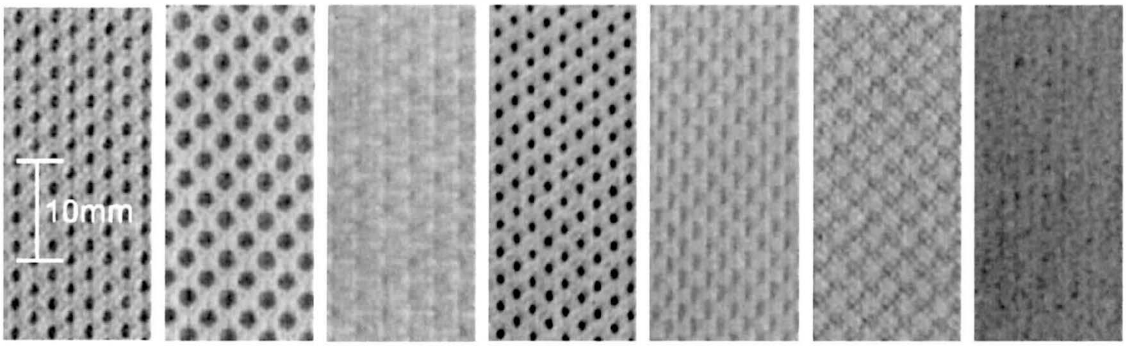


Figure 3-2 Surface features of sweat absorbent liner samples

Table 3-1 Details of sweat absorbent liner samples

Sample	Fabrication method	Material	Thickness (mm)
#1	Air mesh fabric	Polyester	1.8
#2	Air mesh fabric	Polyester	2.3
#3	Nonwoven fabric	Polyester	0.8
#4	Air mesh fabric	Polyester	2.1
#5	Warp knit	Polyester	1.1
#6	Warp knit	Polyester	1.1
#7	Velour (Warp knit)	Polyester	1.5

3.3. Experiment

To study the influence that the SAL had on helmet comfort, the following experiment protocols were implemented.

***Brainstorming**:* To outline evaluation terms for the preliminary sensory tests.

***Preliminary sensory tests**:* Comparison between the hand feel and wearing feel during different states of wetness.

***Principle component analysis**:* Decision of evaluation terms for the main sensory tests.

***Main sensory tests**:* Helmet comfort tests during exercising to break a sweat.

SAL Physical property tests

***Partial correlation analysis**:* To determine the relationship between helmet comfort, fabric hand, and physical properties.

3.3.1. Decision of Evaluation Terms

Panelists held a brainstorming session regarding the texture of the prepared SAL fabric samples. 16 adjective pairs were created for use as evaluation terms for the preliminary sensory tests (c.f. Table 3-2).

3.3.2. Preliminary Sensory Tests to Compare Between the Hand Feel and Wearing Feel

These tests consisted of hand feel and wearing feel tests for comparing with each other. The Semantic Differential (SD) method employing five rating scales was used for these sensory tests. Subjects assessed the fabric hand using the end of their finger and palm without grasping the sample, based on evaluation terms (c.f. Table 3-2). In addition to this, subjects evaluated the wearing feel of safety helmets with an SAL attached to the head band in a dry state. The experiment environment was at a temperature of 20±2°C and a relative humidity of 65±5% .

Japanese male and female university students participated as subjects in this study voluntarily. Table 3-3 summarizes subject details.

Table 3-2 Evaluation terms for sensory tests using the SD method

Roughness component			Mugginess component			Resilience component		
Rough	⇔	Smooth	Muggy	⇔	Fresh	Not resilient	⇔	Resilient
Itchy	⇔	Not itchy	Humid	⇔	Not humid	Not cushioned	⇔	Cushioned
Hard	⇔	Soft	Clammy	⇔	Smooth	Not fluffy	⇔	Fluffy
Coarse	⇔	Fine	Warm	⇔	Cool			
Lumpy	⇔	Not lumpy	Damp	⇔	Not damp			
Feels bad	⇔	Feels good						
Rough on skin	⇔	Gentle on skin						
Stiff	⇔	Flexible						

The underlined terms are the helmet comfort test terms.

Table 3-3 Subject details for preliminary sensory tests

	Condition	No. of Subjects	Age		
			Range	Mean	S.D.
Hand Feel	Dry	8	21-24	22.5	0.93
	Wet (2g)	7	21-24	22.3	0.58
	Wet (10g)	6	21-24	22.3	1.03
Wearing Feel	Dry	10	21-24	22.1	0.99

3.3.3. Principle Component Analysis

Principle component analysis was necessary in order to find the principle components from the results of the preliminary sensory tests that could be used to describe the helmet comfort properties of the various states of the SAL samples used in this study. The analysis conditions included data for four extracted components, using the varimax rotation method.

The results of the principle component analysis, shown in Table 3-4, show that adjective pairs related to “roughness”, “mugginess”, and “resilience” were the principle components which could be used to describe psychological responses in both dry and wet SAL states. However, in the wearing feel tests, adjective pairs related just to “roughness” and “mugginess” were the principle components. The “resilience” component had no contribution to wearing feel.

Table 3-4 Components and contributions as the result of principle component analysis

Test	Condition	Component / Contribution Ratio (%)		
		No. 1	No. 2	No. 3
Hand Feel	Dry	Rough / 40.2%	Muggy / 33.4%	Resilient / 22.3%
	Wet 2g	Muggy / 35.0%	Rough / 24.6%	Resilient / 19.0%
	Wet 10g	Muggy / 37.1%	Rough / 31.0%	Resilient / 19.3%
Wearing Feel	Dry	Muggy / 32.6%	Rough / 30.1%	Cool / 28.0%

3.3.4. Main Sensory Tests; Helmet Comfort Tests

SAL samples: Only #1, #4, #5, and #7 were used to reduce the burden on the subjects in helmet comfort tests. The terms underlined in Table 3-2 are the terms used for the helmet comfort test. The total number of subjects was forty three male university students. Table 3-5 shows subject details.

Subjects exercised to break a sweat using an ergometer (bicycle type) while wearing safety helmets with SAL attached, and sensory tests with seven rating scales using the SD method were carried out for helmet comfort evaluation. The evaluation was checked at four stages: before exercise, at initial perspiration, at maximum perspiration, and after a 10-minute break. In this trial, subjects determined the stages of initial perspiration and maximum perspiration by their decision. After the trial, subjects scored the comfort of the helmet on a scale of 0 to 5 points based on their overall impression of the safety helmet with SAL. Each subject participated in this test only once per day. The experiment environment was at a temperature of 24±2°C and a relative humidity of 65±5% to stimulate perspiration.

Table 3-5 Subject details for helmet comfort tests

Sample	No. of Subjects	Age		
		Range	Mean	S.D.
#1	13	21-33	23.1	3.12
#4	11	21-24	22.2	0.98
#5	10	21-33	23.4	3.50
#7	9	21-24	22.3	1.00

3.3.5. Physical Property Tests

Surface properties (KES-FB4), compression properties (KES-FB3 DC), warm/cool feel (KES-F7), and water absorption (JIS L 1097) were measured in order to investigate the effect of SAL physical properties on helmet comfort. Table 3-6 shows the details of the physical properties test. The experiment environment was at a temperature of 20±2°C and a relative humidity of 65±5%.

Table 3-6 Physical properties tests

Item	Parameter	Remark
Surface properties	Mean of friction coefficient	MIU
	Mean deviation of friction coefficient	MMD
	Geometric roughness	SMD
Compression properties	Compression linearity	LC
	Compressional energy	WC
	Compression resilience	RC
Warm/cool touch	q-max	
Water absorption	Water absorption length	WA

3.4. Results and Discussion

3.4.1. Helmet Comfort Sensory Tests

Figure 3-3~9 show the results of helmet comfort sensory test concerning the "roughness" component. These test terms had a tendency to be rougher in the evaluation stages "before exercise" and "initial perspiration". We determined that small amounts of perspiration increased the response of the SAL surface roughness properties. However, test results were divided into more rough and less rough groups in the evaluation stages of "initial sweat" and "maximum sweat", and "maximum sweat" and "after a break". We determined that response to the "roughness" component could be influenced by the amount of perspiration contained in the SAL, and that it could play either a positive or negative role in the response to surface roughness based on its physical properties. Further, Sample #7 was more highly evaluated than other samples in the test terms concerning "roughness" component.

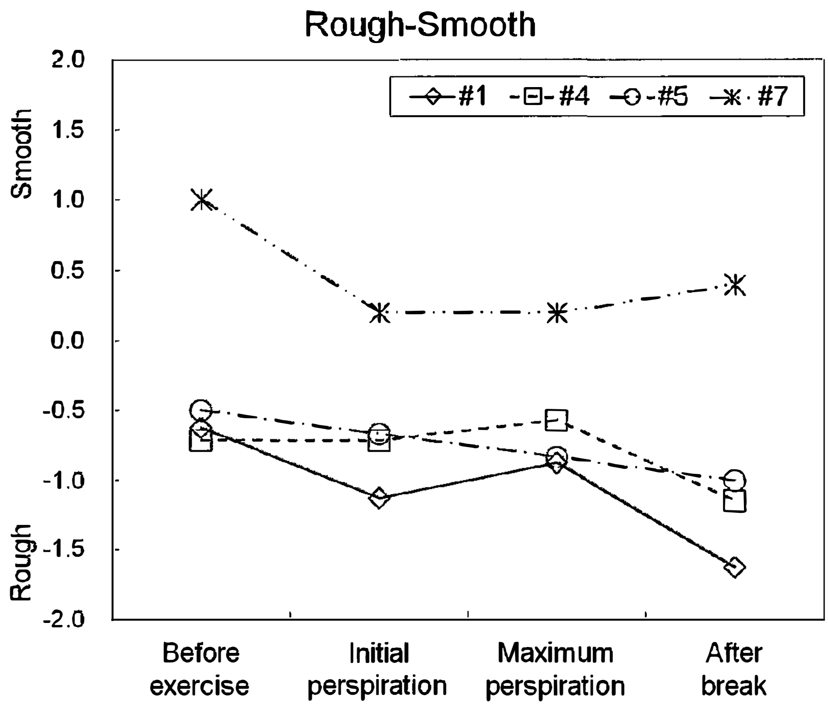


Figure 3-3 Profile of helmet comfort tests: Rough-Smooth

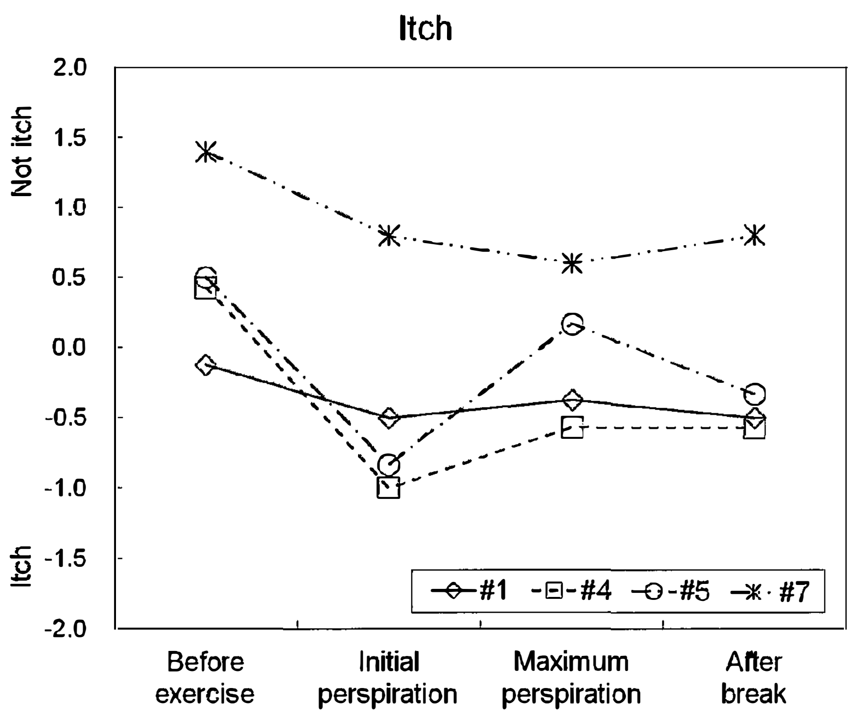


Figure 3-4 Profile of helmet comfort tests: Itch

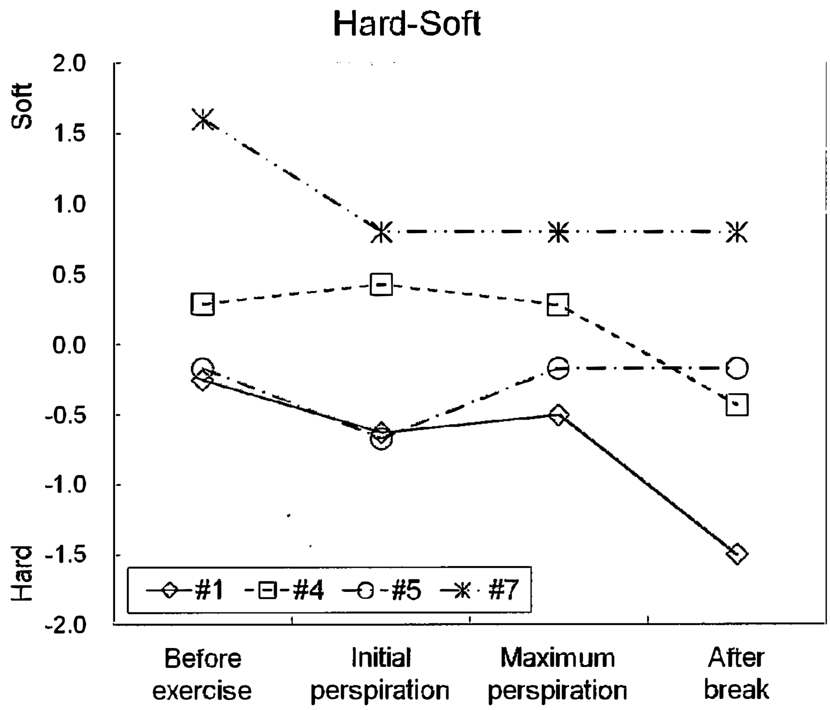


Figure 3-5 Profile of helmet comfort tests: Hard-Soft

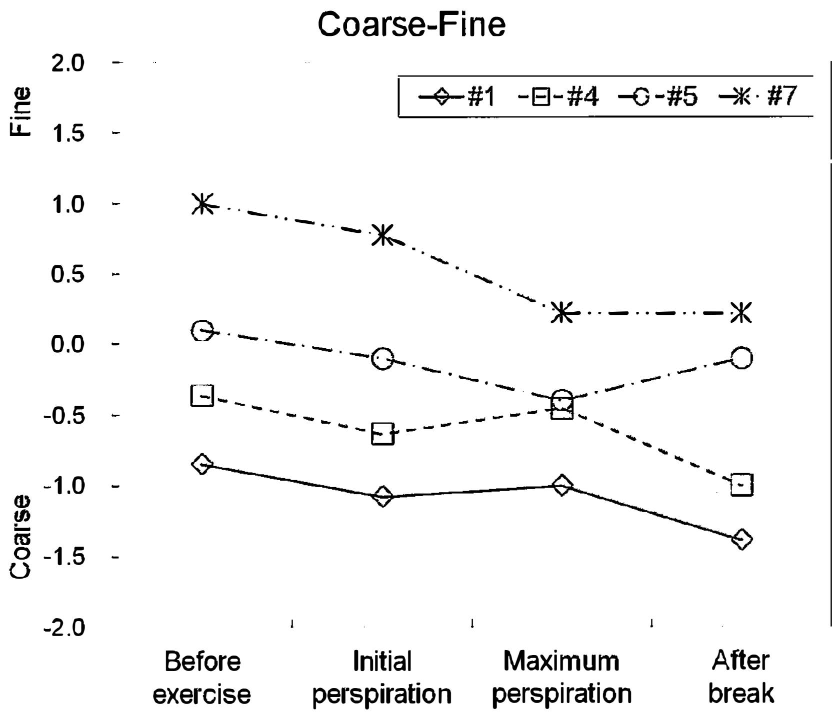


Figure 3-6 Profile of helmet comfort tests: Coarse-Fine

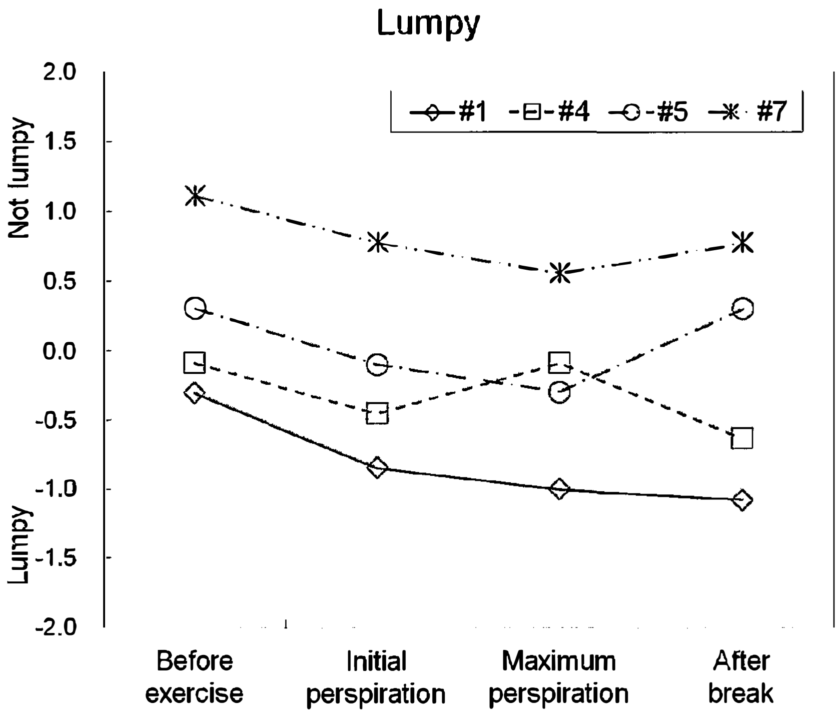


Figure 3-7 Profile of helmet comfort tests: Lumpy

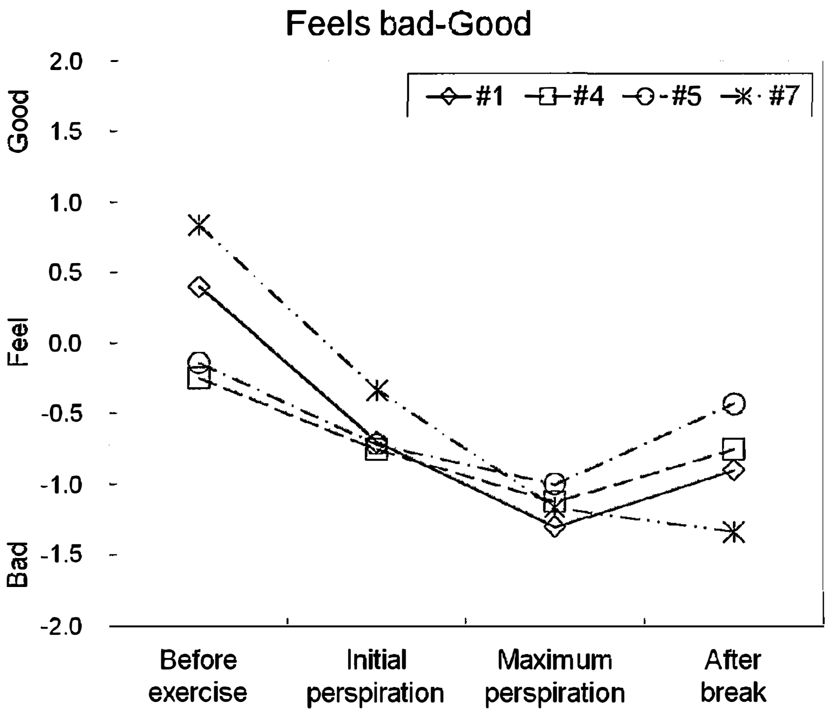


Figure 3-8 Profile of helmet comfort tests: Feels good

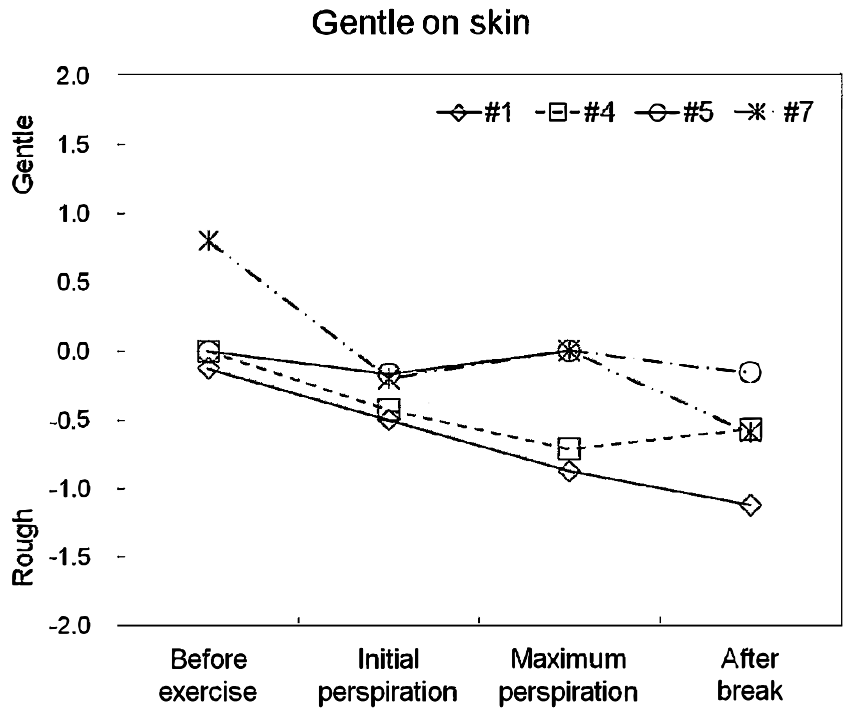


Figure 3-9 Profile of helmet comfort tests: Gentle on skin

Figure 3-10~13 show the results of the helmet comfort sensory test concerning the "mugginess" component. These test terms were negatively evaluated as the amount of perspiration increased, and then went up during the "after break" stage. There were no statistically significant differences between the terms. This showed that the hygrothermal comfort of safety helmets is difficult to enhance by modification of the SAL.

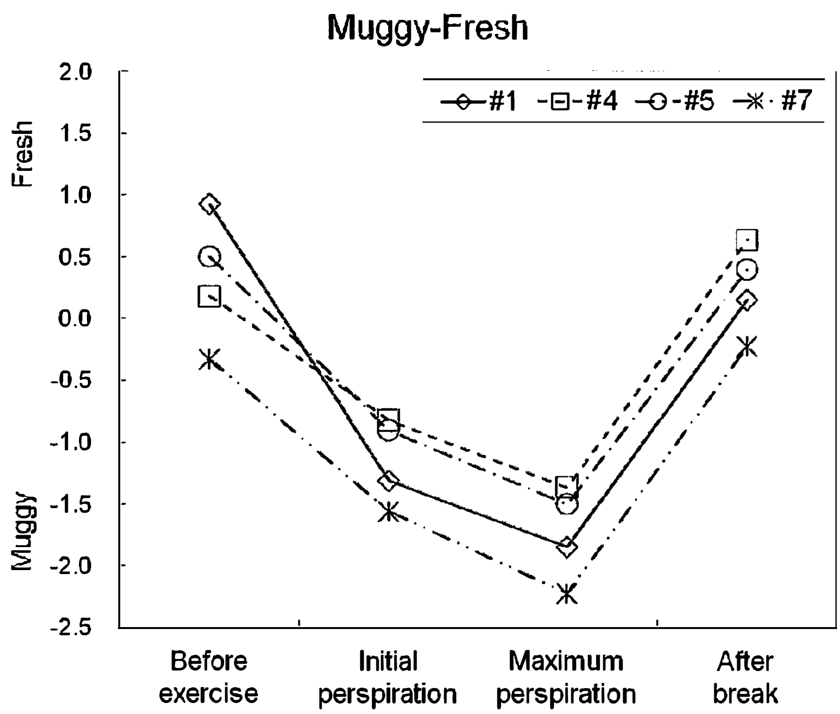


Figure 3-10 Profile of helmet comfort tests: Muggy-Fresh

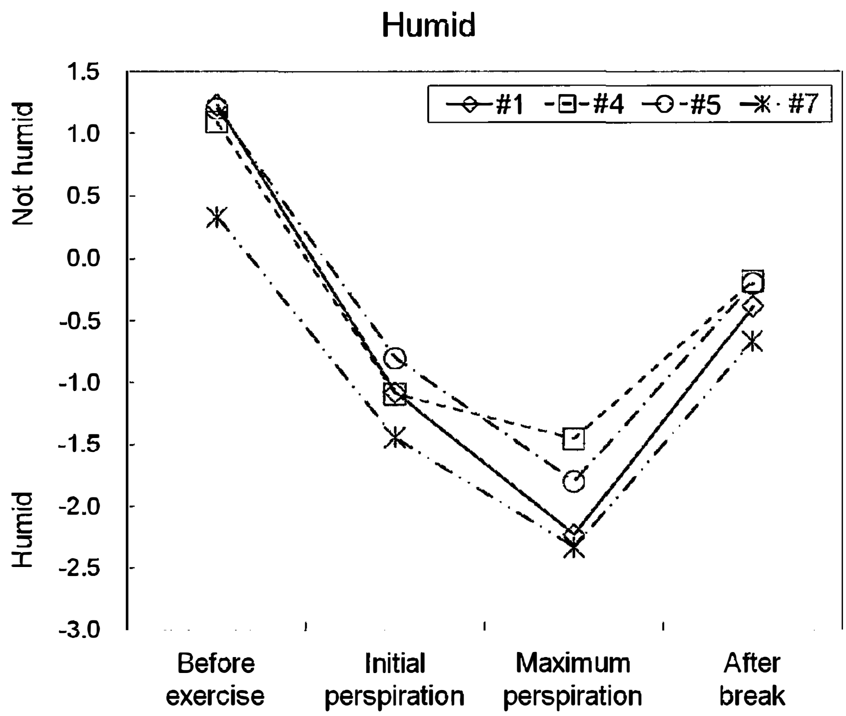


Figure 3-11 Profile of helmet comfort tests: Humid

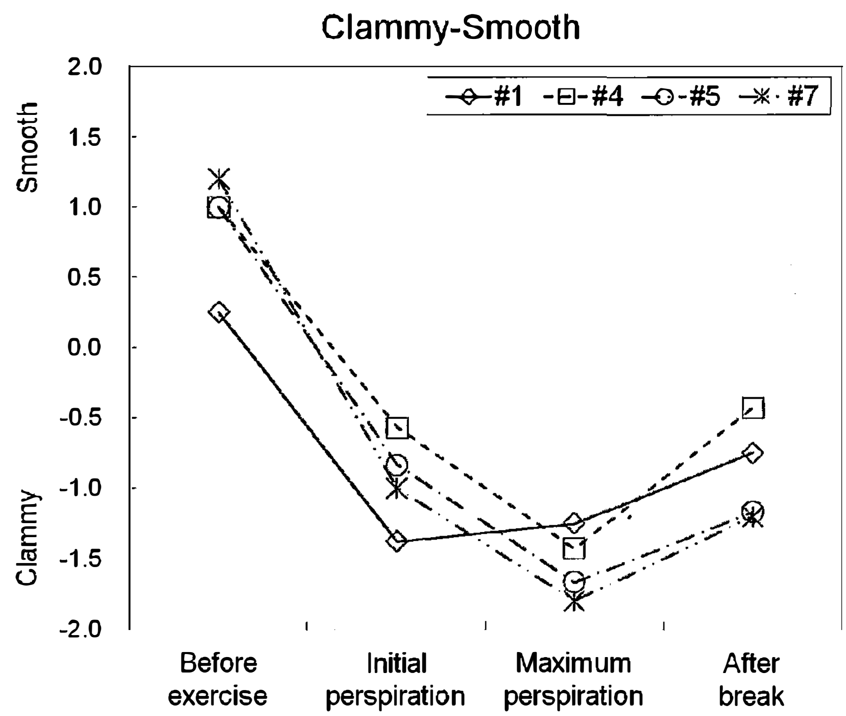


Figure 3-12 Profile of helmet comfort tests: Clammy-Smooth

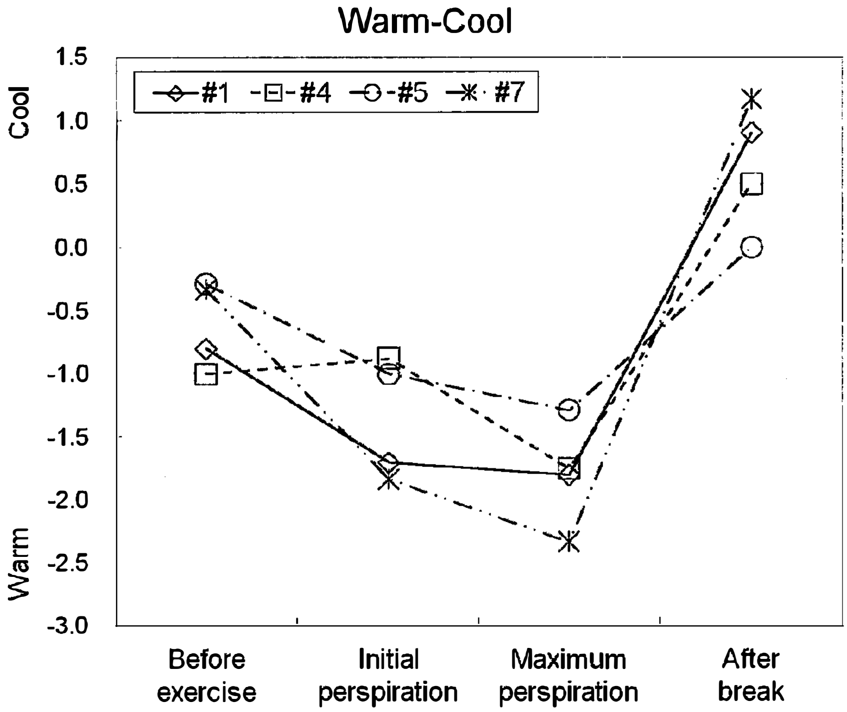


Figure 3-13 Profile of helmet comfort tests: Warm-Cool

Figure 3-14 shows the result of the helmet comfort rating test. The samples were rated in the following order (from highest comfort to lowest): #5, #7, #4, and #1. Even though none of the differences in the tested scores were statistically significant when tested by multiple comparisons in one-way ANOVA using Scheffe's method, SAL Sample #5 was evaluated as more comfortable than Sample #7, which showed better performance than other samples in the test terms concerning "roughness" component. Therefore, it was considered that "roughness" component was not the most influential principle component on helmet comfort.

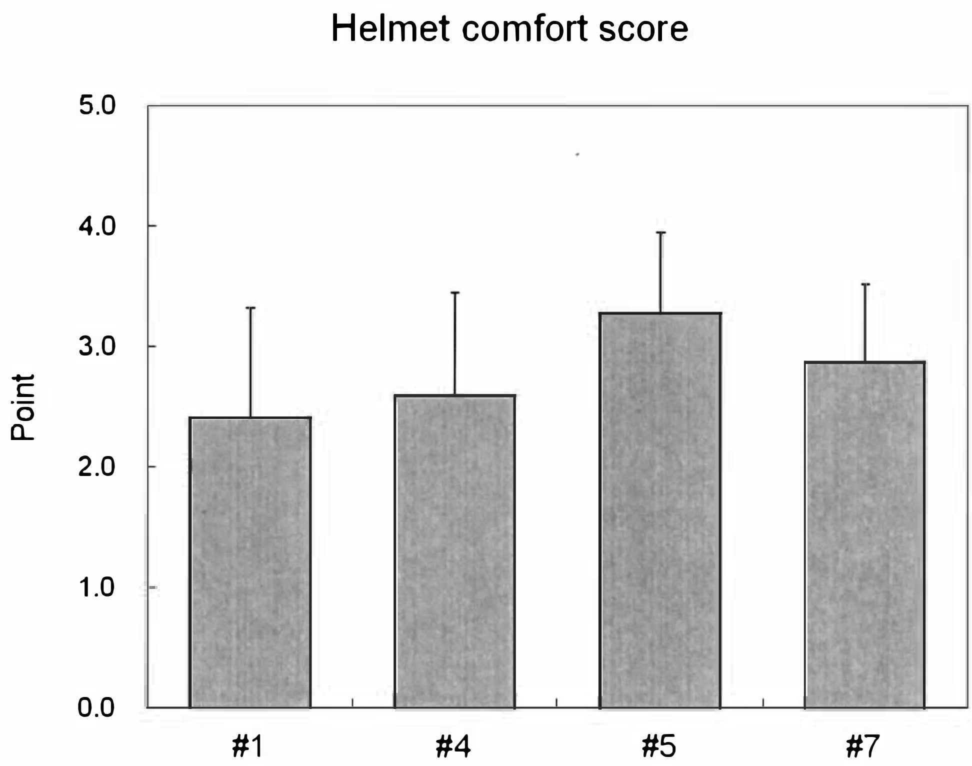


Figure 3-14 Result of helmet comfort rating test

3.4.2. Physical Property Tests

Table 3-5 shows the entire values of the physical property tests.

Table 3-7 Results of physical property tests

Item	Unit	#1	#4	#5	#7
MIU-w[1]	a.u.	0.20	0.18	0.21	0.33
MIU-c[2]	a.u.	0.25	0.23	0.28	0.34
MMD-w	a.u.	0.024	0.026	0.014	0.018
MMD-c	a.u.	0.043	0.047	0.024	0.019
SMD-w	μm	3.4	3.7	5.4	15.2
SMD-c	μm	12.9	12.7	15.7	8.3
LC	a.u.	0.69	0.61	0.61	0.50
WC	gf·cm/cm^2	0.57	0.22	0.30	0.96
RC	%	63.5	66.8	49.1	47.9
q-max	W/m^2	0.081	0.094	0.075	0.043
WA-w	mm	90	118	127	84
WA-c	mm	109	131	141	105

[1]w: Wale direction of fabric, [2]c: Course direction of fabric

3.4.2.1. Results of surface property tests

As a result of mean of friction coefficient (MIU), Sample #7 showed the highest MIU value (c.f. figure 3-15). The MIU values in the course direction were higher than their values in the wale direction. The mechanical property of low MIU value represents the smooth surface feeling of fabrics. However, the result trend of the MIU test inversely matched up with the result trend of the helmet comfort sensory test (c.f. Figure 3-3).

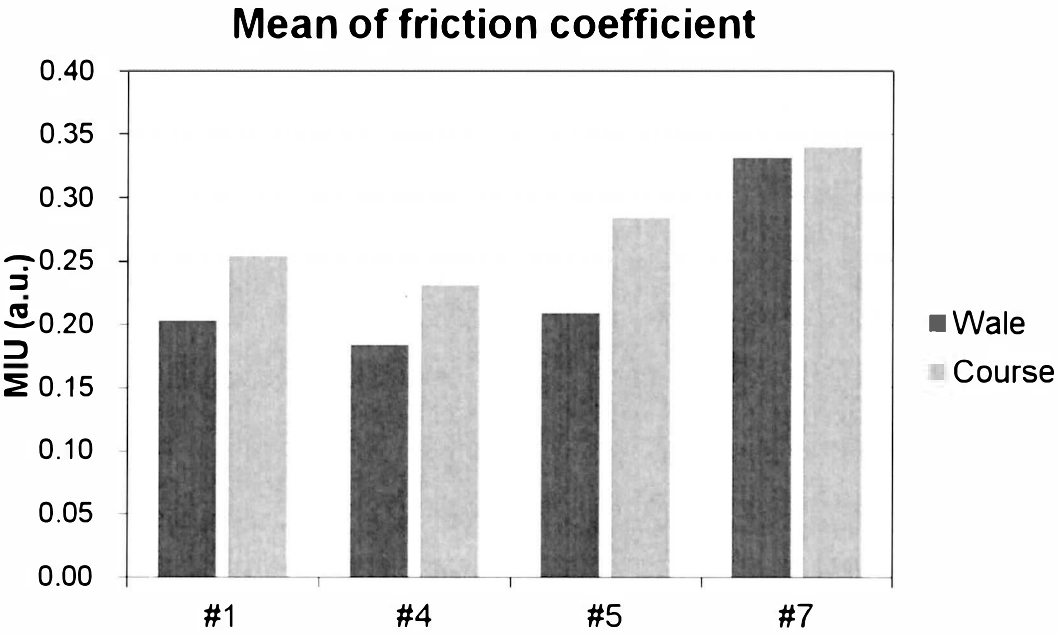


Figure 3-15 Result of surface property test: Mean of friction coefficient (MIU)

As a result of mean deviation of friction coefficient (MMD), Sample #5 showed the lowest MMD value in the wale direction, and the lowest value was Sample #7 in the course direction (c.f. 3-16). The mechanical property of MMD represents being lumpy in texture. The result trend of MMD in the course direction matched up well with the result trend of the helmet comfort test of "Lumpy" and "Coarse-Fine" in the "Before exercise (dry state)" (c.f. Figure 3-7). Therefore, it was considered that the stronger value was perceived as the dominant stimulus in the case where two or more values existed for the contacting directions, because the MMD values in the course direction were higher than their values in the wale direction. And it turned out that the MMD test was useful as a testing method to represent the lumpy texture of thick fabrics.

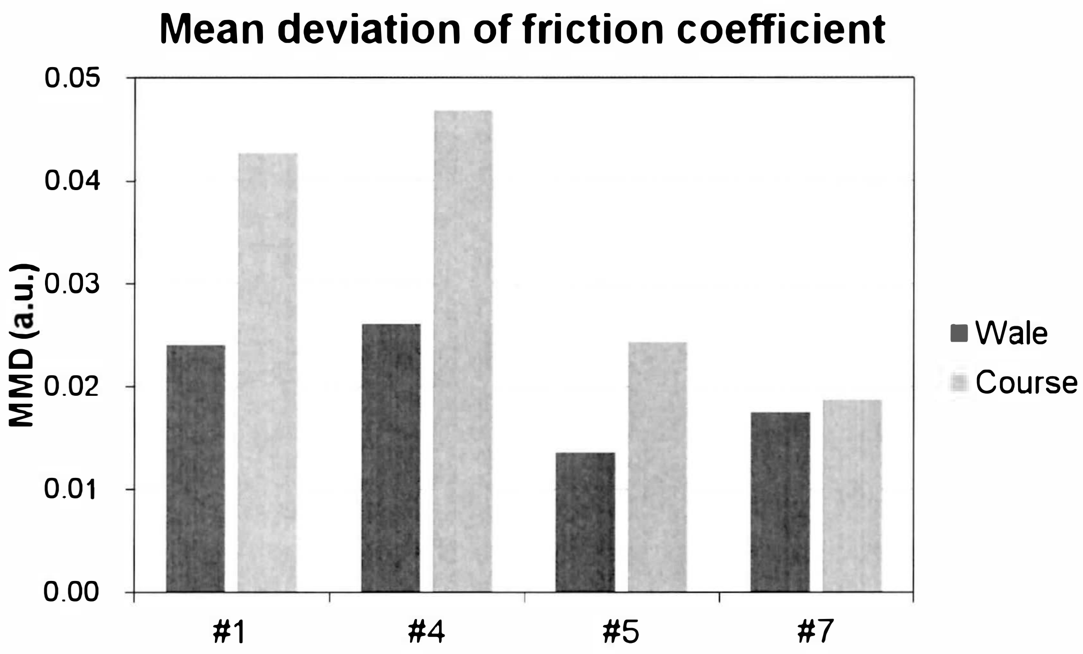


Figure 3-16 Result of surface property test: Mean deviation of friction coefficient (MMD)

As a result of geometric roughness (SMD) test, Sample #7 showed the highest SMD value in the wale direction, and the highest value was Sample #5 in the course direction (c.f. 3-17). The mechanical property of SMD represents the geometric roughness of fabrics. The result trend of SMD in the wale direction matched up precisely with the result trend of the helmet comfort test of "Lumpy" and "Coarse-Fine" in the "Before exercise (dry state)" (c.f. Figure 3-7). However, SMD values in the course direction and higher values in both directions did not match up with the helmet comfort test.

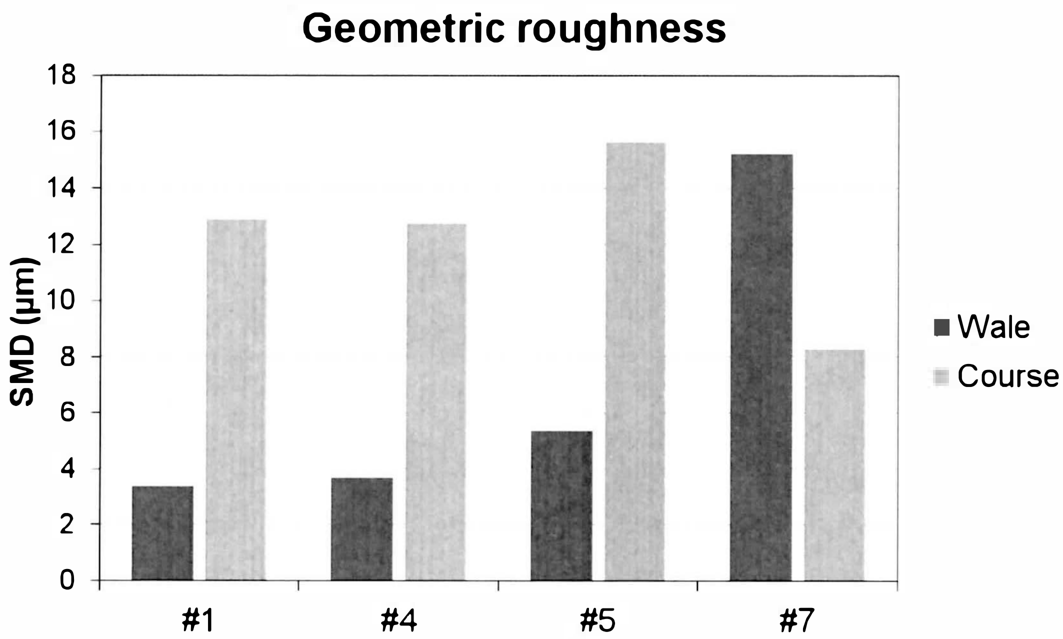


Figure 3-17 Result of surface property test: Geometric roughness (SMD)

3.4.2.2. Results of compression property tests

Figure 3-18~20 show the test results of the compression property tests. As a result of compression linearity (LC), Sample #1 showed the highest value and Sample #7 showed the lowest value (c.f. 3-18). The mechanical property of LC represents the difficulty of compressing the fabrics. In this study, the result trend of the LC test matched up well with the result trend of the helmet comfort test of "Hard-soft" in the "Before exercise (dry state)" (c.f. Figure 3-5).

As a result of compressional energy (WC), Sample #7 showed the highest value and Sample #4 showed the lowest value (c.f. 3-19). As a result of compression resilience (RC), Sample #4 showed the highest value and Sample #7 showed the lowest value (c.f. 3-20). However, the measurement results of WC and RC did not match up with the results of the helmet comfort test.

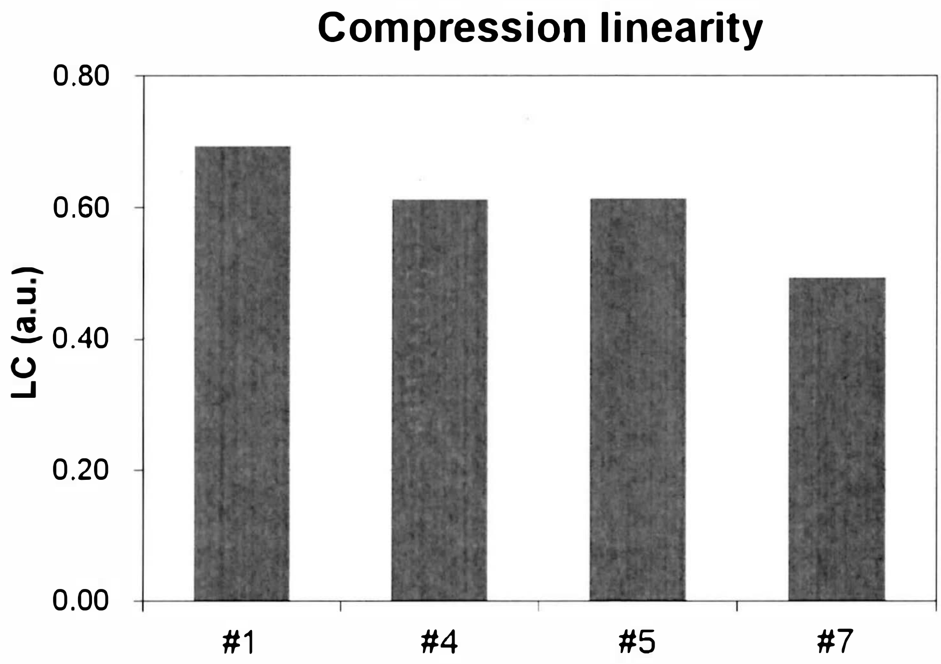


Figure 3-18 Result of compression property test: Compression linearity (LC)

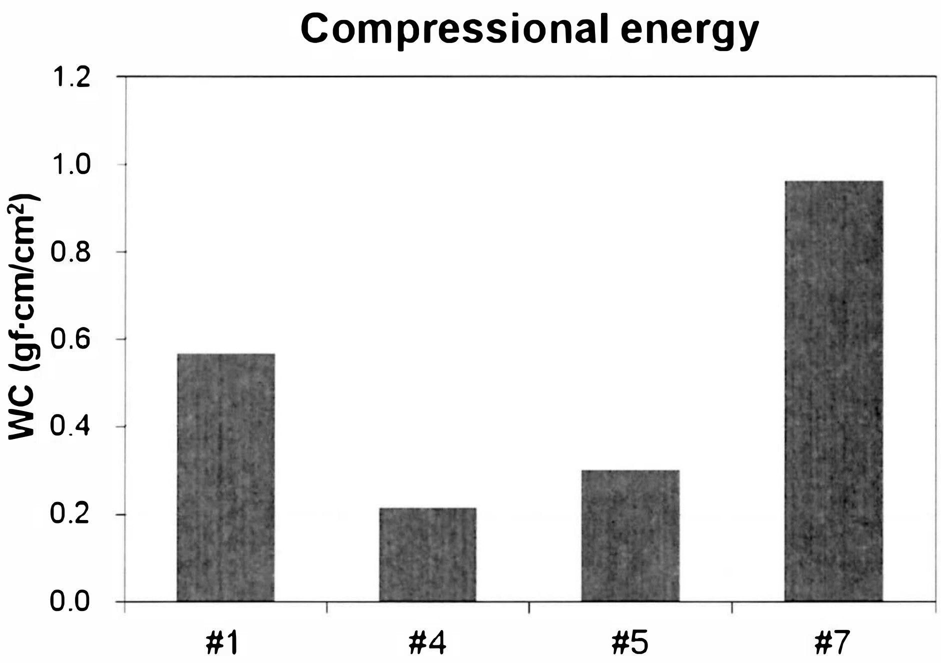


Figure 3-19 Result of compression property test: Compressional energy (WC)

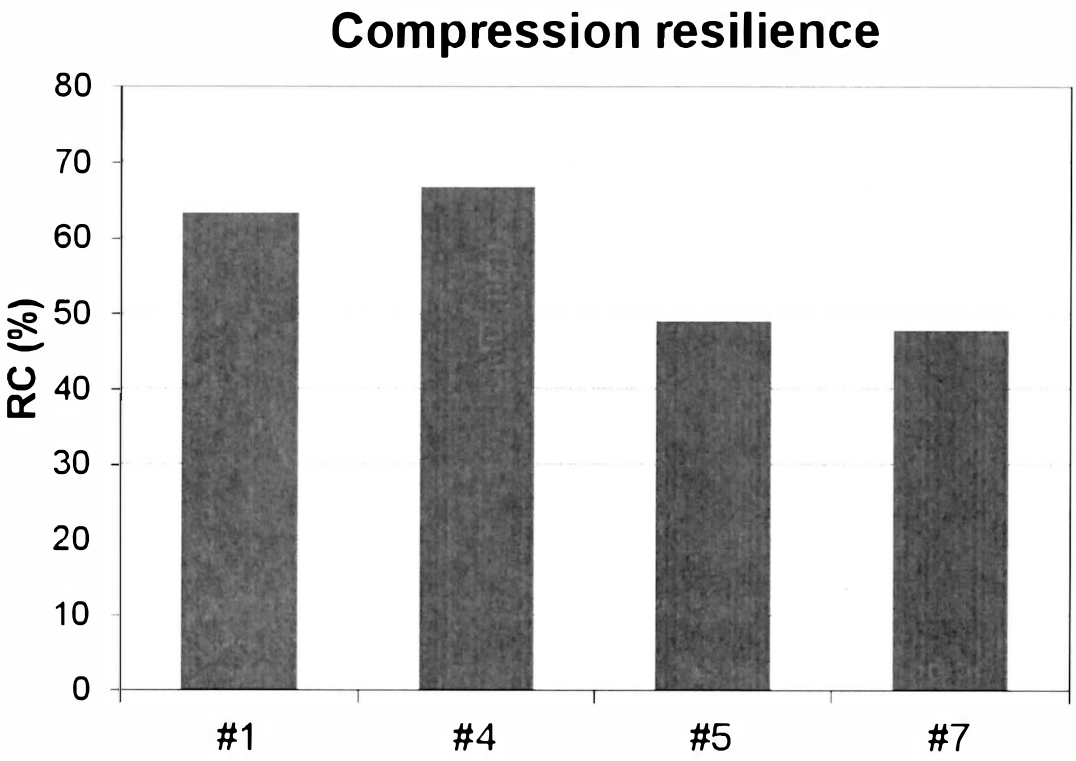


Figure 3-20 Result of compression property test: Compression resilience (RC)

3.4.2.3. Result of warm/cool touch test

Figure 3-21 shows the test result of the warm/cool touch test. As a result of q-max test, Sample #4 showed the highest value and Sample #7 showed the lowest value. The mechanical property of q-max represents the chill touch of the fabrics. In this study, the result trend of the q-max test matched up with the result trend of the helmet comfort test of "Warm-Cool" in the "Before exercise (dry state)" (Figure 3-13).

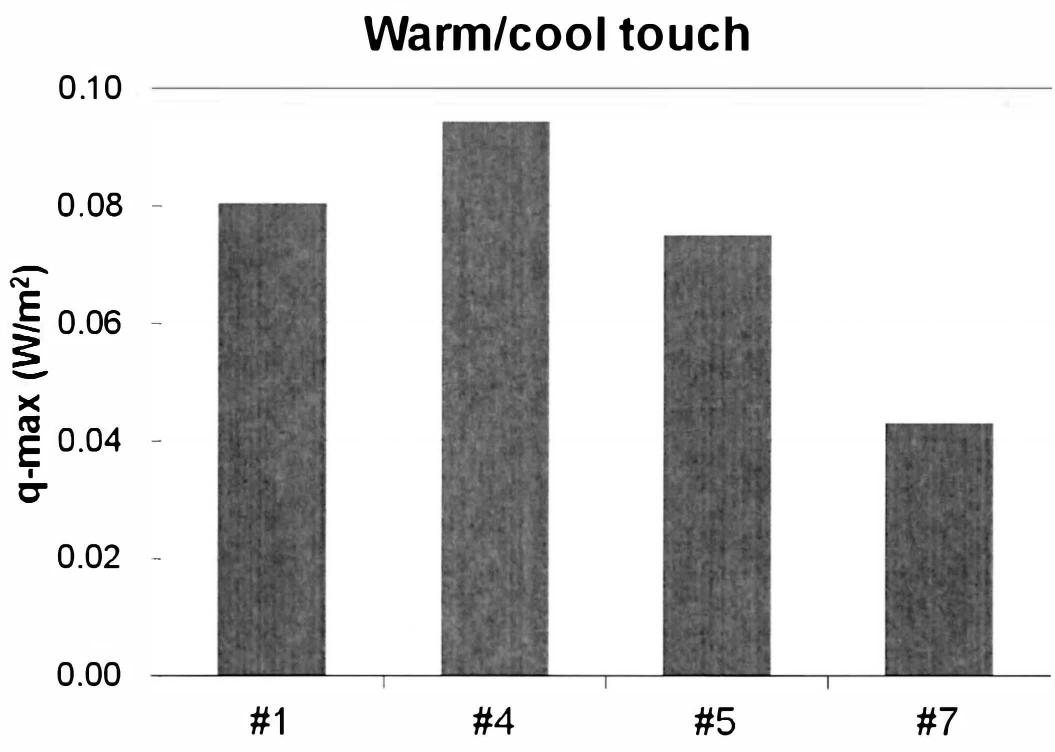


Figure 3-21 Results of warm/cool touch test (q-max)

3.4.2.4. Results of water absorption test

Figure 3-21 shows the test result of the water absorption test. Sample #5 showed the longest water absorption length, and Sample #7 showed the worst water absorption performance. In the results of the surface test, Sample #7 showed better roughness performance than Sample #5. In the results of the helmet comfort rating test, however, Sample #5 evaluated better than Sample #7. Therefore, it was considered that the "Mugginess" component was the most influential principle component on helmet comfort.

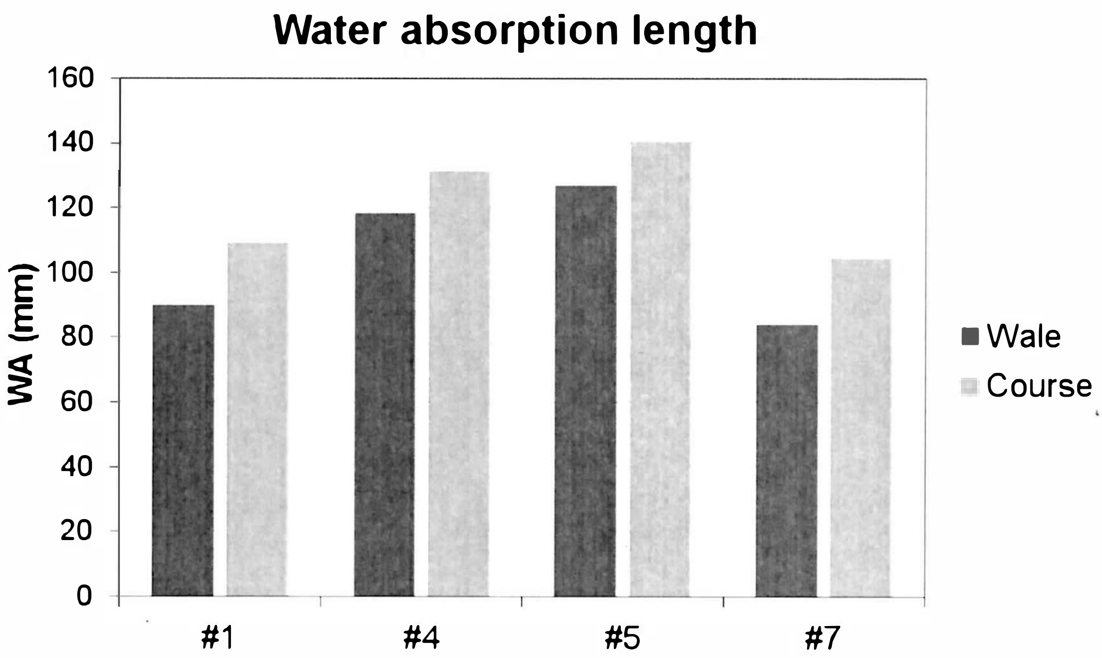


Figure 3-22 Result of water absorption test (WA)

3.4.3. Relation of Helmet Comfort with the Sensory Tests and the Physical Property Tests

We analyzed the relationship of the helmet comfort rank with the sensory tests and the physical properties tests using partial correlation analysis. The evaluation terms with calculated coefficients over ±0.7 were considered to show a strong correlation with helmet comfort. Table 3-6 shows the correlation coefficients of the partial correlation analysis.

From correlations with the helmet comfort sensory tests, we confirmed that the psychological components related to the SAL that affected helmet comfort consisted of the following: (1) "cool" and "feels good" before exercise, i.e. when putting on the safety helmet; (2) "gentle on skin" at the start of perspiration; (3) "feels good" and "gentle on skin" at maximum perspiration; (4) "fine", "not lumpy", and "gentle on skin" when put on again after a break. It was determined that the SAL's forehead feel both while dry and while wet, and also when the helmet was put on again after being taken off, were important components when judging helmet comfort.

The result of correlation with the physical properties test shows that the friction coefficient variance (MMD) and the water absorption length (WA) affected helmet comfort. MMD is known to indicate a rough fabric feel and to show strong negative correlation with all terms determined to affect helmet comfort based on the results of this study (c.f. Figure 3-4).

Table 3-8 Correlation coefficients of helmet comfort with sensory tests and physical property tests

	Item	Condition	R
Helmet Comfort	Fine	After break	0.83
	Not lumpy	After break	0.77
	Cool	Before exercise	0.83
	Feels good	Maximum perspiration	0.89
	Soft	Before exercise	0.99
	Gentle on skin	Initial perspiration	0.93
		Maximum perspiration	0.90
		After break	0.91
Hand Feel	Fine	Dry fabric	0.78
		Wet fabric (2g)	0.83
	Not lumpy	Dry fabric	0.80
		Wet fabric (2g)	0.80
	Cool	Wet fabric (10g)	-0.73
	Feels good	Wet fabric (10g)	0.86
	Not itchy	Wet fabric (2g)	0.89
	Smooth (rough)	Dry fabric	0.85
		Wet fabric (2g)	0.72
		Wet fabric (10g)	0.81
	Gentle on skin	Dry fabric	0.76
		Wet fabric (10g)	0.79
	Smooth (clammy)	Wet fabric (10g)	0.99
Physical Properties	MMD	Wale direction	-0.92
		Course direction	-0.76
		Vertical direction	-0.74
		Horizontal direction	-0.94
	WA	Horizontal direction	0.75

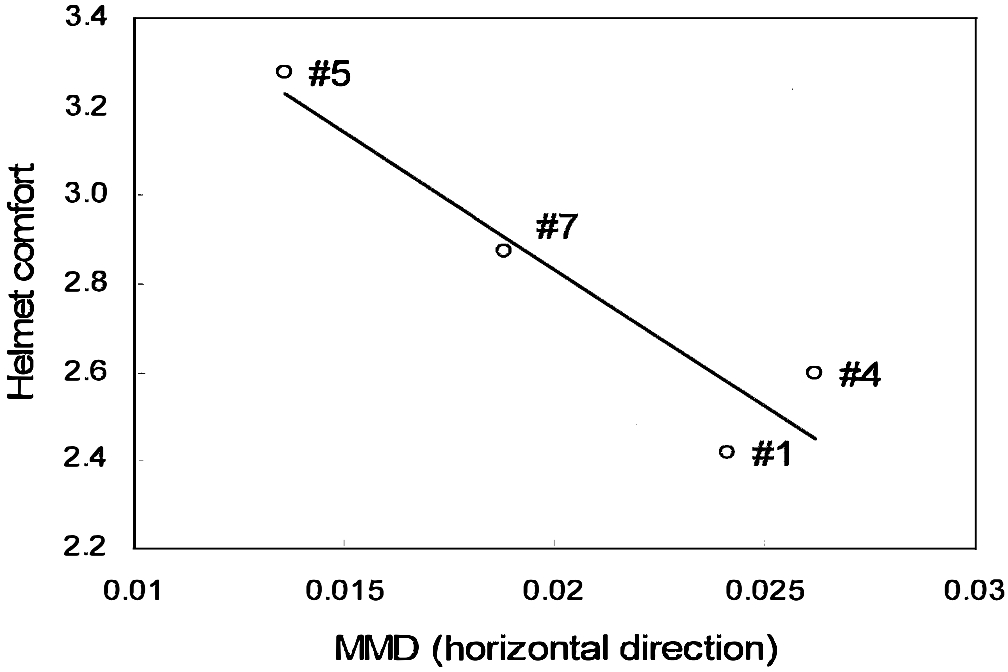


Figure 3-23 Helmet comfort and mean deviation of friction coefficient

3.5. Conclusion

As a result of our experiments, I concluded that the effects of the physical properties of the SAL on fabric hand using hand feel and helmet comfort are as follows.

"Muggy feel" and "rough feel" are the principle components that affect psychological responses to how SAL affects helmet comfort. The roughness component in particular consists of the following: (a) "cool" and "soft" feel when wearing the safety helmet; (b) "gentle on skin" at initial perspiration; (c) "feels good" and "gentle on skin" at maximum perspiration; (d) "fine", "not lumpy", and "gentle on skin" when put on again after a break.

If we optimize the SAL surface roughness properties, it would be possible to improve helmet comfort. SAL with a lower friction coefficient variance measured by KES-FB4 and good absorbency enhance helmet comfort. However, it is difficult to enhance the hygrothermal comfort of safety helmets through modification of the SAL.

Hand feel evaluation of the SAL fabric is effective in predicting helmet comfort. Due to the results showing that SAL containing perspiration played a role in the positive or negative response of surface roughness based on its physical properties, further research and development for a tester is needed to clarify the effects of the surface roughness properties of wet fabrics.

CHAPTER 4

Evaluation of the Texture of Sheepskin

Using a New Hand Evaluation Measurement System

4. Evaluation of the texture of Sheepskin Using a New Hand Evaluation Measurement System

4.1. Introduction

Sheepskin is used to produce sheepskin leather products and soft wool-lined clothing or coverings, including gloves, hats, automotive seat covers, mats for babies and the disabled, and pelts. In particular, it has been found to be effective in reducing the incidence of pressure ulcers [13] and in giving drivers a more comfortable seat in their vehicles [14].

Sheepskin refers to the hide taken from a sheep and is composed of a layer of skin and the attached hair. It has unique fabric handle properties that distinguish it not only from other fabrics, but also from leather products and pile fabrics. Moreover, it is difficult to mechanically predict and control its texture based on its material properties, since sheepskin is a natural material and varies according to each animal. So, quality assessment of sheepskin depends mainly on hand evaluation via sensory tests.

Hand evaluation via sensory test is an important evaluation method when determining the quality and usage of fabrics. The palpate methods used when evaluating the fabric are different depending on the attributes of the evaluator, such as hand evaluation experts vs. users, and male vs. female, as well as the fabrication methods, materials, and uses. Moreover, the evaluation terms used for hand evaluation are different according to the evaluation objectives [15-19].

The Kawabata Evaluation System has been developed to objectively measure fabric handle [6]. This system is not only useful for fabric but also for paper, film, etc. However, with this system it is difficult to measure the mechanical properties of thick materials such as sheepskin and thick-pile fabric. Research on measuring the physical properties of thick fabrics like fur and pile fabrics have been reported [20-23]. However, research on the objective hand evaluation of sheepskin is not sufficient. Therefore, it is necessary to measure the texture properties of sheepskin mechanically.

Sheepskins are evaluated in Japan using unique evaluation terms such as DANRYOKU (perceived elasticity), KEGOMI (richness and fullness of hair), KESABAKI (smoothness and softness of hair), etc.

For this chapter, we focused on DANRYOKU and KEGOMI. The purpose of this study is to clarify the relationship between the tactile sensation and the mechanical properties of sheepskin. It was considered that DANRYOKU was related the compression property and KEGOMI was related the friction property. Therefore, we developed a new hand evaluation measurement system for the measurement of the compression and friction properties of sheepskin multi-axially. The DANRYOKU and KEGOMI of sheepskin were evaluated using sensory tests. The statistical analyses were carried out to determine the mechanical parameters which had an influence on the fabric handle of sheepskin.

4.2. Development of a New Hand Evaluation Measurement System

4.2.1. Structure

In general, when a human manually evaluates thick fabrics, they push and stroke it with their fingertips and palm, and fabric handle is expressed in response to the multi-axial properties. Therefore, sensing technology (or a device) which is capable of measuring multi-axial load is necessary. However, existing testers can only measure single-direction properties. Therefore, we developed a new three-dimensional tactile sensation measurement system (3D-TSMS) to measure the mechanical properties along three axes. The 3D-TSMS imitates the palpate motions of a human hand (c.f. Figure 4-1). The 3D-TSMS is composed of a capacitance three-axis force sensor (PD3-32-05-015, NITTA Corp., Japan) and a 3D Cartesian manipulator (CCR-M14-0403025, NIDEC SANKYO Corp., Japan). The force sensor can measure the applied loads contacting the object in three-axial directions. The 3D-TSMS is controlled by two computers; a manipulator controller (SC3000, NIDEC SANKYO Corp., Japan) and a load measurement computer. The load which is generated when the sensor tip comes in contact with the specimen is detected by the force sensor and the output of the sensor is converted from analog to digital by the DAQ card (National Instruments Corp., US), and then transmitted to the measurement computer. The recorded load value is analyzed by a program designed with LabVIEW (National Instruments Corp., US). The manipulator can be controlled by transmitting the control signal corresponding to the load value to the manipulator controller through RS232C. The sampling frequency of the force sensor is 50Hz, and the signal is filtered through a low-pass filter of 0.3Hz and input to the measurement computer.

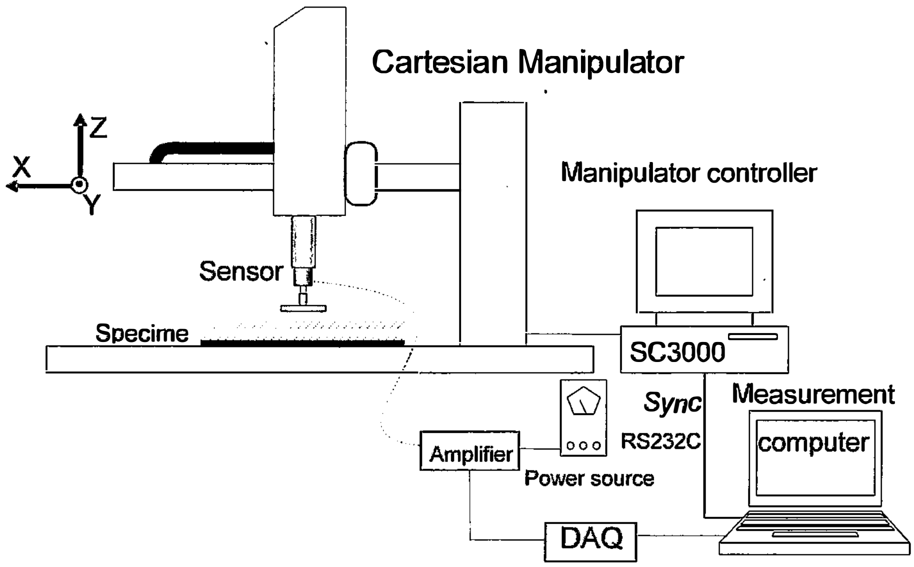


Figure 4-1 Schematic of the three-dimensional tactile sensation measurement system

Figure 4-2 shows the relationships between loads and the output of a force sensor along the three axes. It was verified that loads and the output of the force sensor were showed linear relationships within the range of plus or minus 200 gf and the relationships were determined to be as follow: 0.38 mV/gf in X axis, 0.36 mV/gf in Y axis, and 0.46 mV/gf in Z axis.

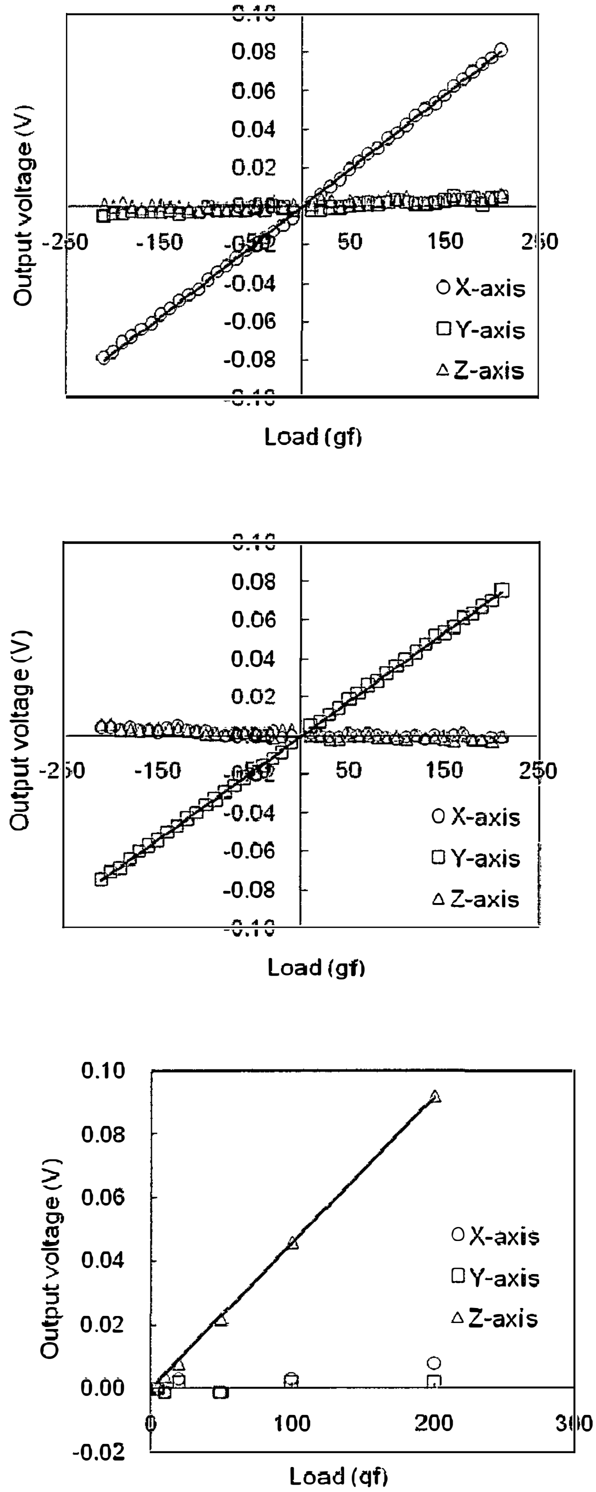


Figure 4-2 Sensor calibration; (top) X-axis, (middle) Y-axis, and (bottom) Z-axis

4.2.2. Features

This system reflected the human palpate motions. The manipulator of this system is able to make up-and-down and back-and-forth as well as rotational movements. Also, the sensor module is changeable according to the intended evaluation. Therefore, 3D-TSMS is expected to be a tester which is able to measure the fabric handle of thick-pile fabrics.

4.3. Experiments

4.3.1. Samples

Five kinds of mouton with different levels of hair density and hair count were used: *fine*, *thin*, *medium*, *dense*, and *thick*. Sample levels are named with consideration of their hair density and hair count. Table 4-1 shows the details of the mouton samples.

Table 4-1 Sample details

Sample Name	Apparent Thickness* (mm)	Hair Length (mm)	Hair Density (/cm^2)	Hair Count (tex)
Fine	31.4	40.5	4262	15.8
Thin	33.9	42.6	2269	17.0
Medium	33.0	41.6	4494	15.5
Dense	32.5	41.2	4629	16.1
Thick	33.1	42.4	2220	25.3

*: Excluding skin thickness

4.3.2. Sensory Tests

Twenty Japanese university students participated in this test on a voluntary basis (Male: 8, Female: 12; Age range: 22-23). Participants compared the texture of each mouton sample against a reference mouton in Japanese. The reference mouton was a *medium* mouton cut to the length of 25 mm, which are usually used for bedclothes in Japan. Participants determined how much greater or less the *DANRYOKU* and *KEGOMI* of the sample mouton were in relation to the reference mouton using 7-point scales (c.f. Figure 4-3). The sample moutons were presented to participants at random and sample names were not provided to them to minimize any potential bias. Participants were instructed in their mother tongue to compress the mouton with their palm and fingertips. The surface of the mouton pairs were covered with a board with a hole measuring 10 cm in length and 20 cm in width in order to ensure consistent control of the palpate method. The test environment was at a temperature of 23±2°C and a relative humidity of 60±5%.

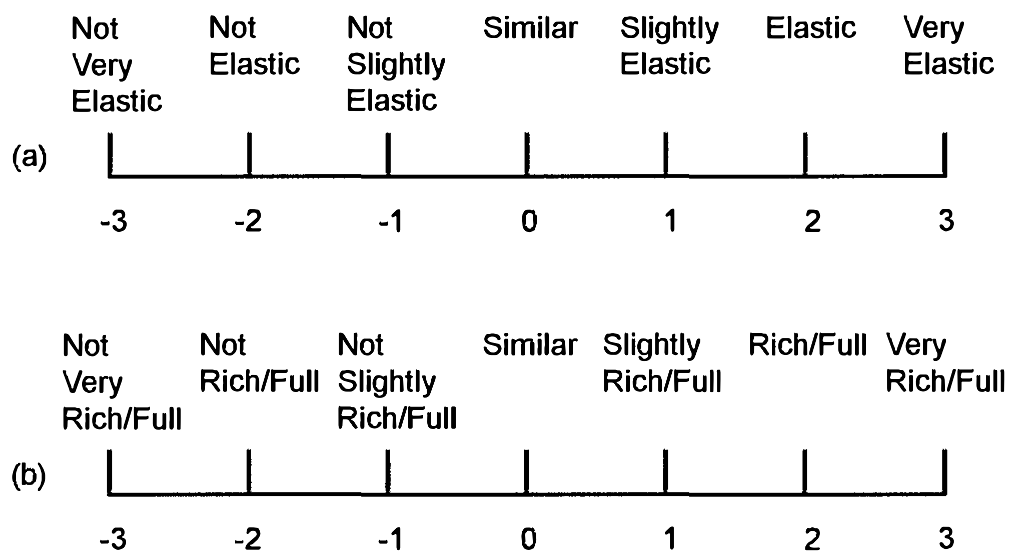


Figure 4-3 Rating scales of *DANRYOKU* (a. perceived elasticity) and *KEGOMI* (b. Richness and fullness of hair)

4.3.3. Compression Test for *DANRYOKU* Using 3D-TSMS

A brass disk-shaped indenter (dia. 50mm) was used as the sensor tip to evaluate the compression properties along the Z-axis as well as along the X-axis and Y-axis as shown in Figure 4-4. The mouton was compressed by the manipulator with an operation speed of 2 mm/sec. Compression was maintained until the output value of the force sensor along the Z-axis reached 30 gf/cm^2. The pressure value of 30 gf/cm^2 was set based on the mean value obtained from the hand evaluations of the mouton samples.

Changes in pressure and displacement during the compression and recovery processes were measured. The loads along the X-axis and Y-axis were measured during these processes. We were able to calculate the generated force and direction in three dimensions by measuring the three axial loads along with the compression and recovery. The measurement was taken five times.

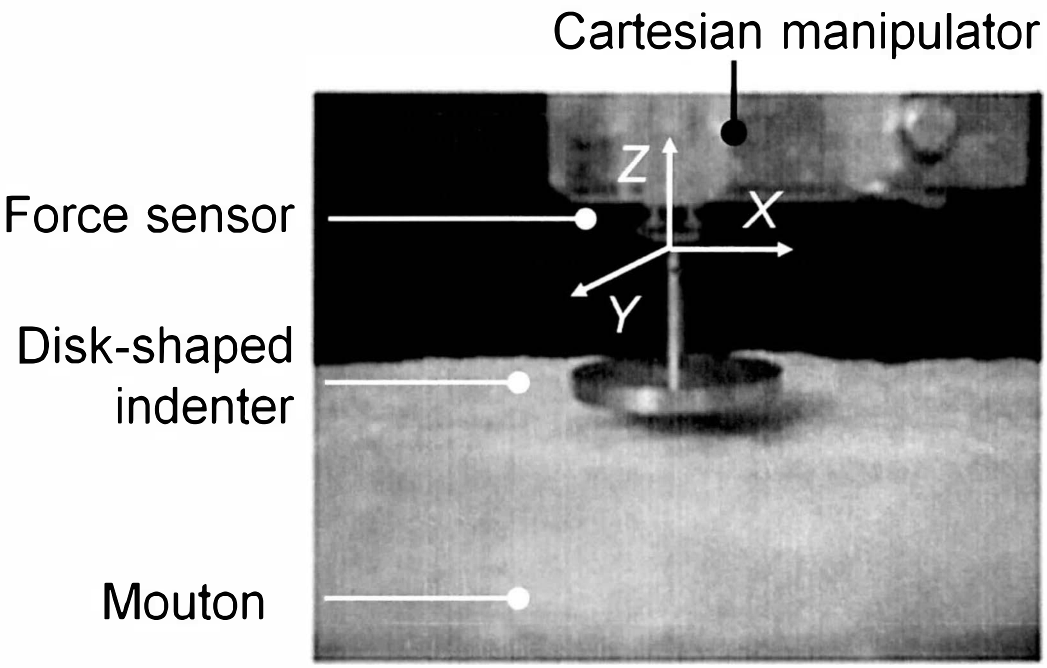


Figure 4-4 Sensor and indenter

4.3.4. Surface Test for *KEGOMI* Using 3D-TSMS

KEGOMI (richness and fullness of hair), one of the mouton' evaluation term, is evaluated usually by the sense obtained by palpate motions of combing by pushing the tips of the digitus primus (thumb), digitus secundus (index finger), and digitus tertius (middle finger) into the hairs. In order to imitate the human palpate motion, 3D-TSMS was operated for the surface test of *KEGOMI* as follows (c.f. Figure 4-5): The surface of the mouton was compressed by the sensor tip with a load of 30 gf along the Z axis, then the sensor unit moved by 80 mm in a horizontal motion with the speed of 5 mm/sec. These measurement conditions were determined from the result of preliminary experiments. A brass spherical-shaped indenter (dia. 16mm) was used as the sensor tip. The shape of the sensor tip imitated fingertips and its diameter was determined by the average of their size. Each sample was tested in the same direction, because sheepskin hairs grow directionally growing. The measurement was taken five times.

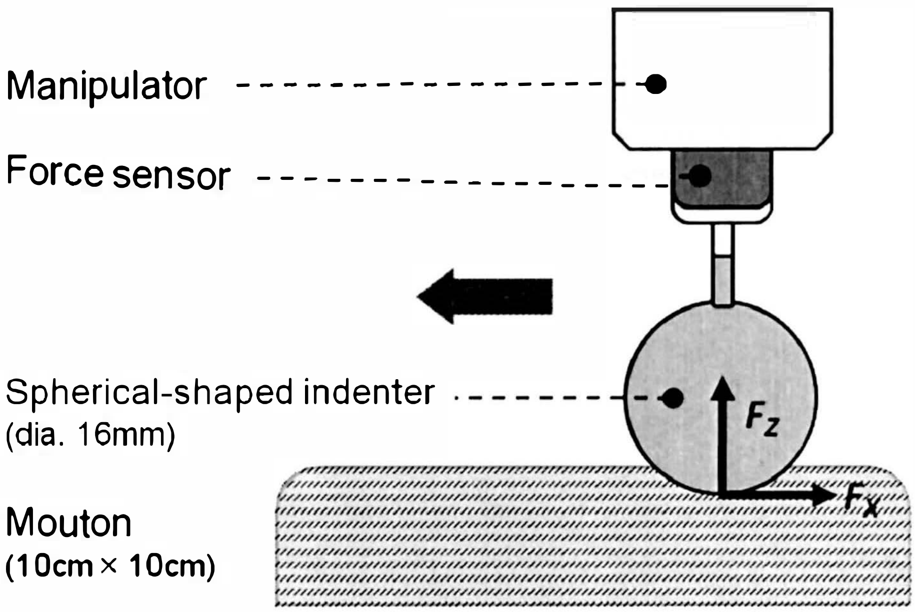


Figure 4-5 Surface test: Compression load is 30 gf, movement speed is 5 mm/s, and displacement is 80 mm.

It was considered that the human sense, which was the criteria for fabric handle evaluation, was related to the surface friction properties of mouton. Therefore, the coefficient of *KEGOMI* friction between the two surfaces of the mouton and the sensor tip when the sensor tip is slid over the surface of mouton was denoted as μ_{KGM}, and defined as follow:

$$\mu_{KGM} = F_X / F_Z \quad (1)$$

where, F_X is the friction force which prevent the sliding of the sensor tip along the X axis, and F_Z is the normal force which compresses the surface of the mouton along the Z axis. The mean of friction coefficient (MIU) and mean deviation of friction coefficient (MMD) were calculated as the surface property parameters of mouton from the measurement results of coefficient of *KEGOMI* friction. These surface property parameters were defined as follows:

$$MIU = \frac{1}{X}\int_0^X \mu dx \quad (2)$$

$$MMD = \frac{1}{X}\int_0^X \left|\mu - \overline{\mu}\right| dx \quad (3)$$

where, x is displacement (position of sensor tip on the surface of mouton), X is sliding distance (80mm in this test), and $\overline{\mu}$ is the mean of μ [6].

4.4. Results

4.4.1. Sensory Tests

4.4.1.1. Sensory Test for *DANRYOKU*

Figure 4-6 shows the results of the sensory test for *DANRYOKU*. This profile is the mean value for 20 participants. The mouton samples were rated in the following order (from highest *DANRYOKU* to lowest): *dense*, *medium*, *fine*, *thick*, and *thin*. Also, with the exception of *medium* and *fine*, the samples displayed significant differences between them when tested by multiple comparisons in one-way ANOVA using Scheffe's method (*dense-medium*: p<0.05 and *fine-thick-thin*: p<0.01).

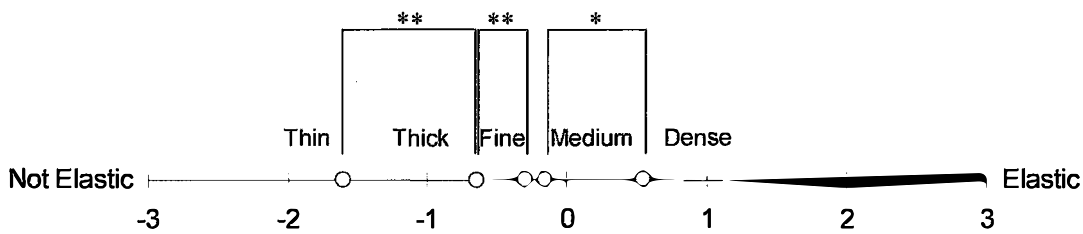


Figure 4-6 *DANRYOKU* (perceived elasticity) profile (: P<0.01, *: P<0.05)**

4.4.1.2. Sensory Test for *KEGOMI*

Figure 4-7 shows the results of the sensory test for *KEGOMI*. This profile is the mean value for 20 participants. The mouton samples were rated in the following order (from highest *KEGOMI* to lowest): *dense*, *medium*, *fine*, *thick*, and *thin*. As results of multiple comparisons in one-way ANOVA using Scheffe's method, both *dense* and *medium* were statistically different from *thin* at the 1% significant level. *Dense* was statistically different from *thick* at the 5% significant level.

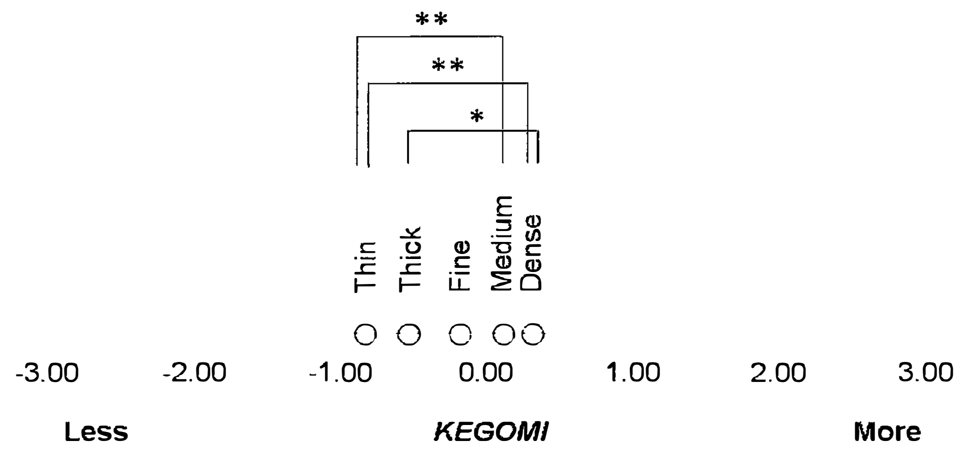


Figure 4-7 *KEGOMI* (richness and fullness) profile (: P<0.01, *: P<0.05)**

4.4.2. Mechanical Property Measurement

4.4.2.1. Compression Test

Figure 4-8 shows the pressure-displacement curves obtained from along the Z-axis of the sensor.

In the case of *dense*, the amount of displacement created by the indenter reaching maximum pressure was small, i.e., the increase ratio of pressure was high. For *thin*, the amount of displacement was large, i.e., the increase ratio of pressure was low. For *dense*, there is a convex shape of the compression curve in the range of 5 to 13 mm approximately. Other mouton samples were observed to have the same behavior, although it was slight in all but the *thin* mouton samples. This phenomenon is believed to occur due to the following reasons: First, the hairs that touch the indenter bear the initial compression, and are compressed and bent when the pressure exceeds a certain threshold. Second, each mouton sample exhibited viscoelastic behavior and hysteresis was observed in the pressure-displacement curve, with the loop area being equal to the energy lost during the compression and recovery cycle. Since the amount of energy lost is different depending on the type of mouton, it is possible to use this as a parameter representing the recovery properties or pressure-relieving properties of mouton.

Figure 4-9 (a), (b), and (c) show the load-displacement curves obtained from along the X-axis and Y-axis of the sensor and their resultant force. In the following charts, 'displacement' represents Z-axis displacement.

In Figure 4-9 (c), the curve for the *dense* sample shows a convex load change with a displacement of approximately 5 mm to 13 mm. The curves of other mouton samples show similar load changes, with the exception of the *thin* mouton. This shows that there is the directionality in the hair of the mouton, and that the load applied along the Z-axis, when the mouton is compressed, is transferred to the X-Y plane. During initial compression the hair is raised, and significant directional transfer of the force applied to the mouton was observed. The hairs start to bend and deform under the progressive compression, and the vertical force is redirected and thus lessened in this state. And then the redirection of the vertical force on the mouton increases again.

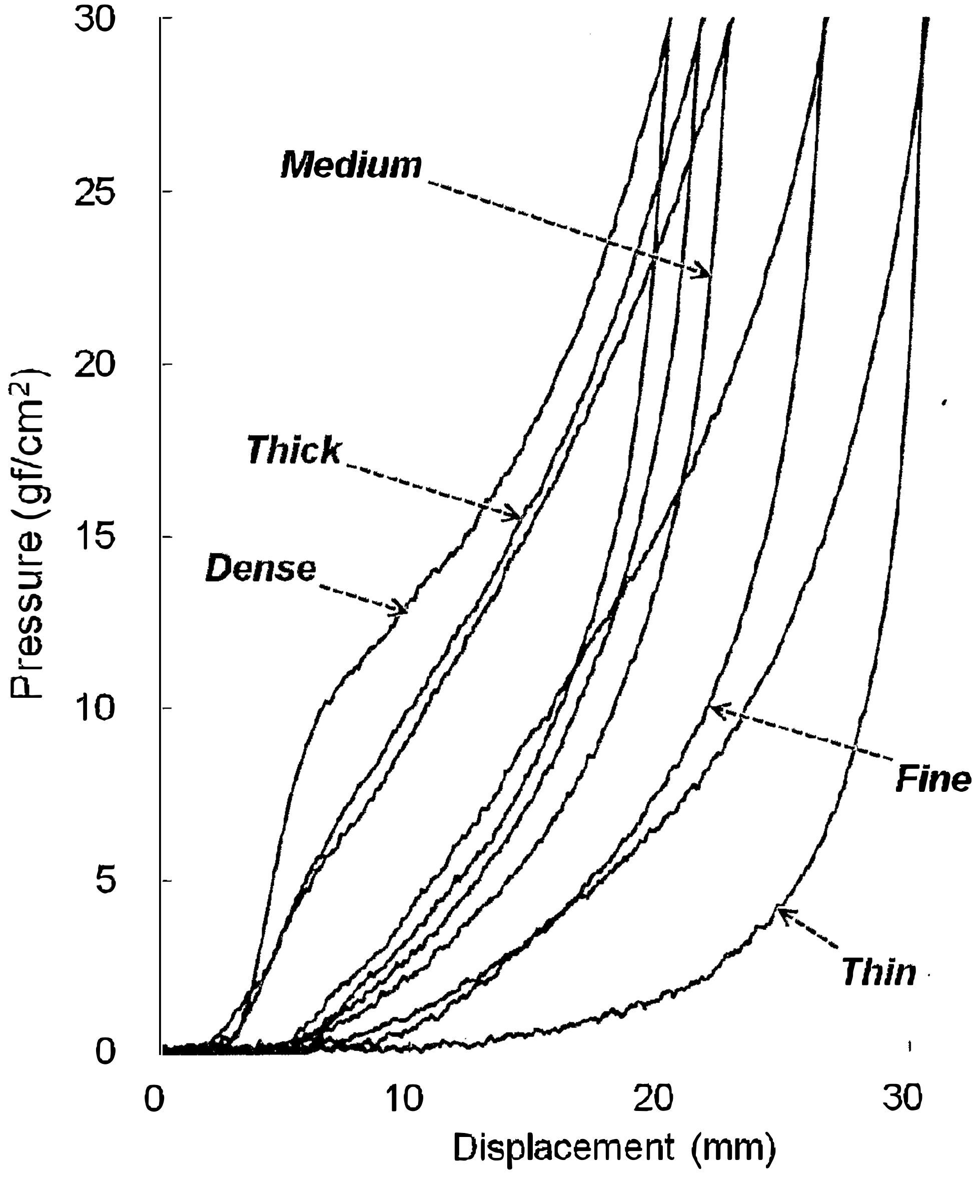
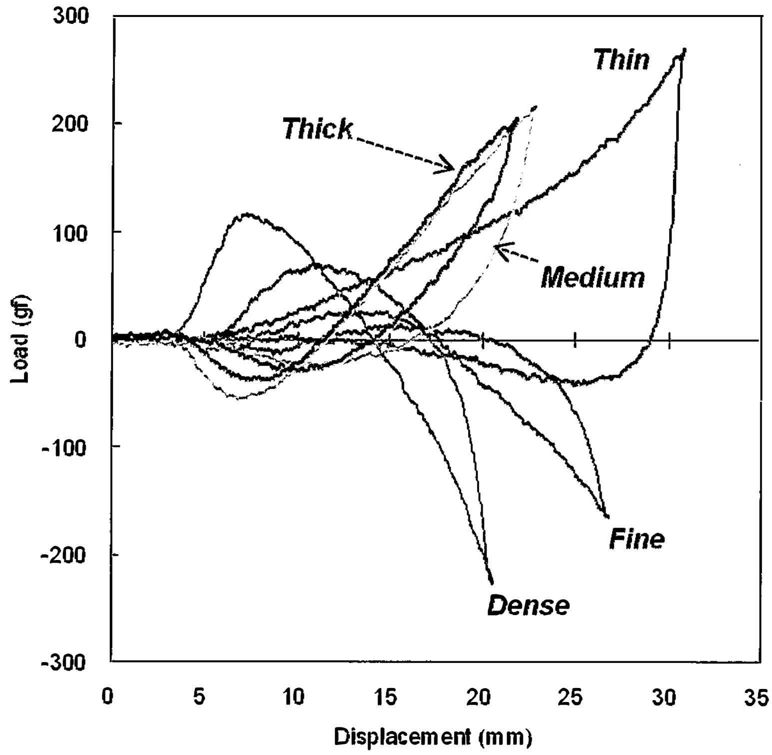
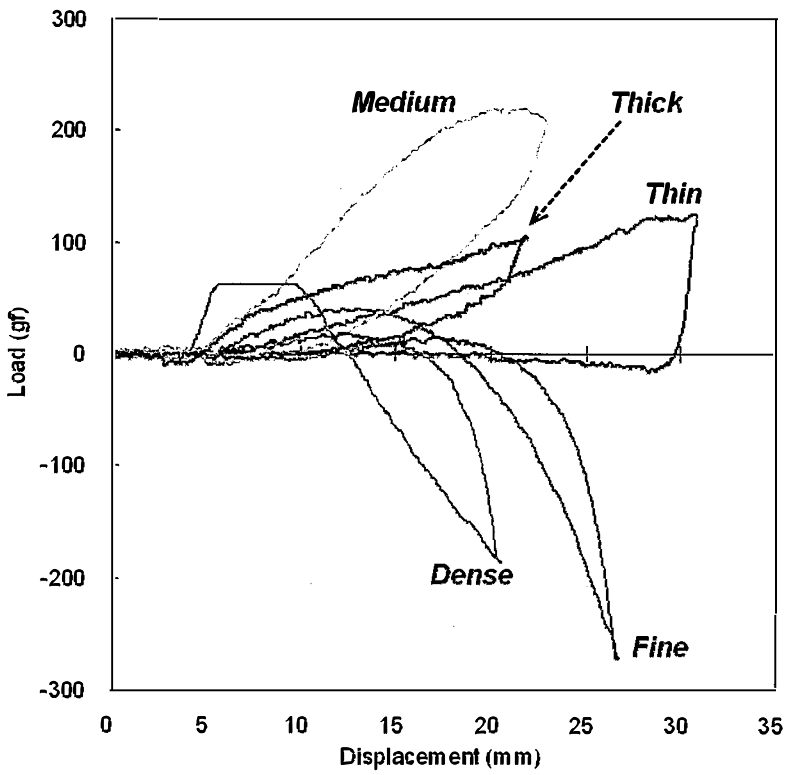


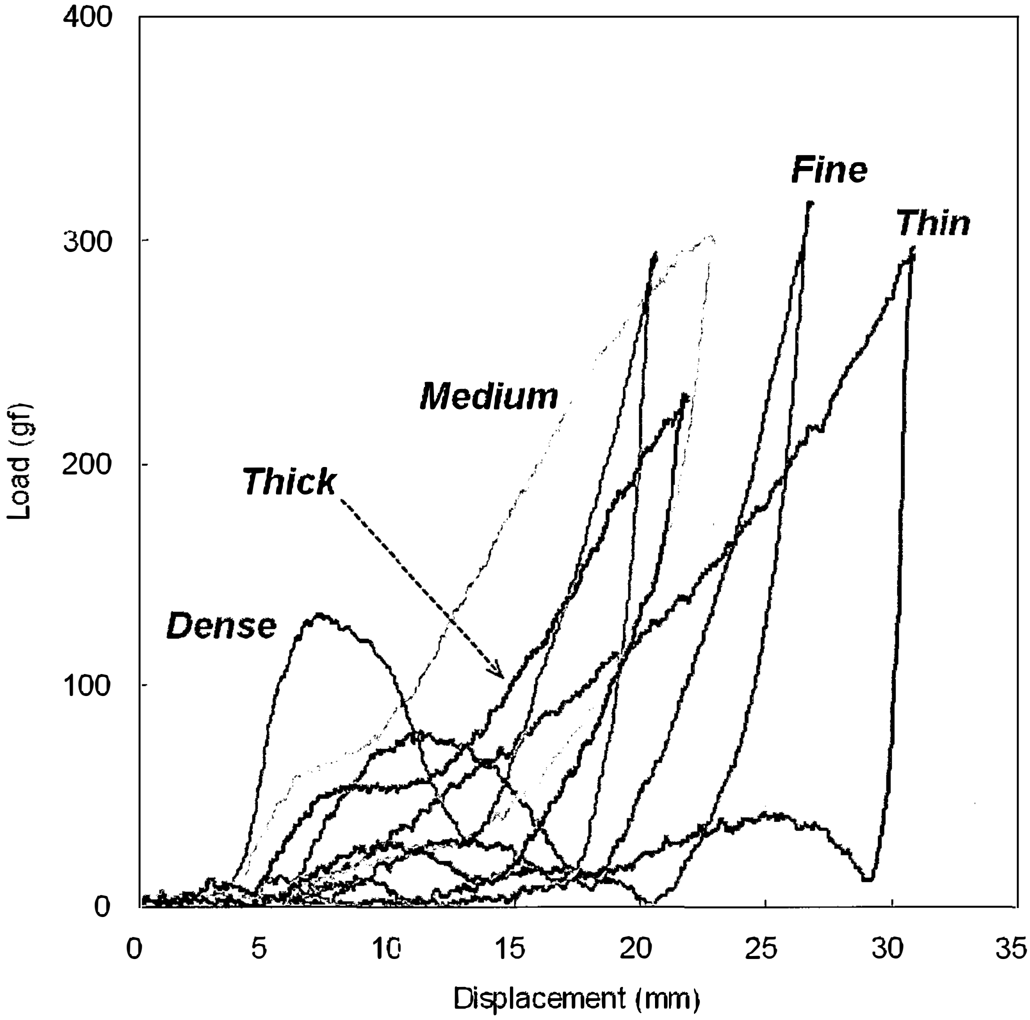
Figure 4-8 Pressure-displacement curve from compression testing


Thin
Thick
Medium
Fine
Dense
Load (gf)
Displacement (mm)
300
200
100
0
-100
-200
-300
0
5
10
15
20
25
30
35

(a)


Medium
Thick
Thin
Dense
Fine
Load (gf)
Displacement (mm)
300
200
100
0
-100
-200
-300
0
5
10
15
20
25
30
35

(b)



(c)

Figure 4-9 Load-displacement curve: (a) along the X-axis, (b) along the Y-axis, and (c) resultant force in the X-axis and Y-axis

4.4.2.2. Compression Property Parameters

Eight parameters were derived to evaluate the mouton compression properties based on the results of the compression testing. The following four parameters were measured from the Z-axis pressure-displacement curve (c.f. Figure 4-10).

Compression linearity *LC* defines compressive hardness as:

$$LC = \frac{WC}{WOC} \text{ [a.u]} \tag{4}$$

where the second parameter *WC* is the compressional energy:

$$WC = \int_{l_1}^{l_{30}} P dl \text{ [gf} \cdot \text{cm/cm}^2\text{]} \tag{5}$$

where *P* is the compression pressure and l_x is the compressed displacement at the pressure x gf/cm^2 and *WOC* defines the area of a right-angled triangle as: $WOC = P_{30}(l_{30} - l_1)/2$

Compressional resilience *RC* is the extent of recovery, or the regained thickness, when the force is removed:

$$RC = \frac{WC'}{WC} \times 100 \text{ [\%]} \tag{6}$$

Where *WC'* is the recovery cycle energy: $WC' = \int_{l_1}^{l_{30}} P' dl$ and *P'* is the pressure in the recovery cycle. Also, the thickness T is measured at the pressure of 1 gf/cm^2 and reported in millimeters [6].

In addition to these parameters, the following three parameters were measured. Compression distance L is measured at the pressure of 1 gf/cm^2 to 30 gf/cm^2.

$$L = l_{30} - l_1 \text{ [mm]} \tag{7}$$

The compressional flexibility coefficient α_{max} represents ease of compression and is defined by:

$$\alpha = \frac{l / l_{30}}{P} \text{ [cm}^2\text{/gf]} \tag{8}$$

The pressure relieving energy ΔE_{PR} is the area of the hysteresis loop and shows the amount of energy lost during a compress and recovery cycle. It is represented by the margin between compression and recovery energy:

$$\Delta E_{PR} = WC - WC' = \int_{l_1}^{l_{30}} (P - P')dl \text{ [gf} \cdot \text{cm/cm}^2\text{]} \tag{9}$$

Furthermore, the continuous mean deviation CMD was measured from the load-displacement curve with the resultant X-Y plane force and Z-axis displacement (c.f. Figure 4-11):

$$CMD = \frac{1}{l_{30}} \int_{l_1}^{l_{30}} \left| F - \overline{F} \right| dl \quad \text{[gf]} \tag{10}$$

where, $\overline{F}$ is the mean of F, and F is the resultant X-Y plane force which is calculated as: $F = \sqrt{F_X^2 + F_Y^2}$ where F_X is the X-axis load and F_Y is the Y-axis load.

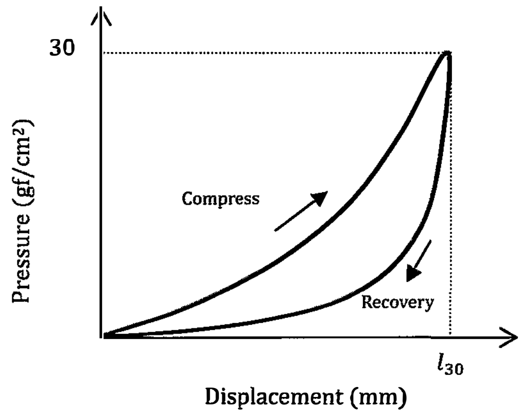


Figure 4-10 Pressure-displacement curve

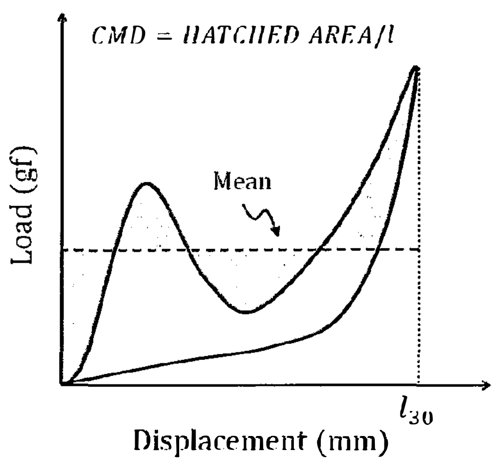


Figure 4-11 Resultant X-Y plane force and Z-axis displacement curve

Table 4-2 shows the results of compression testing using the 3D-TSMS. The measurement results are the mean value of five sampled measurements. Standard deviations are reported in parentheses.

Table 4-2 Compression testing results

		Fine	Thin	Medium	Dense	Thick
LC	(-)	0.79 (0.02)	0.60 (0.01)	0.90 (0.02)	0.97 (0.03)	0.73 (0.08)
WC	(gf・cm/cm^2)	24.8 (0.26)	19.8 (0.50)	26.2 (0.56)	25.4 (0.83)	26.3 (0.38)
RC	(%)	54.5 (0.64)	43.6 (0.67)	50.8 (2.10)	47.8 (1.29)	57.0 (2.57)
T	(mm)	37.2 (0.31)	33.8 (0.58)	39.6 (0.10)	39.9 (0.26)	40.1 (0.14)
L	(mm)	21.0 (0.45)	21.7 (0.63)	19.5 (0.08)	17.3 (0.13)	24.0 (2.53)
α_{max}	(cm^2/gf)	0.68 (0.01)	0.86 (0.01)	0.54 (0.01)	0.48 (0.01)	0.61 (0.06)
ΔE_{PR}	(gf・cm/cm^2)	8.1 (0.43)	4.5 (0.45)	12.5 (0.81)	13.2 (0.77)	8.6 (2.09)
CMD	(gf)	0.33 (003)	0.21 (0.02)	0.05 (0.02)	0.19 (0.05)	0.27 (0.08)

4.4.2.3. Surface Test

Figure 4-12 shows friction coefficient variance curves obtained from the results of surface tests for *KEGOMI*. Table 4-3 shows the calculation results of mean of friction coefficient (MIU) and mean deviation of friction coefficient (MMD) obtained from the friction coefficient variance curves. These results are the mean values for each sample from five measurements. Table 4-4 shows statistical significant differences by multiple comparisons in one-way ANOVA using Scheffe's method. In general, high MIU value indicates that the surface of the fabric does not slip easily. In this system, however, high

MIU value means that it is difficult for the sensor tip to slide within mouton hairs. In MIU, the lowest value was 1.3 for *dense*, and the highest value was 1.7 for *thin*. *Thin* showed a significant difference from *thick*, which was the second highest MIU value, at 5% significant level and also it showed significant differences from other samples (p<0.01).

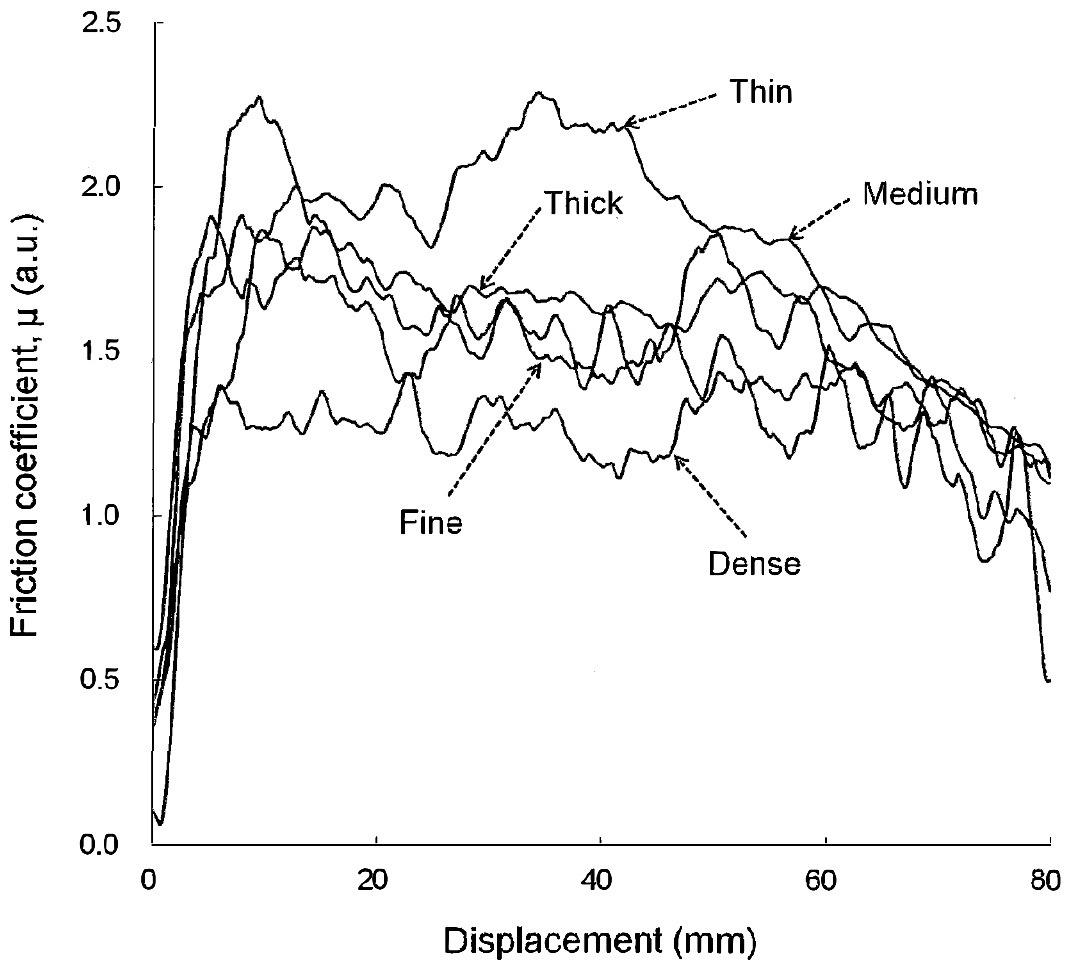


Figure 4-12 Friction coefficient curves of *Fine*, *Thin*, *Medium*, *Dense*, and *Thick*

In KES, high MMD value indicates that the surface of the fabric is uneven. In this system, however, high MMD value means that there is wide variation in the horizontal movement of sensor tip on the surface of mouton or within the mouton hairs. In MMD, the lowest value was 0.0007 for *dense*, and the highest value was 0.0012 for *thin*. The difference between *dense* and *thin* was significant at 5% significant level. However, other samples had no significant differences between each other.

Table 4-3 Surface property parameters of mouton samples

	MIU (-)	MMD (-)
Fine	1.5	0.9×10^{-3}
Thin	1.7	1.2×10^{-3}
Medium	1.4	0.8×10^{-3}
Dense	1.3	0.7×10^{-3}
Thick	1.5	1.1×10^{-3}

Table 4-4 Significant differences between mouton samples (upper triangle: MIU, lower triangle: MMD; **: P<0.01, *: P<0.05)

MMD \ MIU	Fine	Thin	Medium	Dense	Thick
Fine		**		**	
Thin			**	**	*
Medium					*
Dense		*			**
Thick					

4.5. Discussion

Correlation analysis and multi-regression analysis were performed to determine the mechanical property parameters which had an influence on the fabric handle: *DANRYOKU* and *KEGOMI* of sheepskin.

4.5.1. Relationship between *DANRYOKU* and Compression Properties

4.5.1.1. Correlation Analysis between Sensory Test and Compression Properties

Table 4-5 shows the simple correlation coefficients between the sensory test results and the compression property parameters measured by the 3D-TSMS. Perceived elasticity showed a strong positive correlation with LC, WC, T, and ΔE_{PR}, and a strong negative correlation with L and α_{max}. However, in the results of a test for no correlation, which was carried out due to the small number of samples, only LC, α_{max}, and ΔE_{PR} showed statistically significant differences.

Table 4-5 Simple correlation coefficient between perceived elasticity and compression properties

Characteristic value	Simple correlation coefficient for *DANRYOKU*	P
Compression linearity; LC	0.97	<0.01
Compression energy; WC	0.76	
Compression resilience; RC	0.28	
Thickness at the pressure 1gf/cm^2; T	0.79	
Compression distance; L	-0.71	
Flexibility coefficient; α_{max}	-0.93	<0.05
Pressure relieving energy; ΔE_{PR}	0.93	<0.05
Continuous mean deviation; CMD	-0.17	

LC correlated strongly with perceived elasticity and had a simple correlation coefficient of 0.97 (c.f. Figure 4-13 (a)). A higher LC value indicates the linearity of the compression curve due to compression and translates to greater perceived elasticity in the mouton when touched by a human hand as reflected in the 3D-TSMS measurement results. This is usually an indication of compressive hardness. It shows that LC corresponds to perceived elasticity because the convex load change that appears during the initial compression process contributes to the linearity of the compression curve similar to the *dense* mouton sample. Therefore, we have determined that one of the notable features of compression behavior for moutons which are perceived elastic is a convex shape curve during initial compression.

α_{max} was employed to express the ease of compression of a viscoelastic material. This is equal to the ratio of the compression strain divided by the pressure. α_{max} shows a high value for a large compression distance, as is seen at low pressure. The *thin* mouton samples have the highest α_{max} value, and this parameter corresponds to the tactile sensation when coming into contact with a mouton sample with poor perceived elasticity. α_{max} correlated negatively with perceived elasticity and had a simple correlation coefficient of -0.93. Therefore, it is believed that α_{max} is a negative mechanical parameter indicating the perceived elasticity of mouton.

ΔE_{PR} is the area of the hysteresis loop on the pressure-displacement curve which shows the amount of energy lost during a compress and recovery cycle. So, ΔE_{PR} was believed to be a negative indicator of the mouton recovery properties. Also, compressional resilience, RC, is known to be a parameter which represents the recovery properties of fabric. However, there was weak correlation between RC and perceived elasticity, while ΔE_{PR} correlated strongly with perceived elasticity and displayed a simple correlation coefficient of 0.93 (c.f. Figure 4-13 (b)). In the case of sheepskins, unlike the viscoelastic properties of general fabrics, it is considered that humans perceive elasticity when the gap between the compress energy and recovery energy is wide.

From the results of the above-mentioned correlation analysis, it is believed that humans perceive elasticity when the mouton is difficult to compress and has a low elastic restoration force. In other words, if energy applied to the mouton is absorbed by the deformation, friction, or interference of the mouton hair and elastic energy is reduced, the elasticity of the mouton is evaluated as being high.

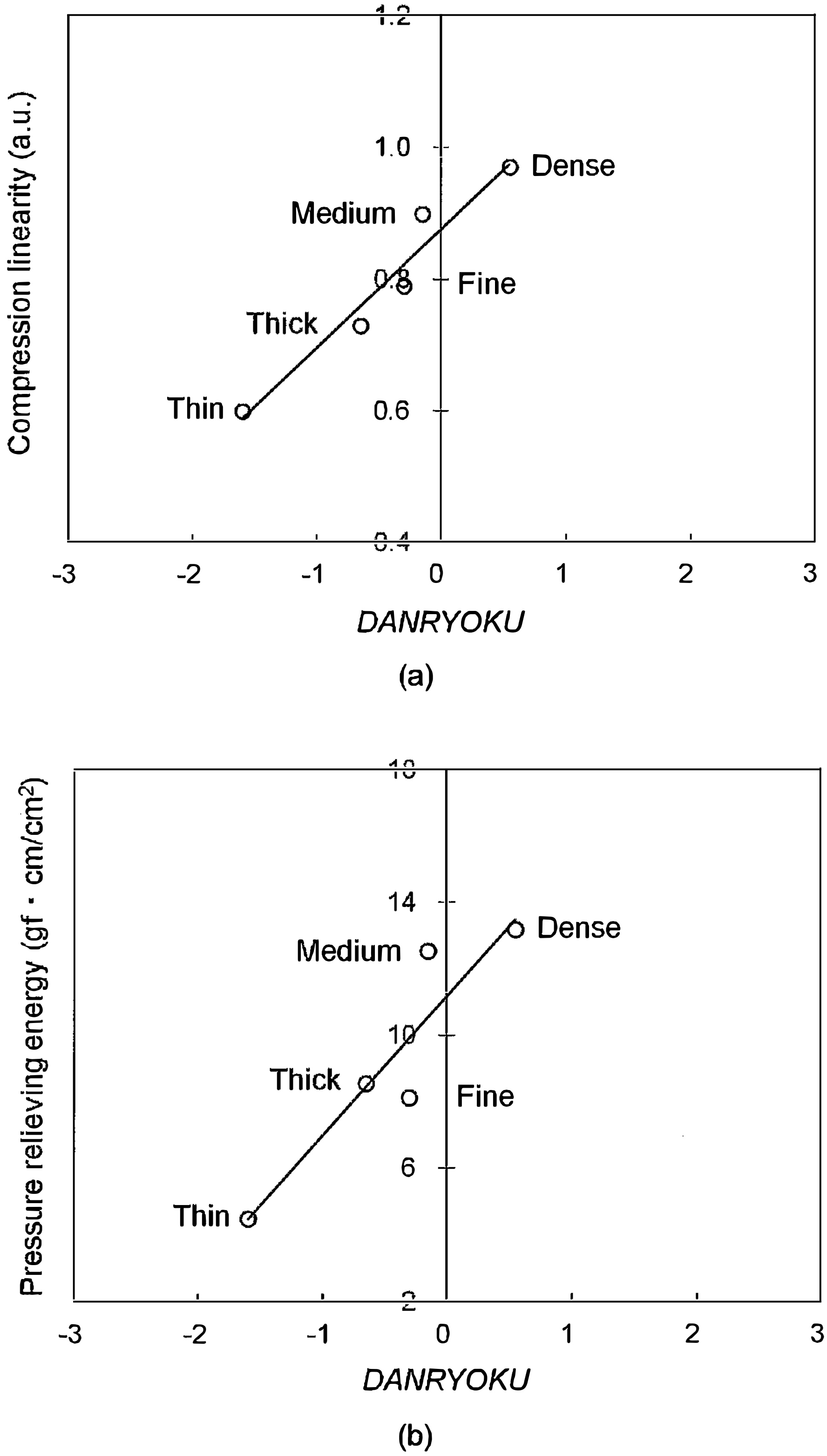


Figure 4-13 Relationships between *DANRYOKU* and compression properties: (a) compression linearity and (b) pressure relieving energy

4.5.1.2. Multiple Regression Analysis between Sensory Tests and Compression Properties

Multiple regression analysis was carried out to determine which variables influenced *DANRYOKU*. The dependent variable was the perceived elasticity and independent variables were the compression parameters provided by compression testing. A forward selection method was used to select variables, since the number of samples was lower than the number of variables. For the variable selection F-value, both F-in and F-out were 2.0, and the confidence interval was 95%. Table 4-6 shows the results of the multiple regression analysis.

Table 4-6 Results of the multiple regression analysis (independent variable: all compression parameters, variable selection: forward selection method, F-in: 2.0, F-out: 2.0, confidence interval: 95%)

Predictor	PRC	SPRC	F	T	P	SE	PC	SC
LC	5.34	0.98	1771.7	42.1	0.02	0.13	1.00	0.97
CMD	1.83	0.24	869.1	29.5	0.02	0.06	1.00	-0.17
α_{max}	-0.49	-0.09	16.2	-4.0	0.16	0.12	-0.97	-0.93
Constant	-4.76		722.5	-26.9	0.02	0.18		

PRC: Partial Regression Coefficient, SPRC: Standard Partial Regression Coefficient, SE: Standard Error, PC: Partial Correlation, SC: Simple Correlation

The variables LC, CMD, and α_{max} all turned out to influence the perceived elasticity. CMD showed a higher standard partial regression coefficient than α_{max}, even though it did not correlate with strongly the perceived elasticity. Also, as a result of the partial regression coefficient test, CMD was shown to be a significant variable at the 0.05 level. However, α_{max} made no significant difference on the dependent variable

(P>0.05), even though it correlated negatively with the perceived elasticity, and there was a multicollinearity between LC and α_{max} because both variables correlated strongly with each other (R: -0.94) and also α_{max} was inversely similar to the mechanical parameter LC. So, it was determined that α_{max} was inappropriate as a variable to explain the perceived elasticity.

4.5.2. Relationship between *KEGOMI* and Physical Properties

4.5.2.1. Correlation Analysis between Sensory Test and Surface Properties

Correlation analysis was carried out to determine the relationship between the sensory test results for *KEGOMI* and the physical property parameters of mouton.

Figure 4-14 shows the relationship between the hair density of mouton and *KEGOMI*. In general, it is considered that *KEGOMI* feeling relate closely with the hair density. As a result of correlation analysis, *KEGOMI* correlated strongly with the hair density (R=0.93, P<0.05). However, moutons samples were divided by two groups. In particular, the sensory test values for *thin* and *thick* showed opposite results for their hair density, even though they had no significant difference. Therefore, it was hard to describe *KEGOMI* as only hair density.

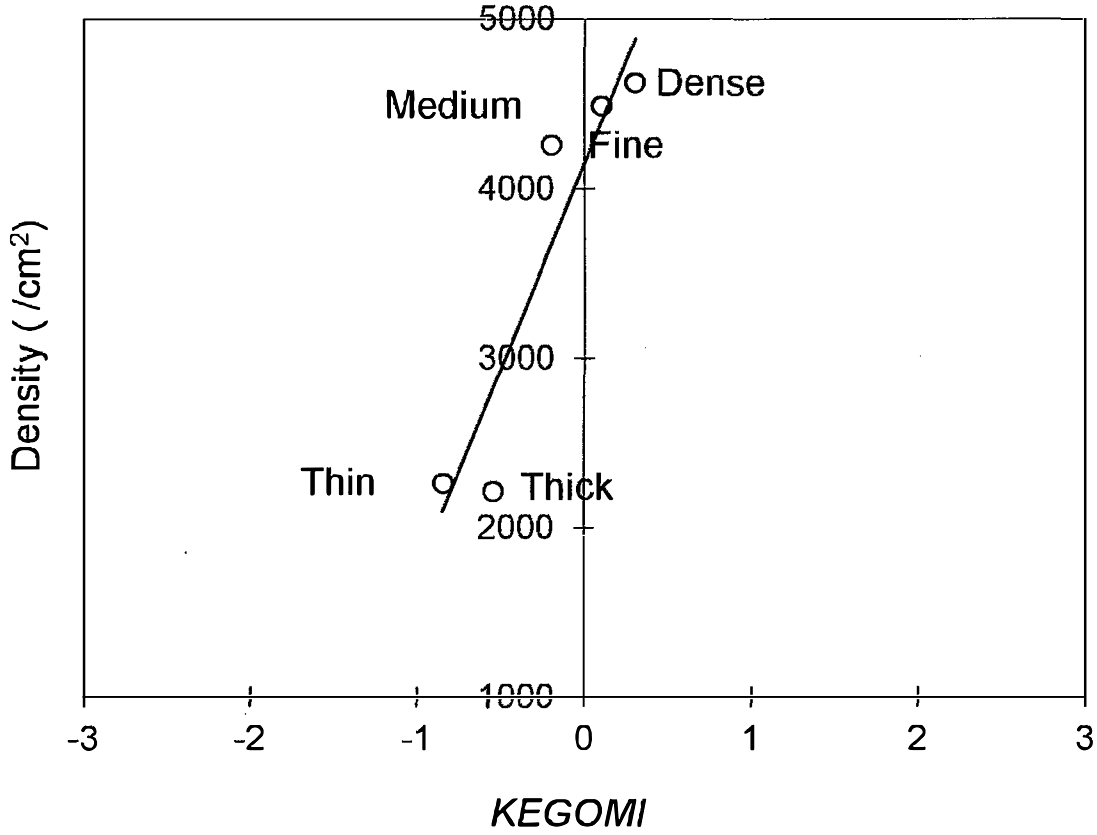


Figure 4-14 Relationship between hair density and *KEGOMI*

Figure 4-15 shows the relationship between MIU and *KEGOMI*. As a result of correlation analysis, *KEGOMI* correlated strongly with MIU ($R=-0.98$, $P<0.01$). *Dense* was evaluated as the highest *KEGOMI* mouton and showed the lowest MIU value. It was considered as follows: When the sensor tip compressed the surface of mouton, which had high hair density, with 30gf of load, it contacted the mouton hairs in a shallow condition. Therefore, the frictional force between the sensor tip and the surface of mouton hairs became small. And also, the friction coefficient showed low value, since the raised mouton hairs were even. In the case of *thin* mouton, on the contrary, since the sensor tip contacted the mouton hairs in a deep condition, frictional force was increased. *Thick* mouton, which was evaluated as having more *KEGOMI* than *thin* mouton in sensory tests, showed higher MIU value than *thin*, even though they had similar hair density.

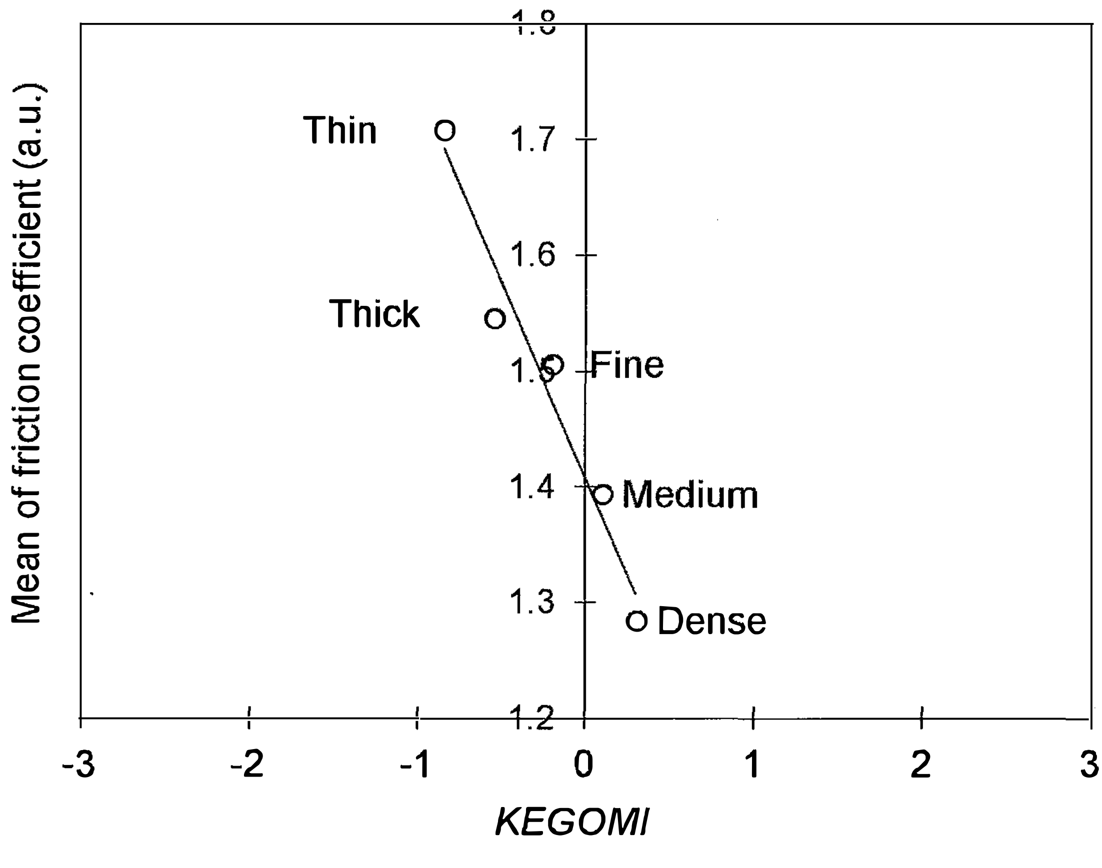


Figure 4-15 Relationship between mean of friction coefficient (MIU) and *KEGOMI*

Figure 4-16 shows the relationship between mean deviation of friction coefficient (MMD) and *KEGOMI*. As a result of correlation analysis, *KEGOMI* had strong negative correlation with MMD (R=-0.99, P<0.01). MMD shows the variance of the waveform of friction coefficient curve. Low MMD value means that mouton hairs are raised with good evenness. *Dense* mouton showed the lowest MMD value and was rated as having the most *KEGOMI*. It was considered that the hairs of *dense* mouton were dense and even. In the case of *thin* mouton, on the contrary, it was considered that MMD value was higher than *thick*, which had similar hair density to *thin* mouton, because *thin* mouton had low hair density and uneven hairs.

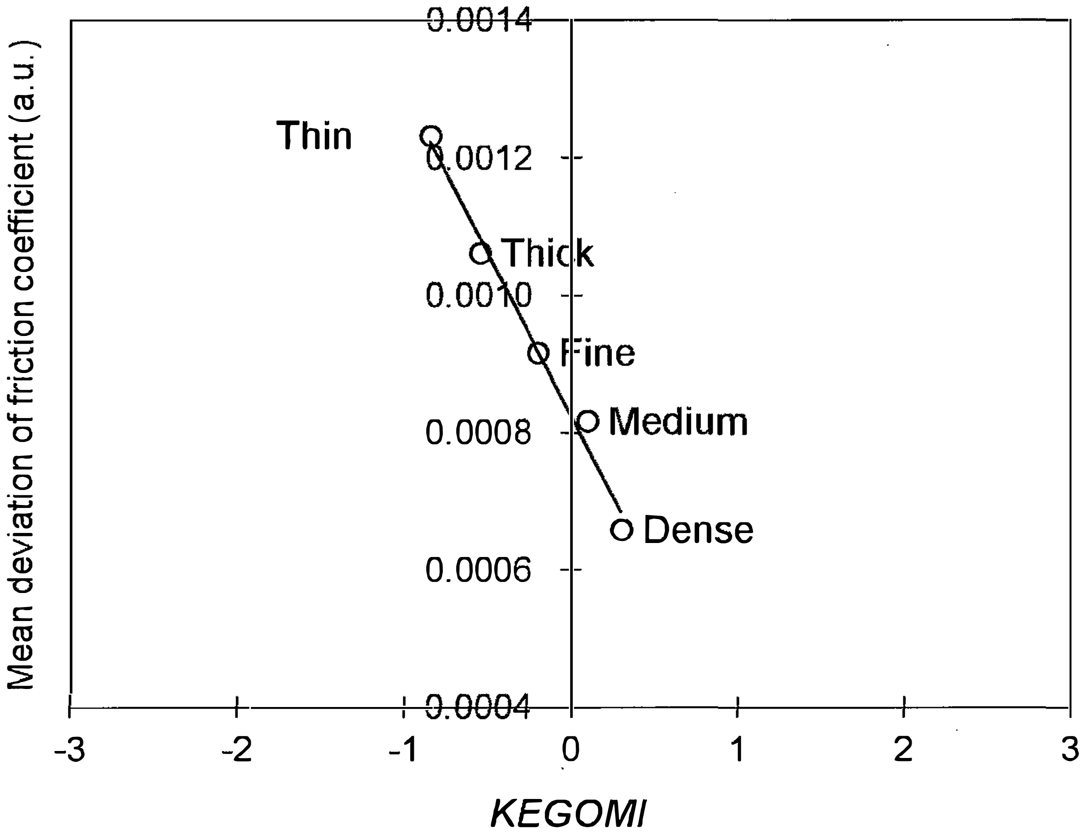


Figure 4-16 Relationship between mean deviation of friction coefficient (MMD) and *KEGOMI*

From the above discussions, it was determined that the perceived *KEGOMI* is the sense caused by multiple factors which are related to the hair density and hair behaviors of mouton. Also, it was considered that *KEGOMI* evaluation, which was based on the human tactile sense, was made possible by measuring the mean of friction coefficient (MIU) and the mean deviation of friction coefficient (MMD) using 3D-TSMS for *KEGOMI*.

4.5.2.2. Multiple Regression Analysis between Sensory Tests and Surface Properties

Multiple regression analyses were carried out to determine which variables influenced *KEGOMI*. The dependent variable was the perceived *KEGOMI* and independent variables were the hair density, the mean of friction coefficient (MIU), and the mean deviation of friction coefficient (MMD). Tables 4-7, 8, and 9 show the results of multiple regression analyses. Table 4-10 shows the accuracy of each analysis.

All independent variables were appropriate as variables to explain the *KEGOMI*, because the hair density was less than 0.05 of P value, and MIU and MMD were less than 0.01 of P value. It was determined that MIU and MMD were closely related to *KEGOMI*, because both variables were more than 0.9 of adjusted multiple determination coefficient. From these results, it was considered that *KEGOMI* was influenced a great deal by the frictional properties of mouton hairs not only hair density. In particular, MMD showed the highest value of standard partial regression coefficient which represented the impact of the independent variables on dependent variable. However, from the results of multiple comparison (c.f. Table 4-4), MMD showed few significant differences between each mouton sample and the measurement values of

Table 4-3 were small. Therefore, it was considered that MIU was a more appropriate parameter for the quantitative evaluation of *KEGOMI* than MMD.

Table 4-7 Result of multiple regression analysis (independent variable: density, confidence interval: 95%)

Predictor	PRC	SPRC	F	T	P	SE	PC	SC
Density	3.56E-04	0.9291	18.9389	4.3519	0.0224	8.18E-05	0.93	0.93
Constant	-1.51311		24.4668	-4.9464	0.0159	0.3059		

Table 4-8 Result of multiple regression analysis (independent variable: average of friction coefficient, confidence interval: 95%)

Predictor	PRC	SPRC	F	T	P	SE	PC	SC
MIU	-2.8619	-0.9791	69.5120	-8.3374	0.0036	0.3433	-0.98	-0.98
Constant	4.0180		61.3281	7.8312	0.0043	0.5131		

Table 4-9 Result of multiple regression analysis (independent variable: mean deviation of friction coefficient, confidence interval: 95%)

Predictor	PRC	SPRC	F	T	P	SE	PC	SC
MMD	-2103.71	-0.9931	214.1831	-14.6350	0.0007	143.7452	-0.99	-0.99
Constant	1.7330		158.2153	12.5784	0.0011	0.1378		

Table 4-10 Accuracy of multiple regression analyses

Predictor	Density	MIU	MMD
Multiple determination coefficient	0.86	0.96	0.99
Adjusted multiple determination coefficient	0.82	0.95	0.98
Multiple correlation coefficient	0.93	0.98	0.99
Adjusted multiple correlation coefficient	0.90	0.97	0.99

4.6. Conclusions

In this study, we measured the compression and surface properties using a three-dimension tactile sensation measurement system (3D-TSMS), which consists of a Cartesian manipulator and a three-axis force sensor.

As the results of compression test, seven parameters were calculated to indicate the compression properties of sheepskin as follows: compression linearity, compressional energy, compressional resilience, thickness, compression distance, compressional flexibility coefficient, and pressure relieving energy from the vertical pressure-displacement curve. In addition, the continuous mean deviation was calculated from the load-displacement curve in the resultant X-Y plane force and the Z-axis displacement. The sensory test results of *DANRYOKU* (perceived elasticity) of five kinds of sheepskin were statistically compared with eight compression property parameters. In statistical analysis results, compression linearity turned out to be the most influential mechanical parameter on perceived elasticity, as highly elastic sheepskin displayed a convex shape curve during the initial compression process which contributed to the linearity of the compression curve. The load applied vertically on the mouton hair was transferred horizontally. During this process, the applied energy was absorbed through interaction with the mouton hairs via bending deformation, friction, and interference. These behaviors disturbed the recovery of hairs. This phenomenon was reflected in continuous mean deviation and pressure relieving energy. Therefore, *DANRYOKU* of sheepskin could be evaluated by the measurement of compression linearity, continuous mean deviation, and pressure relieving energy.

In the surface test, the mean of friction coefficient and mean deviation of friction coefficient were calculated to indicate the surface properties of sheepskin by the measurement of the friction coefficient variations. The sensory test results of *KEGOMI* (feeling for the richness and fullness of hairs) of five kinds of sheepskin were statistically compared with the both surface property parameters. As the statistical analysis results, *KEGOMI* was influenced a great deal by the resistance, which was represented in the friction property, and it was related to the mean of friction coefficient and mean deviation of friction coefficient. It was determined, particularly, that the mean of friction coefficient was a useful parameter to evaluate *KEGOMI* quantitatively. Humans perceived the richness and fullness of sheepskins when their hairs were dense and even.

Furthermore, it was verified that the 3D-TSMS was a useful instrument as a hand evaluation device for the compression and surface properties of thick-pile fabrics that accurately reflects the sensorial properties of the human hand.

CHAPTER 5

Conclusions

5. Conclusions

This thesis was written with two major goals in mind. The first goal was to clarify how the deterioration or changing of the texture of thick fabrics, which touch the skin directly, influences psychological and physiological response. The second goal was the development of a new hand evaluation measurement system which reflected the human tactile sense as well as being able to measure the physical properties of thick fabrics.

The subjective perception of comfort of clothing by a wearer or user is determined by psychological and physiological processes, which are evoked by various physical stimuli. Many works have been carried out to estimate the psychological response using sensory tests and to measure the physical properties using textile test standards as well as the KES method. However, there are few studies on the physiological response to texture deterioration.

In Chapter 2, I discussed the physiological and psychological responses to the deterioration of the texture of pile cloths due to washing. In the case of babies and disabled people, cloths are used passively and it is considered that passive touch has more influence on the physiological response. Therefore, multiple washed pile cloth samples were prepared for this research and sensory tests were passively carried out to investigate the psychological response. In order to figure out the influence on the physiological response, the indexes of the activity of the autonomic nervous system were measured.

As a result of physical property tests, there was a threshold of washing frequency at which the texture of towel cloth deteriorated rapidly: Washed between 10 and 30 times in this study. This physical behavior corresponded approximately to physiological and psychological responses. Furthermore, the texture of deteriorated pile cloth caused sympathetic nerve activation. In other words, the texture of pile cloth is deteriorated after the threshold of washing frequency and deteriorated texture gives stress.

As a result of correlation analyses, RC, SMD, and water absorption correlated strongly with LF/HF and HF/(HF+LF) ratio. Therefore, the autonomic nervous system response could be estimated from the measurement of material properties such as surface property, compression property, and water absorption. Among these material property parameters, SMD particularly corresponded to both physiological and psychological response.

However, MIU did not represent the deterioration of pile cloth due to washing, even though it was the one of the friction parameters, because the static load of MIU measurement module was not able to adjust for the specific load when humans evaluated the texture of pile fabrics. Therefore, this issue was considered in a new fabric handle measurement system (Chapter 4): Three-dimensional tactile sensation measurement system (3D-TSMS).

In Chapter 3, I discussed the influence of sweat absorbent liners on helmet comfort. The sweat absorbent liner (SAL) plays the roles of giving the helmet fit and the sweat absorption. Helmet comfort changes due to the sweating during work or exercise. When wearing a helmet, touch is also passive. However, the hand evaluation, which is an active touch, plays an important role in the expectations for helmet comfort both when helmet makers design a helmet and when users purchase a helmet. Therefore, the effects of the physical properties of the SAL on helmet comfort were investigated and forehead feel was statistically compared with hand feel.

As results of experiments, the effects of the mechanical properties of the SAL on fabric hand using hand feel and helmet comfort were concluded as follows: "muggy feel" and "rough feel" are the principle components that affect psychological responses to how SAL affects helmet comfort. Particularly, "muggy feel" is the most principle component. The roughness component in particular consists of the following: (a) "cool" and "soft" feel when wearing the safety helmet; (b) "gentle on skin" at initial perspiration; (c) "feels good" and "gentle on skin" at maximum perspiration; (d) "fine", "not lumpy", and "gentle on skin" when put on again after a break.

If we optimize the SAL surface roughness properties, it would be possible to improve helmet comfort. SAL with a lower mean deviation of friction coefficient measured by KES-FB4 and good water absorbency enhance helmet comfort. However, it is difficult to enhance the hygrothermal comfort of safety helmets through modification of the SAL. Hand feel evaluation of the SAL fabric, which is active touch, is effective in predicting the helmet comfort, which is passive touch.

In Chapter 4, a new hand evaluation measurement system, three-dimensional tactile sensation measurement system (3D-TSMS) was suggested. I tried to verify this system by carrying out the evaluation of sheepskin (mouton) handle. 3D-TSMS was composed of a three-dimensional Cartesian manipulator and a three-axis force sensor module to imitate the human palpate motions and tactile sense. The manipulator is able to make up-and-down and back-and-forth as well as rotation movements. The force sensor can measure the applied loads contacting the object in three axial directions. Also, the sensor module is interchangeable in accordance with the intended evaluation. Therefore, 3D-TSMS is expected to be a tester which is able to measure the fabric handle of thick-pile fabrics.

Sheepskins are evaluated in Japan using unique evaluation terms such as *DANRYOKU* (perceived elasticity), *KEGOMI* (richness and fullness of hair), *KESABAKI* (smoothness and softness of hair), etc. Therefore, it is necessary to measure the fabric hand properties of sheepskin mechanically. For this study, *DANRYOKU* and *KEGOMI* were focused on and the relationship between the tactile sensation and the mechanical properties of sheepskin were determined.

As the results of compression test for the evaluation of *DANRYOKU*, seven parameters were calculated to indicate the compression properties of sheepskin as follows: compression linearity (LC), compressional energy (WC), compressional resilience (RC), thickness (T), compression distance (L), compressional flexibility coefficient (α_{max}), and pressure relieving energy (ΔE_{PR}: area of hysteresis loop) from the vertical pressure-displacement curve. In addition, the continuous mean deviation (CMD) was calculated from the load-displacement curve in the resultant X-Y plane force and the Z-axis displacement. The sensory test results of *DANRYOKU* of five kinds of sheepskin were statistically compared with eight compression property parameters. In statistical analysis results, LC turned out to be the most influential mechanical parameter for *DANRYOKU*, as highly elastic sheepskin displayed a convex shape curve during the initial compression process which contributed to the linearity of the compression curve. The load applied vertically on the mouton hair was transferred horizontally. During this process, the applied energy was absorbed through interaction with the mouton hairs via bending deformation, friction, and interference. These behaviors disturbed the recovery of hairs. This phenomenon was reflected in the continuous mean deviation and pressure relieving energy. Therefore, *DANRYOKU* of sheepskin could be evaluated by the measurement of LC, CMD, and ΔE_{PR}.

In the surface test for the evaluation of *KEGOMI*, mean of friction coefficient (MIU) and mean deviation of friction coefficient (MMD) were calculated to indicate the surface properties of sheepskin by the measurement of the friction coefficient variations. The sensory test results of *KEGOMI* for five kinds of sheepskin were statistically compared with the both surface property parameters. As the statistical analysis results, *KEGOMI* was influenced a great deal by the resistance, which was represented in the friction property and it was related to MIU and MMD. In particular, MIU was a useful parameter to evaluate the *KEGOMI* quantitatively. Humans perceived the richness and fullness of sheepskins when their hairs were dense and even.

Furthermore, it was verified that the 3D-TSMS was a useful instrument as a hand evaluation instrument for the compression and surface properties of thick-pile fabrics that accurately reflects the sensorial properties of the human hand.

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