1. INTRODUCTION

The present paper investigates the sensation of clothing comfort felt by the wearer in terms of psychophysiological responses, by making psychological evaluations and measuring autonomic nervous activity indices.

Undershirts strongly affect clothing comfort because they are in close contact with the human body. There are three main factors that determine the clothing comfort of garments: the climate within the clothing, the texture of the clothing, and pressure acting on the clothing [1]. Highly functional yarns and fabrics have been developed to make comfortable undershirts.

Not only the material properties of the fabric, but also how the person wearing the undershirt feels is important. It is necessary to measure and evaluate the clothing comfort sensation in response to various complicated changes in situations, owing to exercise and temperature differences.

A number of studies have evaluated undershirts through subjective evaluation of the psychological sensation felt during the wearing of clothing and through measurement of physiological responses, such as measurement of changes in the skin surface temperature and humidity within the clothes [2,3]. However, it is not completely known how the physical properties of the cloth affect the clothing comfort sensation felt by the wearer.

In addition, attempts have been made to use not only the subjective sensation, but also the responses of the autonomic nervous system in evaluating clothing comfort. As an example, when comparing the heart rate variability power spectrum between wearing comfortable pajamas and wearing uncomfortable (wrinkling) pajamas, the high-frequency (HF) power tends to be greater when wearing comfortable pajamas [4].

Other studies have measured the heart rate variability and fingertip blood flow when physical properties of the clothing substrate change through processing, such as softening and gluing [5]. It has been shown that a glued sample generates large discomfort and a high degree of nervousness.

A previous study [6] investigating heat and moisture transfer characteristics of undershirts compared electrocardiograms (ECGs) of participants wearing a polypropylene (PP) with quick-drying polyester blend undershirt or a PP with hygroscopic wool blend undershirt. It was found that it was difficult to enhance the sympathetic nerve activity of the participant wearing the polyester blend undershirt having good moisture transport characteristics. Another study [7] reported the possibility that the sympathetic nervous activity is lower after exercise when wearing an undershirt with a quick-drying material blend, compared with the case of wearing a cotton undershirt.

The above studies suggest the effectiveness of evaluating the clothing comfort sensation by measuring the activity of the autonomic nervous system. However, in previous studies, the stimulation conditions of the samples were simplistic and remarkably different. The effectiveness of measuring and evaluating physiological responses for undershirts having similar properties has not been completely clarified.
In the present research, therefore, we prepared undershirts having the same hydrophobic materials and similar other material properties, namely PP and polyester (polyethylene terephthalate, PET). We measured the psychological and physiological responses of the state of sweating induced by exercise as a complex situation when participants wore the undershirts. We investigated to what extent subtle differences in the physical properties affect the sensation of clothing comfort felt by the wearer and indices of the autonomic nervous systems, related to the sensation of clothing comfort, when participants wore undershirts made from similar materials and perspired. This study was conducted with the approval of Shinshu University’s ethical committee for research on humans.

2. MATERIALS AND METHODS

2.1 Materials

The yarn samples were two types of yarn: PP and PET yarns. Generally, a highly absorbent fiber material such as cotton is used for undershirts, but this research has the background of aiming at the design of undershirts that allow moisture to easily transport from the skin side to the outside when sweating. Therefore, we used hydrophobic fibers such as PET and PP as the materials. Table 1 gives the specifications of the two types of yarn. Knitted fabric shirts were prepared using these yarns on the skin side.

Table 2 gives the knitting structure of the undershirt samples and the mixing ratio of the materials used in the fabrics. Two types of turtleneck T-shirt were made. The knitting structures were unified with two-layer structures of honeycomb on the skin side and a plain stich on the outside (Figure 1). On the outside, all samples were unified with PET, and the material on the skin side differed depending on the sample. The skin side of the PET/PP structure was PP yarn while the skin side of the PET/PET structure was PET yarn.

2.2 Material properties of samples

The surface, thermal transport, moisture management, and air permeability properties, which are closely related to the comfort sensation felt when the wearer perspires, were measured. Table 3 gives the mean values and standard deviations of the material properties and results of significant differences between samples obtained in a Student’s t-test. All experiments were conducted at 20±1 °C in an environment with relative humidity of 65%±3%. These environmental conditions were in accordance with the relevant Japanese Industrial Standard. The specimens were kept in the described environment for at least 24 h before measurements were carried out. Each measurement was made five times, and the mean value and standard deviation were calculated.

As surface characteristics, the mean value of the dynamic friction coefficient (MIU), standard deviation of the dynamic friction coefficient (MMD), and surface roughness of fabrics (SMD) [µm] were measured using a KES-FB4 surface tester (Kato Tech, Inc., Kyoto, Japan) [8].

The thermal transport properties of the fabrics were evaluated using a KES-F7 Thermo-Lab (Kato Tech, Inc., Kyoto, Japan) [9]. The measured property indices were q-max [W/cm²] (i.e., the heat flux of thermal conduction when the sample was touched by the testing board), thermal conductivity [W/(m·K)] (i.e., the rate of heat flow through a unit area and unit thickness of the fabric when there is a temperature difference between the two sides of the specimen), and the insulation rate [%].

The moisture management properties of the fabric samples were evaluated employing two methods: using a moisture management tester (MMT; SDL Atlas, Inc., South Carolina, USA) and the BOKEN method (BQE A 028) [10]. The BOKEN method (BQE A 028) was used to measure the wicking and drying rate [%].

Table 1: Specifications of the yarn samples

| Yarn    | Material            | Diameter [mm] | Twist factor [-] | Porosity [%] | The number of hairiness [n/10m] | Elongation [%] |
|---------|---------------------|---------------|------------------|--------------|---------------------------------|---------------|
| PP      | Polypropylene spun yarn 100% | 0.221         | 3.53             | 56.4         | 0                               | 21.9          |
| PET     | Polyester spun yarn 100%    | 0.209         | 3.27             | 52.2         | 1                               | 13.1          |

Table 2: Knitting structure of the undershirt samples and mixing ratio

| Fabric sample | Knitting structure and material | Total mixing ratio [%] |
|---------------|--------------------------------|------------------------|
| Outside:      | Skin side:                     |                        |
| Plain stich   | Honeycomb                      |                        |
| PET/PP        | Polyester yarn 100%            | Polypropylene yarn 100%| Polyester 44% / Polypropylene 56% |
| PET/PET       | Polyester yarn 100%            | Polypropylene yarn 100%| Polyester 100% |

Figure 1: The knitting structure of fabric samples; (a) outside of fabrics (plain stich), (b) skin side of fabrics (honeycomb)
The air permeability of each fabric sample was measured using a KES-F8 tester (Kato Tech, Inc., Kyoto, Japan) [11]. The measured property index was the air flow resistance [kPa·s/m]. We also measured the geometrical properties; thickness [mm] and weight [g/m²] of the fabrics. The fabric thickness was determined using a KES-FB3 tester (Kato Tech, Inc., Kyoto, Japan). The weights of fabrics were calculated by weighing 100-mm-square specimens with an electronic balance.

The Student's t-test was carried out on all measured indices and property values.

The above measurements of the material properties of PET/PP and PET/PET samples revealed the following features. PET/PP has characteristics of a low dynamic friction coefficient and low surface roughness (SMD). PET/PP has significantly lower thermal conductivity than PET/PET, even though q-max of PET/PP is higher. In addition, because values of the accumulative one-way transport index and wicking and drying rates are larger, PET/PP has strong moisture transfer from the skin surface to the outside. In the previous study [6], the thermal conductivity was significantly different (thermal conductivity; 0.596 - 0.783 [W/(m·K)]). In addition, the wicking and drying rates of the previous study was about twice that of 20.0 to 11.8 [%]. There were larger differences than the ranges of this study.

PET/PET is thicker and has a higher insulation rate. In addition, it has lower air flow resistance and thus higher air permeability. However, in the previous study [7], there was a much bigger difference in the values of the air flow resistance (air flow resistance; 0.041 - 0.084 [kPa·s/m]).

The two samples used in this study showed some significant differences between the samples due to the small variance of the measured data, but it is considered that the samples do not have absolute large differences.

### 2.3 Methods

An experiment was performed to evaluate the psychophysiological responses of participants wearing two types of undershirt sample having different characteristics.

Ten healthy male college students participated in the experiment (age: 21.8 ± 0.8 years, height: 173.7 ± 7.2 cm, mass: 64.2 ± 4.8 kg, body mass index: 21.3 ± 1.6). The participants were advised to refrain from eating food for 2 h before the experiment, from consuming alcohol for 24 h before the experiment, and from consuming caffeine on the day of the experiment [12]. Each participant followed the experimental procedures for one sample per day, taking 2 days in total to complete the experiment. The experiment was carried out at the same time of day in consideration of the circadian rhythm of humans, to avoid potential bias resulting from the effect of thermoregulation [13].

The participants first changed clothes, putting on a T-shirt (100% cotton) and bottoms (cotton 54% and polyester 46%) to ensure the same initial state. The participants then

| Material property                  | PET/PP Mean ± SD | PET/PET Mean ± SD | Significant difference by Student’s t-test |
|------------------------------------|------------------|-------------------|------------------------------------------|
| Weight mass per area [g/m²]        | 157.2 ± 2.1      | 164.8 ± 3.0       | **                                       |
| Thickness thickness [mm]           | 1.09 ± 0.01      | 1.38 ± 0.01       | **                                       |
| Surface MIU: Mean value of dynamic friction coefficient [-] | 0.222 ± 0.003 | 0.378 ± 0.003 | **                                       |
| MMD: Deviation of dynamic friction coefficient [-] | 0.010 ± 0.001 | 0.011 ± 0.001 | **                                       |
| SMD: Surface roughness [µm]       | 4.85 ± 0.28      | 6.87 ± 0.22       | **                                       |
| Thermal transport                  |                  |                   |                                          |
| q-max [W/m²]                       | 824 ± 13         | 678 ± 4           | **                                       |
| Thermal conductivity [W/(m·K)]     | 0.0604 ± 0.001   | 0.0664 ± 0.000    | **                                       |
| Insulation rate [%]                | 24.7 ± 1.3       | 30.3 ± 0.4        | **                                       |
| Wicking and drying rate [%]        | 26.5 ± 4.0       | 19.3 ± 2.5        | *                                        |
| Wetting Time (skin side) [sec]     | 4.66 ± 2.37      | 13.16 ± 4.52      | *                                        |
| Wetting Time (outside) [sec]       | 1.78 ± 0.31      | 1.48 ± 0.23       | *                                        |
| Absorption rate (skin side) [%/s]  | 14.2 ± 4.3       | 39.4 ± 8.8        | **                                       |
| Absorption rate (outside) [%/s]    | 62.3 ± 12.3      | 44.8 ± 2.9        | *                                        |
| Maximum wetted radius (skin side) [mm] | 9.0 ± 2.2      | 15.0 ± 0.0        | **                                       |
| Maximum wetted radius (outside) [mm] | 30.0 ± 0.0      | 21.0 ± 2.2        | **                                       |
| Spreading speed (skin side) [mm/s] | 1.57 ± 0.65      | 1.17 ± 0.30       | **                                       |
| Spreading speed (outside) [mm/s]   | 8.73 ± 0.41      | 3.81 ± 0.47       | **                                       |
| Accumulative one-way transport index [%] | 1509 ± 166 | 717 ± 113         | **                                       |
| Air permeability Air flow resistance [kPa·s/m] | 0.041 ± 0.002 | 0.035 ± 0.001 | **                                       |

(**p<0.01, *p<0.05)
entered a room with a constant temperature and relative humidity of 20 °C and 65% respectively, and rested for 15 min to allow their bodies to adjust to the temperature. ECG electrodes were then attached to the participants’ skin. The ECG was attached via a bipolar chest lead and the signal was amplified by an ECG100C amplifier (BIOPAC Systems, Inc., Goleta, CA, USA). Temperature and humidity sensor electrodes (Hygrochron; KN Laboratories, Inc., Osaka, Japan) were also attached to four parts of the body (i.e., the left side of the chest, the abdomen, the upper back, and the lower back) to measure the mean skin surface temperature and the mean humidity within the clothes. A pulse measurement transducer (TSD200-MRI; BIOPAC Systems, Inc.) was attached to each participant’s right index finger, and the transducer was amplified by a PPG100C amplifier (BIOPAC Systems, Inc.) to measure the finger plethysmogram. The location of these sensors attached to the body is shown in Figure 2.

Each participant randomly wore one of the two sample undershirts. The experiment took 60 min in total (Figure 3). Each participant first rested for 20 min and then exercised on an aero bike (75XLIII; Konami Sports Life Co., Ltd., Kanagawa, Japan) for 10 min at an intensity of 55% – 65% of their maximum heart rate [bpm], calculated using the expression “220 – age in years”. After exercising, each participant rested again for 30 min. The maximum heart rate value was taken as a guide to moderate aerobic exercise in daily life [14].

During the 60-min duration of the experiment, we measured each participant’s physiological and psychological responses, to evaluate the comfort sensation when the two sample undershirts were worn and to investigate the autonomic nerve activity of the participant.

Temperature and humidity sensors were used to measure the mean skin surface temperature and the mean humidity within the clothing throughout the 60-min experiment. The average value of the temperature at the four points of the upper body (i.e., the chest, abdomen, upper back, and lower back) was calculated as the skin surface temperature. Similarly, the average value of the humidity at the four points of the upper body was calculated as the humidity within the clothing.

We employed the semantic differential method for psychological measurements. The sensations felt by the participants were measured five times in total at intervals of 10 min, except while exercising. There were nine evaluation term pairs: Hot – Cool, Sticky – Slippery, Stuffy – Dry, Rough – Smooth, Hard – Soft, Heavy – Light, Thick – Thin, Poor texture – Good texture, and Uncomfortable – Comfortable. The evaluation scale comprised seven levels (i.e., extremely, very, slightly, neither, slightly, very, and extremely), and a score of −3 to +3 was given to quantify the evaluation. In the present study, the term “stuffy” is defined as the sensation of sweatiness due to heat and humidity. This term translates as “mure” in Japanese. Poor texture–Good texture is the total contact sensation felt by the contact between the skin surface and fabrics. In addition to the other mechanical properties (Rough – Smooth, Hard – Soft, Heavy – Light, Thick – Thin), we also prepared this term to evaluate the overall contact sensation.

To monitor the physiological responses, ECG signals and a finger plethysmogram were recorded a total of five times at intervals of 2 min.

The above signals were sampled at a frequency of 2000 Hz. The results from the ECG, which measures activity of the autonomic nervous system, were analyzed, together with the thermophysical indices and psychological response data. Time-series data pertaining to the time between adjacent R waves (i.e., the R–R interval) were obtained, and the electrocardiographic RR interval (CVRR) was calculated using the coefficient of variation (CV) of the value of the R–R interval for each period of 2 min. The CVRR expresses the fluctuation of the heartbeat, with a higher value indicating an increase in parasympathetic nerve activity [15]. In addition, time-series data pertaining to the time between R–R intervals were obtained, and a spline interpolation was
performed. The integral ratio of the spline curve from the fast Fourier transform analysis was obtained by dividing the integral of low frequency (LF) (0.04–0.15 Hz) by the integral of HF (0.15–0.40 Hz) on the power spectrum. LF/HF was calculated as the ratio of LF and HF. LF/HF is a sympathetic nerve activity index, and the stress experienced is considered to increase with the value of the index [16].

The rising point during each beat was calculated from the pulse wave obtained by the pulse measurement transducer. The time difference between the value of the pulsation and the R wave of the electrocardiogram was obtained, and the pulse transit time (PTT) was calculated. The PTT is negatively correlated with blood pressure because the pulse wave transit time becomes shorter with vasoconstriction, and it was measured as an index of the blood pressure fluctuation. MATLAB software (MathWorks, Inc., Natick, MA, USA) was used in the analysis.

3. RESULTS

3.1 Physical conditions of the wearing state

Figure 4 depicts the mean skin surface temperatures. The values are means for the 10 participants. A two-way factorial analysis of variance was performed on the mean values of the absolute skin temperature every 10 min with two factors (i.e., the sample and time). There were two levels of sample (i.e., PET/PP, and PET/PET) and seven levels of time (i.e., 0, 10, 20, 30, 40, 50, and 60 min). Two-way analysis of variance revealed a significant difference in the factor of time (p<0.01). The temperatures of both samples increased significantly for 10 min from the start. The value for PET/PP was consistently larger than that for PET/PET over the 60 min of the experiment.

Table 4 gives the calculated difference between the maximum temperature before exercise and the minimum temperature after exercise. The temperature decreased after exercise for both samples. The difference between the maximum temperature before exercise and the minimum temperature after exercise was 0.63 °C for PET/PP and 0.83 °C for PET/PET.

Figure 5 shows the average humidity within the clothing for 10 participants over the course of the experiment. A two-way analysis of variance revealed a significant difference in the factor of time (p<0.01). For both samples, the humidity suddenly increased immediately after exercise. Afterward, the humidity dropped to a neutral level.

It was confirmed that the participants perspired as a result of exercise, and the perspiration generated a physical stimulus, such as a decrease in the skin surface temperature and a rapid increase in humidity within the clothes after exercise.

3.2 Psychological sensations

3.2.1 Changes in the exercise/rest process

Results of the psychological sensations due to changes in the pre-resting, exercise, and post-resting process are first described.

Average values and standard deviations of the data obtained for all evaluation term pairs in the semantic differential method were calculated for each of the 10 participants. Figure 6 shows the average values of the evaluation terms at each moment in time. A larger value indicates a more positive impression.
Evaluation values presented in Figure 6(c) for the time after exercise are smaller than those presented in Figure 6(a) and (b) for the pre-rest time. The psychological impression also changed significantly before and after exercise as in physical conditions; the skin surface temperature and the humidity within the clothing.

A two-way factorial analysis of variance was performed for all evaluation terms in each 10-min interval with two factors (i.e., the sample and elapsed time). Results are presented in Table 5. There were two levels of sample (i.e., PET/PET and PET/PET) and five levels of time (i.e., 0, 10, 30, 40, and 50 min). There was no significant interaction for any term pair. There were significant differences in evaluation terms except for Rough – Smooth and Hard – Soft in the factor “time”. When sweating, the roughness and hardness sensations of the undershirts did not change significantly. However, sensations of discomfort, such as a hot sensation, stuffy sensation, and sticky sensation, were greatly strengthened by exercise. Following these sensations, the overall sensations of texture and comfort also deteriorated.

A multiple regression analysis was performed to investigate which psychological factors make up the comfort sensation. The Uncomfortable–Comfortable pair was used as objective variables, and the remaining evaluation terms were adopted as explanatory variables using the data of all time zones. The analysis adopted the stepwise method of the statistical analysis software R (R Core Team (2019). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.).

Table 6: Multiple regression analysis for all time zones

| Coefficients     | Partial regression coefficient | Std. Error | t value | p value       |
|------------------|--------------------------------|------------|---------|---------------|
| (Intercept)      | 0.103                          | 0.061      | 1.682   | 0.096         |
| Stuffy – Dry     | 0.385                          | 0.060      | 6.409   | **< 0.05**    |
| Poor texture – Good texture | 0.413          | 0.074      | 5.583   | **< 0.05**    |
| Rough – Smooth   | 0.173                          | 0.066      | 2.615   | 0.010*        |
| Thick – Thin     | -0.098                         | 0.063      | -1.557  | 0.123         |

Multiple R-squared: 0.752
Adjusted R-squared: 0.742
p value: < 2.2e-16**

(***p < 0.01, *p < 0.05)
and texture sensation were high, and these factors greatly affected the comfort sensation in the process of pre-rest, exercise, and post-rest.

Factor analysis was performed for all nine evaluation terms except Uncomfortable–Comfortable, to identify what kind of potential psychological factors participants mainly felt in the exercise/rest process. The software R was used in the analysis. Results are given in Table 7. The number of factors was set to three because there were three factors with eigenvalues of 1.0 or more. Promax rotation was performed.

The contribution ratio of factor 1 was 32.3%. The explanatory variables with a large factor loading were Hot–Cool, Sticky–Slippery, and Stuffy–Dry sensations. Factor 1 thus reflects a sensation related to the thermal and moisture transport characteristics of fabrics.

Explanatory variables with large factor loadings of factor 2 were Poor texture–Good texture, Rough–Smooth, and Hard–Soft. Factor 2 thus reflected a sensation related to the texture felt when touching fabrics.

The explanatory variables with a large factor loading of factor 3 were Heavy–Light and Thick–Thin. Factor 3 thus reflected a physical sensation of the fabric itself.

Factor analysis revealed that the three main potential factors were the sensation of thermal and moisture transport characteristics, the sensation of the skin texture, and the physical sensation of the skin in the exercise/rest process.

### 3.2.2 Differences between samples

The scores at each moment in time did not change as largely between samples as between processes. However, two-way analysis of variance showed a significant difference in the factor “sample” for Hot–Cool and Stuffy–Dry as seen in Table 5.

The differences between the scores of samples were calculated for Hot–Cool and Stuffy–Dry to compare the scores between samples. Figure 7 shows the time change in the average values of the difference for PET/PET and PET/PP when the PET/PP value was set to zero (PET/PET–PET/PP).

Regarding the scores of Hot–Cool, a large difference was observed between the samples at pre-rest (0 min and 10 min). Tukey’s multiple comparison test showed a significant difference of 1% between samples at 0, 10, and 40 min from the start of the experiment. The values of PET/PP were higher than those of PET/PET at these times.

Multiple comparisons made adopting Tukey’s test revealed a significant difference between scores of the sensory evaluation Stuffy–Dry for the samples at 0, 30, and 50 min. At these times, the values for PET/PP were higher than the values for PET/PET.

In particular, a large difference was observed between the samples immediately after exercise (30 min). It was found that the stuffy sensation of PET/PP was weaker.

### 3.3 Autonomic nervous activity index

Table 8 gives the average values of CVRR and LF/HF for each sample obtained from the ECG, and PTT obtained from the finger plethysmogram. These are autonomic nerve activity indices. The average values and standard deviations were calculated from 10 participants. Regarding LF/HF, there were three outliers that were much higher than the average value of all data (> Mean + 3SD). The values were 13.4 at 38–40 min of PET/PP, 11.0 at 58–60 min of PET/PP and 11.3 at 58–60 min of PET/PET. Therefore, the averages value and standard deviations of 9 participants were used for these times of each sample for LF/HF.

We investigated significant differences in the values of CVRR and PTT between samples in a two-way factorial analysis of variance and multiple comparisons made adopting Tukey’s test. The two factors were samples and elapsed time. For LF/HF, we performed Mann-Whitney
U-test between samples at each time because some outliers were excluded and sometimes the numbers of data were not equal in the samples.

Tukey’s tests revealed significantly higher values of the CVRR for PET/PP than for PET/PET at 38–40 and 58–60 min (p<0.01). The CVRR score for PET/PP was significantly higher than that for PET/PET at 38–40 and 58–60 min. The activity of parasympathetic nerves predominantly enhanced when wearing PET/PP than when wearing PET/PET.

There were no significant differences in LF/HF or PTT between samples. When comparing both samples in terms of LF/HF values for each participant, 4 to 6 out of 10 participants had high PET/PP values except at 8–10 min. There was no statistically significant difference because the sample ranks varied depending on the participants and the absolute values also varied, even the outliers were excluded.

Similar to LF/HF in PTT, when comparing both samples for each participant, 5 to 7 out of 10 participants had higher PET/PP values. There were no outliers like LF/HF, but there were some participants with high absolute values, so there was no significant difference.

Regarding CVRR, the 5 to 7 out of 10 participants had higher PET/PP values than PET/PP, but the difference between PET/PP and PET/PP was small even if the values of PET/PET were higher. As a result, there were some significant differences in the average value of 10 participants.

Although the variance was large, LF/HF tended to increase for both samples after exercise and then decrease. The PTT tended to decrease after exercise and then increase.

### 3.4 Relationships between psychological sensations and the autonomic nervous activity index

To investigate the relationship between the comfort sensation and autonomic nervous system activity, correlation analysis was performed using average values for 10 participants, for each sample at 10, 40, and 50 min, at which time there were data for all measurement items. High negative correlation (p<0.01) was found between LF/HF obtained from the ECG and the psychological values of the Uncomfortable–Comfortable evaluation as shown in Figure 8.

Figure 9 shows the results of the psychological scores of Stuffy–Dry after exercise and the CVRR score, which were significantly different between samples. There was

### Table 8: Mean value and standard deviation (SD) of the CVRR and LF/HF for each sample obtained from the ECG, and the PTT obtained from the ECG and finger plethysmogram over time

| Autonomic nerve activity index | 8–10min Mean ± SD | 18–20min Mean ± SD | 38–40min Mean ± SD | 48–50min Mean ± SD | 58–60min Mean ± SD |
|--------------------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| CVRR [-]                       | PET/PP            | 5.37 ± 1.25       | 5.35 ± 1.56       | 5.53 ± 1.90       | 5.15 ± 0.84       | 6.47 ± 2.12       |
|                                | PET/PET           | 5.13 ± 1.50       | 5.48 ± 1.60       | 4.75 ± 1.13       | 5.51 ± 1.60       | 5.63 ± 1.61       |
| LF/HF [-]                      | PET/PP            | 2.11 ± 1.65       | 2.00 ± 1.80       | 2.91 ± 1.96       | 2.21 ± 1.84       | 1.82 ± 1.16       |
|                                | PET/PET           | 1.29 ± 0.74       | 2.41 ± 2.72       | 2.81 ± 2.03       | 2.42 ± 2.07       | 2.33 ± 2.37       |
| PTT [s]                        | PET/PP            | 0.31 ± 0.17       | 0.28 ± 0.14       | 0.19 ± 0.10       | 0.18 ± 0.04       | 0.24 ± 0.08       |
|                                | PET/PET           | 0.32 ± 0.25       | 0.32 ± 0.15       | 0.16 ± 0.09       | 0.22 ± 0.14       | 0.21 ± 0.13       |

(** p<0.01, * p<0.05)
a significant difference in the stuffy sensation immediately after exercise and at the time of the last measurement, and the values of PET/PET were lower, indicating a stuffier sensation.

The CVRR value for the PET/PET sample was smaller after exercise and at the time of the last measurement. This suggests that the CVRR was greater when the stuffy sensation was weaker.

4. DISCUSSION

4.1 Physical conditions of the wearing state

A drastic increase in humidity within the clothes during exercise was observed around 30 min as seen in Figure 5. This result indicates that the participants perspired immediately after exercise. There was no significant difference in the humidity and thus no difference in the degree of perspiration between samples. Afterward (at 40 min), a decrease in skin surface temperature due to a sweat-chill was observed for both samples (Figure 4). Although there was no difference in humidity within the clothes, there was a difference in the temperature reduction between the samples. The result is considered to relate to the moisture management characteristics of the undershirts. The temperature drop of PET/PP was smaller because the sample had a significantly higher accumulative one-way transport index and a wicking and quick drying property (Table 3). The moisture on the skin surface was considered to move to the outside quickly, and it was difficult to chill the skin surface.

4.2 Psychological sensations

Two-way analysis of variance in the sensory evaluation revealed significant differences in the factor “sample” only for Hot–Cool and Stuffy–Dry in Table 5. This is considered to be due to thermal and moisture transport properties. There were significant differences in the thermal sensation Hot–Cool between the samples at the pre-rest time. The value of q-max of the samples is thought to relate to this result. It has been recognized that q-max correlates with human contact coolness. It is therefore considered that PET/PP with a larger value of q-max provided a cool sensation. It is also possible that PET/PP has smaller surface irregularity (SMD) and therefore a large area of contact with the skin, which might increase thermal transfer.

Significant differences in the sensory evaluation Stuffy–Dry were observed between samples after exercise (at 30 and 50 min). The values for PET/PP were higher than those for PET/PET. The sensation of stuffiness was weaker for PET/PP. This may be explained by the thermal and moisture transport properties and surface properties of fabrics being related. The sensation of stuffiness is a complex factor of the sensations of warmth and touch [17]. PET/PP had a high q-max, which means a stronger contact cooling sensation, and a lower dynamic friction coefficient (MIU) and small surface irregularity (SMD), and easy to remove moisture on the skin surface because of the accumulative one-way transport index and wicking and drying rates of the moisture transport properties. This may have weakened the sensation of stuffiness.

4.3 Autonomic nervous activity index

The sympathetic nerve activity index LF/HF changed greatly and the sympathetic nerve activity was enhanced after exercise. These observations correspond to the result that the sensation of clothing comfort changed significantly in the exercise/rest process. There was high correlation between the comfort sensation and LH/HF values in the exercise/rest process. It is possible that LF/HF is useful in estimating comfort in situations involving dynamic change, such as the pre-rest, exercise, and post-rest process. This result is similar to the results of previous studies in that the stress of the skin touching sensation and thermal sensation when wearing clothing enhance the activity of sympathetic nerves [4-7, 18]. However, there was no significant difference between samples due to the large variability among participants. It was not possible to capture the subtle differences in material characteristics of the samples using LF/HF at this time.

Figure 9 shows that differences between samples might affect the CVRR when the participants felt the psychological stuffy sensation. The stuffy sensation might be generated by the thermal stimulus of perspiration due to exercise and the effect of moisture. It is possible that such a complex thermal discomfort sensation can be estimated using the CVRR. A previous study [19] reported that the CVRR can be significantly higher when wearing work wear with a fan to prevent heat stroke than when wearing work wear without a fan. The CVRR is therefore an index of comfort related to stuffiness and thermal stimulus. At this time, it is considered that the CVRR is higher for PET/PP owing to the proper management of heat and moisture after perspiration. It is considered that the difference in thermal and moisture transport characteristics of the samples is reflected in the parasympathetic nerve activity of the participants.
Significant differences were observed between samples in terms of Hot–Cool and Stuffy–Dry (Table 5) due to the stimulation in this experiment, which was thermal changes such as body temperature rise and perspiration due to exercise. It is considered that CVRR, which is the parasympathetic nervous system index, can be used to evaluate the differences in the physical conditions and psychological responses related to different thermal changes in the samples, rather than the sympathetic nervous system activity indices like LF/HF and PTT.

In the case of the difference in the samples is larger in terms of comfort sensation or other psychological sensations, it may be a significant difference between the samples in LF/HF and PTT as shown in Figure 8, which shows the correlation of LF/HF and clothing comfort sensation.

5. CONCLUSION

Two types of undershirts made from PP and PET, which have similar properties, were prepared. Psychophysiological responses were measured for these undershirts when worn during exercise to investigate the difference felt by participants between the samples.

It was found that the humidity in the clothes rose sharply, and the skin surface temperature dropped after exercise. As a psychological sensation, the sensation of stuffiness increased and participants felt discomfort after exercise. In such an exercise/rest process, LF/HF obtained from the ECG has a high negative correlation with clothing comfort in the measurement results of autonomic nervous activity. There is the possibility of estimating discomfort when sweating due to exercise from LF/HF.

Participants felt a difference between samples only in the thermal sensation and the sensation of stuffiness. This indicates differences in the thermal and moisture transfer characteristics of the samples. Additionally, differences in the stuffiness sensation felt when wearing the samples after exercise corresponded with the CVRR obtained from the ECG, which is an index of parasympathetic nerve activity. The possibility of using the CVRR to estimate a complex discomfort sensation related to thermal and moisture transport characteristics, such as a stuffiness sensation, was shown. The measurement of psychophysiological responses thus has potential application in evaluating the clothing comfort sensation when similar clothing materials are worn.

In future work, we will confirm the present results while increasing the number of participants and material samples.

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Effectiveness of a Method of Evaluating the Clothing Comfort Sensation in a Perspiration State by Measuring Psychophysiological Responses

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