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ORIGINAL ARTICLE

Study on Cardiovascular and Respiratory Responses Relevant to Tactile Softness Evaluation

– Based on ECG and PPG Analysis –

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Abstract: The main purpose of this study is to explore physiological parameters that are usable for tactile softness differentiation. Two pillows and a cushion which were different in tactile softness (perceived compressibility and resilience) were chosen as the samples. 10 healthy students participated in the physiological test. Each of them was tested on three days, twice a day with the same sample involved. Each subject was required to keep quiet, compress the sample and keep quiet again in succession during a whole test. ECG (electrocardiography), PPG (photoplethysmography) and RSP (respiration) signals were recorded simultaneously during each physiological test. Several parameters indicating cardiovascular and respiratory reactions were calculated based on these signals. The statistical analysis results revealed that, HFnorm (normalized power of high-frequency components) calculated from the power spectrum of PWTT (pulse wave transmitting time) might be a very promising parameter which can be used for tactile softness differentiation.
Keywords: *ECG, PPG, Softness*

1. INTRODUCTION

Nowadays, some home textiles like towels, pillows, cushions and mattresses are very essential in our daily life. We are making contact with these products so frequently that we have to pay more attention to the selection of them. In general, with respect to such products as towels, pillows, cushions and mattresses, their appearances play an important part in affecting the visual comfort of our living environment, and their textures play an important role in determining the tactile comfort of our living environment [1, 2]. In a word, without them, it will be difficult for us to lead a comfortable life.

Different kinds of products usually have different intended uses, and therefore are manipulated in different ways in reality. In the cases of pillows and cushions, we commonly use them as head or body supports in our daily life. Therefore, the capacity to offer suitable softness is very essential for them to help us achieve a comfortable posture. In the shoes of developers, it is more effective to evaluate the softness of products by mechanical measurement. For most consumers, it is the most convenient way to evaluate the softness of products by hand touch. Unlike the mechanically measured softness, the softness perceived via hand touch is affected by not only the deformability of products (e.g., compressibility, flexibility) but also the individual characteristics of touchers (e.g., physical condition, early experience, personality) as well as the surroundings (e.g., temperature and humidity, social culture) [2]. In consequence, the softness subjectively perceived by the consumers ought to be even more complex than the softness mechanically measured by the developers. Considering that the softness perceived via hand touch is associated with our psychophysiological reactions to the deformability of materials, we suppose that there is a possibility to find a way to discriminate between materials which are different in perceived softness through psychophysiological measurement.

In this study, we are about to ascertain the cardiovascular and respiratory reactions caused by the involvement with deformable materials like pillows and cushions firstly. The electrocardiography (ECG) is to be applied to study the variability of heart rate (HR), the photoplethysmography (PPG) is to be applied to study the variability of blood pressure (BP), and the respiration (RSP) signal is to be recorded to study the variability of respiration. Ultimately, we aim to find one or more cardiovascular and/or respiratory parameters that are usable for tactile softness differentiation.

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2. EXPERIMENTAL

2.1 Subjects

10 healthy university students (5 males and 5 females) aged between 20 and 30 years old participated in the experiment. The subjects were required to refrain from doing intensive exercise, smoking and drinking coffee on test day.

2.2 Materials

Figure 1 shows the general images of samples used in the experiment. “P1” was a pillow made of 1.6 kg or so of OrsaEliocel foam (L × W × H = 72 cm × 42 cm × 11 cm). “P2” was a cushion covered with a kind of fabric made of 85% polyester and 15% cotton and filled with 0.7 kg or so of small feathers (L × W × H = 45 cm × 45 cm × 13 cm). “P3” was a pillow covered with a kind of fabric made of 100% polyester and filled with 1.0 kg or so of Urethane foam (L × W × H = 40 cm × 60 cm × 13 cm).

The sensory attributes of “P1”, “P2” and “P3” were investigated via a sensory test which was carried out under the environmental condition of “24°C ± 1°C, 50% ± 4% RH”. Eight pairs of terms, namely “Cool – Warm”, “Damp – Dry”, “Sticky – Slippery”, “Rough – Smooth”, “Incompressible – Compressible”, “Nonresilient – Resilient”, “Uncomfortable–Comfortable” and “Unpleasant–Pleasant”, were involved in the sensory test. The rating scale was designed with the semantic differential (SD) method.

Figure 2 shows the sensory test results. Since both the perceived compressibility (easiness to compress) and the perceived resilience (easiness to recover) contribute to the perception of softness, the overall tactile softness ought to depend on the evaluation results about “Incompressible – Compressible” and “Nonresilient – Resilient”. According to Figure 2, “P2” was a sample of poor softness, as it was considered to be a little incompressible and nonresilient; “P1” and “P3” were two samples of good softness, as “P1” was thought to be moderately compressible and resilient while “P3” was thought to be a little compressible and resilient.

Figure 1: Samples Used in the Experiment

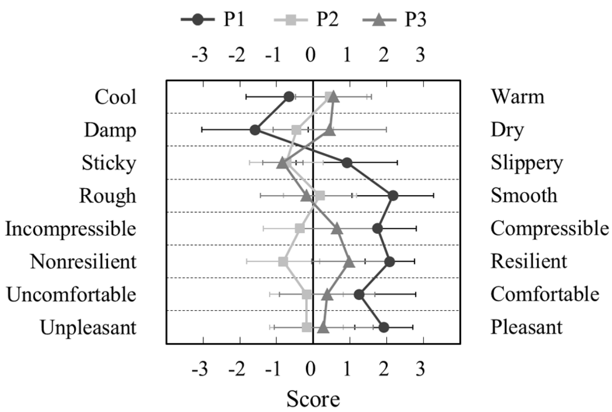


Figure 2: Sensory Attributes of the Samples

2.3 Environment and equipment

The physiological tests were conducted in a climate chamber under the environmental condition of “24°C ± 1°C, 50% ± 4% RH”. The MP100 data acquisition system (BIOPAC Systems Inc., New York, USA), as shown in Figure 3, was used to record ECG, PPG and RSP signals. The ECG signal was detected by three ECG electrode leads (LEAD110S-R, BIOPAC Systems Inc., New York, USA) fixed on the skin surface of the right collarbone, the manubrium of the sternum and the region between the 7th rib and the 9th rib on the left side. The PPG signal was detected by an earclip PPG transducer (TSD200C, BIOPAC Systems Inc., New York, USA). The RSP signal was detected by a fast response thermistor fixed under the left nostril (TSD101B, BIOPAC Systems Inc., New York, USA).

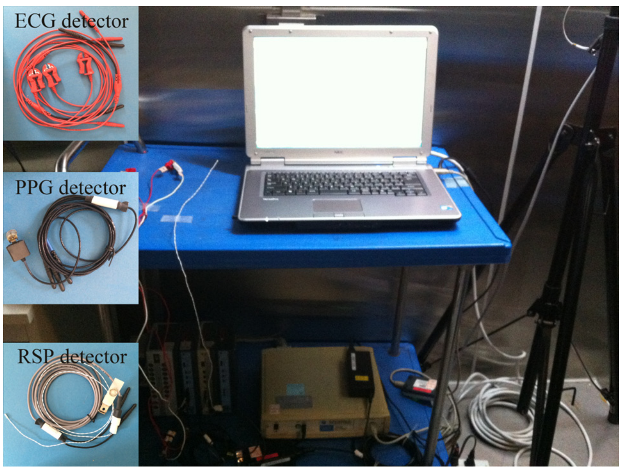


Figure 3: The MP100 Data Acquisition System

2.4 Measurement

Each subject was tested on three days, and different samples were involved on the three days. The sequence that “P1”, “P2” and “P3” were used on the three days was randomly determined. Figure 4 shows the physiological test procedure within one day. According to it, before the starting of the first physiological test, a subject had to change his/her top and then seat himself/herself

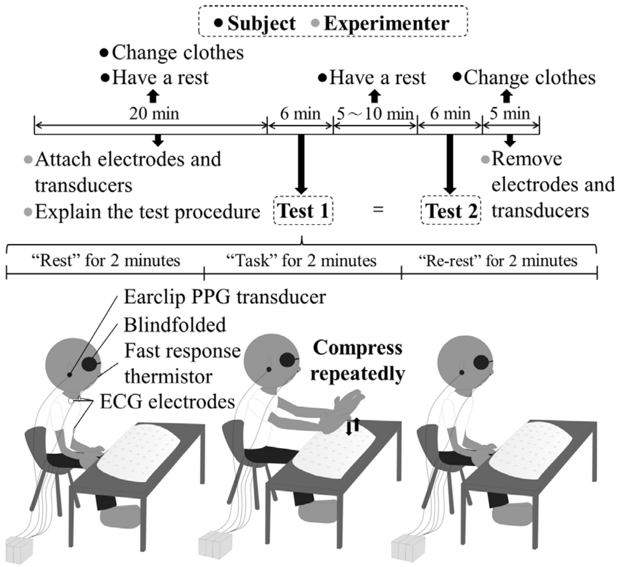


Figure 4: The Physiological Test Procedure

in the chair to have a rest; meanwhile, the experimenter had to equip the subject with the MP100 data acquisition system and then explain the physiological test procedure to the subject. After the 20 minutes of preparatory stage, a subject had to go through two 6-minute physiological tests in succession, between which there were 5 to 10 minutes for the subject to have a rest. Each physiological test was comprised of three successive conditions: "Rest", "Task" and "Re-rest". Under "Rest" and "Re-rest" conditions, a subject had to do nothing but keep being seated quietly in the chair; under "Task" condition, a subject had to keep compressing the presented sample rhythmically. The subjects were blindfolded throughout each physiological test. During each test, ECG, PPG and RSP signals were recorded simultaneously at a sampling frequency of 2000 Hz.

2.5 Data acquisition

The signals recorded in the first physiological test were preferentially read in for data acquisition. When any of these signals were abnormal, the signals recorded in the second physiological test were read in instead for data acquisition.

The consecutive data of RRI (R-R interval: the interval between the peak points of two adjacent R-waves) and RTI (R-T interval: the interval between the peak point of an R-wave and the peak point of the following T-wave) were calculated based on the ECG signal. The consecutive data of H_P (height of pulse wave: the amplitude difference between the maximum peak point and the minimum valley point of a pulse wave) were calculated based on the PPG signal. The consecutive data of PWTT (pulse wave transmitting time: the interval between the peak point of an R-wave in ECG and the first valley point of the following pulse wave in PPG) were calculated based on ECG and PPG signals. The consecutive data of T (time duration of a breath: the interval between the peak points of two adjacent respiratory waves) were first calculated based on the RSP signal, and then they were converted into the consecutive data of RR (respiratory rate: the number of breaths per minute) with the equation "$RR_i = 1/T_i$".

Under "Rest" condition, the data from the 15th second to the 105th second were extracted for calculation; under "Task" condition, the data from the 135th second to the 225th second were extracted for calculation; under "Re-rest" condition, the data from the 255th second to the 345th second were extracted for calculation. Table 1 shows the parameters calculated under the three conditions.

- In time domain, the average (Mean) and the coefficient of variation (CV) of RRI, RTI, H_P, PWTT and RR, as well as the corresponding root-mean-square (RMS) of the amplitude of RSP signal, were calculated.
- In frequency domain, fast Fourier transform (FFT) was applied to estimate the power spectral density (PSD) of RRI and PWTT. The power of low-frequency (LF: 0.04 Hz – 0.15 Hz) components and the power of high-frequency (HF: 0.15 Hz – 0.4 Hz) components were first calculated, and then they were used to calculate the normalized power of HF components (HFnorm: HFnorm = HF / (LF + HF) × 100%).

3. RESULTS AND DISCUSSION

3.1 Cardiovascular and respiratory reactions to the involvement with deformable materials

The values of the parameters shown in Table 1 were converted into Z-scores, and then two-way analysis of variance (ANOVA) was applied to test the statistical significance of main effects of the "sample" type ("P1", "P2" and "P3") and the test "condition" ("Rest", "Task" and "Re-rest")

Table 1: Parameters in Time and Frequency Domains

Time-domain Parameters	
• RRI (mean)	• RRI (cv)
• RTI (mean)	• RTI (cv)
• H_P (mean)	• H_P (cv)
• PWTT (mean)	• PWTT (cv)
• RSP (rms), RR (mean)	• RR (cv)
Frequency-domain Parameters	
• HFnorm (RRI)	
• HFnorm (PWTT)	

on each parameter. Table 2(A) – Table 2(D) show the two-way ANOVA results for parameters on which the "sample" type and/or the test "condition" had significant main effects.

According to Table 2(A), the test "condition" had a significant effect on the CV of RTI ($p < 0.01$). Figure 5(A) shows the least significant difference (LSD) test results about the corresponding significant effect of the test "condition". Obviously, without sorting out the samples, the CV of RTI under "Task" condition was significantly larger than the CV of RTI under "Rest" condition ($p < 0.01$)

Table 2: ANOVA Results for Parameters Showing Significant Main Effects (** $p<0.01$, * $p<0.05$)

(A) Dependent Variable: RTI (cv)					
Source	*SS*	*df*	*MS*	*F*	*p*
Sample	1.451	2	0.725	0.120	0.888
Condition	85.849	2	42.924	7.072	0.001 **
Sample × Condition	0.582	4	0.146	0.024	0.999
Error	491.636	81	6.070		
Total	579.517	89	6.511		
(B) Dependent Variable: RR (cv)					
Source	*SS*	*df*	*MS*	*F*	*p*
Sample	6.873	2	3.437	2.357	0.101
Condition	20.581	2	10.290	7.059	0.001 **
Sample × Condition	1.876	4	0.469	0.322	0.863
Error	118.077	81	1.458		
Total	147.407	89	1.656		
(C) Dependent Variable: HFnorm (RRI)					
Source	*SS*	*df*	*MS*	*F*	*p*
Sample	6.513	2	3.257	4.803	0.011 *
Condition	2.333	2	1.167	1.720	0.185
Sample × Condition	2.532	4	0.633	0.933	0.449
Error	54.927	81	0.678		
Total	66.306	89	0.745		
(D) Dependent Variable: HFnorm (PWTT)					
Source	*SS*	*df*	*MS*	*F*	*p*
Sample	11.042	2	5.521	3.895	0.024 *
Condition	16.561	2	8.280	5.842	0.004 **
Sample × Condition	14.094	4	3.524	2.486	0.050 *
Error	114.804	81	1.417		
Total	156.500	89	1.758		
(E) Dependent Variable: HFnorm (PWTT)					
Between Samples	*SS*	*df*	*MS*	*F*	*p*
Condition = Rest	2.963	2	1.481	1.536	0.233
Condition = Task	21.315	2	10.657	5.194	0.012 *
Condition = Re-rest	0.858	2	0.429	0.347	0.710
(F) Dependent Variable: HFnorm (PWTT)					
Between Conditions	*SS*	*df*	*MS*	*F*	*p*
Sample = P1	19.707	2	9.853	7.979	0.002 **
Sample = P2	0.095	2	0.047	0.098	0.907
Sample = P3	9.381	2	4.691	2.444	0.106

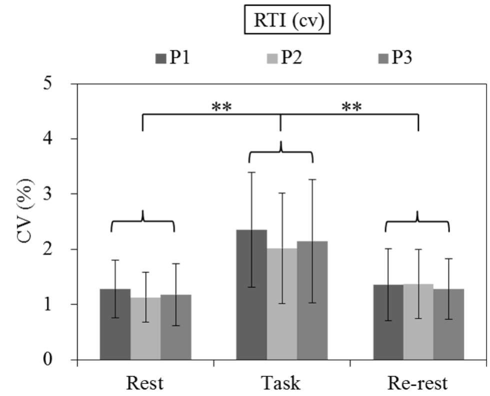
and that under "Re-rest" condition ($p < 0.01$). From a physiological standpoint, RTI is directly related to the duration of ventricular depolarization and repolarization [3, 4]. Consequently, the above results indicated that, owing to the active contact with deformable materials, the variation of ventricular depolarization and repolarization duration increased. However, the increment in the variation of ventricular depolarization and repolarization duration did not change with the samples.

According to Table 2(B), the test "condition" had a significant effect on the CV of RR ($p < 0.01$). Figure 5(B) shows the LSD test results about the corresponding significant effect of the test "condition". According to it, without sorting out the samples, the CV of RR under "Task" condition was significantly larger than the CV of RR under "Rest" condition ($p < 0.01$) and that under "Re-rest" condition ($p < 0.05$). To some extent, the CV of RR signifies the uniformity of respiration. From the above results we got to know that, the active contact with deformable materials disturbed the respiratory rhythm and led the uniformity of respiration to decrease. Similarly, the decrement in the uniformity of respiration did not change with the samples, either.

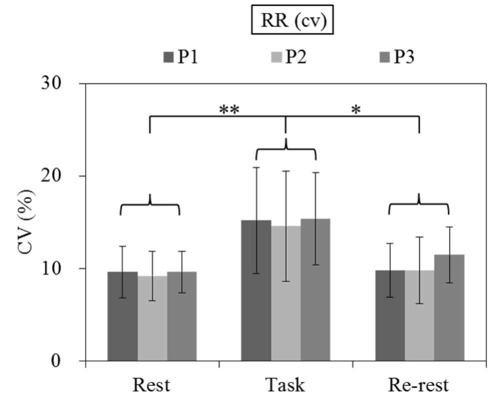
According to Table 2(C), the "sample" type had a significant effect on HFnorm calculated from the power spectrum of RRI ($p < 0.05$). Figure 5(C) shows the LSD test results about the corresponding significant effect of the "sample" type. It can be seen that, without sorting out the test conditions, the HFnorm (RRI) related to "P3" was significantly different from the HFnorm (RRI) related to "P1" ($p < 0.05$) and that related to "P2" ($p < 0.01$). Although the main effect of the test "condition" on HFnorm (RRI) was not statistically significant, it seemed that the HFnorm (RRI) under "Task" condition was lower than the HFnorm (RRI) under "Rest" condition. Furthermore, the decrement of the HFnorm (RRI) from "Rest" condition to "Task" condition seemed to change with the samples. As is well known, HFnorm calculated from the power spectrum of RRI indicates the balance between the parasympathetic innervation and the sympathetic innervation of HR [5]. The above results made us to suppose that, the active contact with deformable materials tend to cause the sympathetic innervation of HR to increase and/or the parasympathetic innervation of HR to decrease.

According to Table 2(D), both the "sample" type and the test "condition" had significant effects on HFnorm calculated from the power spectrum of PWTT ("Sample": $p < 0.05$; "Condition": $p < 0.01$). Since the interactive effect between the "sample" type and the test "condition" was statistically significant ($p < 0.05$), one-way ANOVA was applied to test the simple main effects of the “sample” type and the test “condition” on HFnorm (PWTT). According to Table 2(E), the “sample” type had a significant effect on the HFnorm (PWTT) under “Task” condition ($p < 0.05$). The HFnorm (PWTT) under the “Task” condition of touching “P2”, as shown in Figure 5(D), was significantly larger than the HFnorm (PWTT) under the “Task” condition of touching “P1” ($p < 0.05$) and that under the “Task” condition of touching “P3” ($p < 0.05$). According to Table 2(F), the test “condition” had a significant effect on the HFnorm (PWTT) related to “P1” ($p < 0.01$). The HFnorm (PWTT) under the “Task” condition of touching “P1”, as shown in Figure 5(D), was significantly lower than the HFnorm (PWTT) under the corresponding “Rest” condition ($p < 0.05$) and that under the corresponding “Re-rest” condition ($p < 0.05$). On the whole, in terms of “P1” and “P3” which were of good softness, HFnorm (PWTT) tended to decrease because of the active contact and then go to recover after the active contact; in terms of “P2” which was of poor softness, the corresponding change trends of HFnorm (PWTT) were not noticeable enough. As reported, the variations of PWTT correlate well with the variations of BP [6-8]. On the basis of the above results, we suppose that the variations of BP will change in different ways when deformable materials perceived to be different in tactile softness are compressed.

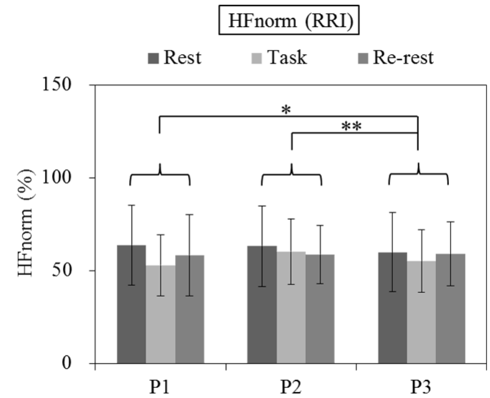
In summary, among the parameters tested in this study, only four parameters, namely RTI (cv), RR (cv), HFnorm (RRI) and HFnorm (PWTT), showed some significant reactions to the involvement with deformable materials. RTI (cv) and RR (cv) were magnified because of the active contact, but the increment from “Rest” condition to “Task” condition and the decrement from “Task” condition to “Re-rest” condition failed to show any between-sample differences. HFnorm (RRI) and HFnorm (PWTT) tended to decrease because of the active contact, and the decrement from “Rest” condition to “Task” condition and/or the increment from “Task” condition to “Re-rest” condition seemed to change with the samples. However, only the change trends of HFnorm (PWTT) turned out to be statistically significant. Considering that the samples used in this study were mainly different in tactile softness, the between-sample differences in the change trends of HFnorm (PWTT) might be ascribed to the between-sample differences in tactile softness. As a consequence, we suppose that HFnorm (PWTT) ought to be a promising parameter that can be used for tactile softness differentiation.



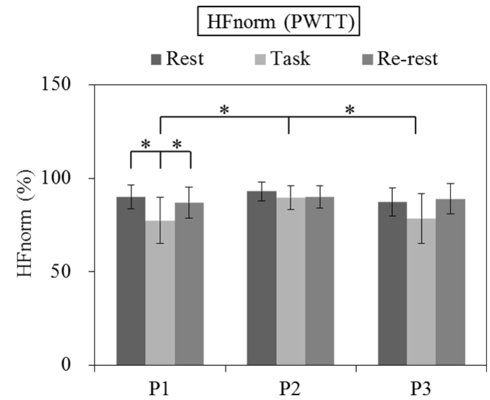
(A) LSD Test Results for RTI (cv)



(B) LSD Test Results for RR (cv)



(C) LSD Test Results for HFnorm (RRI)



(D) LSD Test Results for HFnorm (PWTT)

Figure 5: Post Hoc Test Results for Parameters Showing Significant Main Effects (** $p<0.01$, * $p<0.05$)

3.2 Discussion about the usability of HFnorm (PWTT) in tactile softness differentiation

One-way ANOVA was applied to test the between-sample differences in the decrement of HFnorm (PWTT) from “Rest” condition to “Task” condition and the increment of HFnorm (PWTT) from “Task” condition to “Re-rest” condition. Table 3 shows the corresponding ANOVA results. It is obvious that, there were significant between-sample differences in both change trends. Figure 6 shows the corresponding LSD test results. According to it, from “Rest” condition to “Task” condition, the decrement caused by touching “P1” was significantly larger than the decrement caused by touching “P2” ($p < 0.05$), whereas neither the decrement caused by touching “P1” nor the decrement caused by touching “P2” was significantly different from the decrement caused by touching “P3”; from “Task” condition to “Re-rest” condition, there was no significant difference between the increment caused by stopping touching “P1” and the increment caused by stopping touching “P3”, but the increment caused by stopping touching “P2” was significantly lower than the increment caused by stopping touching “P1” ($p < 0.01$) and that caused by stopping touching “P3” ($p < 0.05$). In summary, when “P1” and “P2” were compared, both the decrement caused by the active contact and the increment caused by the termination of active contact showed significant differences; when “P2” and “P3” were compared, only the increment brought about by the termination of active contact showed a significant difference. All in all, the above results indicated that, HFnorm (PWTT) could be relied on to differentiate deformable materials of good softness from deformable materials of poor softness, but its effectiveness in distinguishing between deformable materials of good softness still needed to be verified by further studies in the form of recruiting more subjects, involving more samples, changing the test duration and so on.

Table 3: One-way ANOVA Results for the Change Trends of HFnorm (PWTT) (** $p<0.01$, * $p<0.05$)

(A) From “Rest” Condition to “Task” Condition					
Source	*SS*	*df*	*MS*	*F*	*p*
Between Samples	816.203	2	408.101	3.362	0.050 *
Within Samples	3277.792	27	121.400		
Total	4093.994	29			
(B) From “Task” Condition to “Re-rest” Condition					
Source	*SS*	*df*	*MS*	*F*	*p*
Between Samples	1456.358	2	728.179	5.087	0.013 *
Within Samples	3864.852	27	143.143		
Total	5321.209	29			

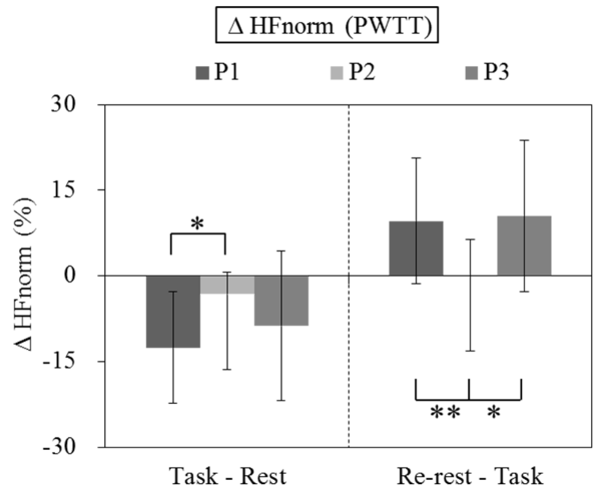


Figure 6: Post Hoc Test Results for the Change Trends of HFnorm (PWTT) (** $p<0.01$, * $p<0.05$)

In fact, PWTT is the sum of PEP (pre-ejection period) and a-PWTT (pulse wave transmitting time in the artery) [9]. PEP is the period just before the blood is pumped into the aorta by the heart. a-PWTT is the time taken by the pulse wave to travel from the aorta to a peripheral artery. a-PWTT is directly related to BP. When BP is high, the arterial walls are tense and hard, the pulse wave travels faster, and then a-PWTT is shortened; when BP is low, the arterial walls have less tension, the pulse wave travels slower, and then a-PWTT is lengthened [10]. Since the change in PEP over a short period of time is negligible in most cases, it is believed that PWTT corresponds to a-PWTT, and therefore correlates to BP [11, 12]. In general, it is difficult to determine the actual BP from PWTT, but the variability of PWTT is adequate to estimate the variability of BP [13]. That is to say, the variability of PWTT in time and frequency domains ought to be consistent with the variability of BP in time and frequency domains.

Power spectral analysis is a very common way to study the variability of HR and BP in frequency domain. By means of power spectral analysis, the variations of HR and BP can be roughly divided into two groups, namely LF components ranging from 0.04 Hz to 0.15 Hz and HF components ranging from 0.15 Hz to 0.4 Hz. A great many studies have shown that, the LF variations of HR are jointly mediated by the parasympathetic system and the sympathetic system, and they are very sensitive to some sympathetic activators like mental stress and exercise; the HF variations of HR are mainly mediated by the parasympathetic system, and they are highly associated with the respiratory sinus arrhythmia

(RSA) [14]. Concerning the variations of BP, they are greatly affected but not determined only by the variations of HR. As hypothesized, the LF variations of BP are predominantly caused by the variations in sympathetic vasomotor tone and systemic vascular resistance; the HF variations of BP result almost entirely from the direct effect of the HF variations of HR [15, 16]. Taking into account the consistency between BP variability and PWTT variability, we suppose that the above hypothesis is also suitable for accounting for the frequency-domain variations of PWTT.

HFnorm (PWTT) is a frequency-domain parameter which indicates the proportion of HF variations in the overall variations (the sum of LF and HF variations) of PWTT. The value of HFnorm (PWTT) depends on both the power of LF components and the power of HF components in the power spectrum of PWTT. By taking the results related to “P1” and “P2” for example, Figure 7 shows the LF power and the HF power calculated under different conditions. Obviously, the LF power increased considerably while the HF power decreased considerably as a result of the active contact with “P1”, a sample of good softness; by comparison, the LF power increased slightly while the HF power decreased slightly because of the active contact with “P2”, a sample of poor softness. In summary, the above results convinced us that both the LF variations and the HF variations of PWTT were associated with the tactile softness of deformable materials. When a sample of better softness was compressed, the LF variations of PWTT increased more, whereas the HF variations of PWTT decreased more. Accordingly, HFnorm (PWTT) which is determined by the expression “HF (PWTT) / (LF (PWTT) + HF (PWTT)) × 100%” showed a larger decrement. To account for such a phenomenon from a physiological standpoint, when a material perceived to be softer is compressed, the range of hand motion is larger, the frequency of hand motion is lower, and the hand feeling is comfortable, such behavioral and psychological states may enhance the sympathetic modulation of vasomotor tone and restrain the parasympathetic modulation of heart rate rhythm, as a result, the LF variations of BP are increased while the HF variations of BP are decreased.

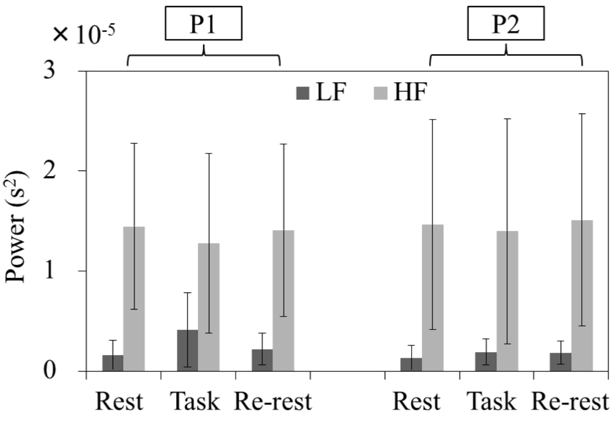


Figure 7: The Average Power of LF Components and HF Components in the Power Spectrum of PWTT

4. CONCLUSIONS

In this study, the cardiovascular and respiratory reactions to the involvement with deformable materials which were different in tactile softness were examined. Based on the analysis results for several parameters calculated from the ECG, PPG and RSP signals, the following conclusions were drawn:

- The variation of ventricular depolarization and repolarization duration increased because of the active contact with deformable materials; however, the increment in the variation of ventricular depolarization and repolarization duration did not change with the levels of perceived softness.
- The active contact with deformable materials decreased the uniformity of respiration, but the decrement in the uniformity of respiration did not change with the levels of perceived softness, either.
- The dominance of the parasympathetic innervation of HR tended to decrease because of the active contact with deformable materials, and the decrement in the dominance of the parasympathetic innervation of HR tended to change with the levels of perceived softness.
- Owing to the antipodal reactions of LF variations and HF variations of PWTT to the active contact with deformable materials, HFnorm (PWTT) proved to be a very promising parameter that can be used for tactile softness differentiation.
- It seems that the complex regulatory mechanism of BP, which involves not only the cardiac autonomic modulation but also the vasomotor function as well as some extrinsic behavioral and experimental factors, makes the variations of PWTT more sensitive to the tactile softness perceived by hand touch comparing with the variations of RRI.

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