Fibers and Polymers 2005, Vol.6, No.1, 89-94

Physiological Signal Analyses of Frictional Sound by Structural Parameters of Warp Knitted Fabrics

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(Received October 7, 2004; Revised February 7, 2005; Accepted February 14, 2005)

Abstract: The purpose of this study is to offer acoustical database of warp knitted fabrics by investigating frictional sound properties and physiological responses according to structural parameters such as construction, lap form, and direction of mutual guide bar movement. Fabric sounds of seven warp knitted fabrics are recorded, and Zwicker's psychoacoustic parameters - loudness(Z), sharpness(Z), roughness(Z), and fluctuation strength(Z) - are calculated. Also, physiological responses evoked by frictional sounds of warp knitted fabrics are measured such as electroencephalogram (EEG), the ratio of high frequency to low frequency (HF/LF), respiration rate (RESP), skin conductance level (SCL), and photoplethysmograph (PPG). In case of constructions, frictional sound of sharkskin having higher loudness(Z) and fluctuation strength(Z) increases RESP. By lap form, open lap has louder and larger fluctuating sound than closed lap, but there aren't significant difference of physiological responses between open lap and closed lap. In direction of mutual guide bar movement, parallel direction evokes bigger changes of beta wave than counter direction because of its loud, rough, and fluctuating sound. Fluctuation strength(Z) and roughness(Z) are defined as important factors for predicting physiological responses in construction and mutual guide bar movement, respectively.

Keywords: Frictional sound, Physiological response, Physical sound property, Psychoacoustic parameter, Warp knitted fabric

Introduction

Frictional sound generated by rubbing a fabric against another gives us comfort or discomfort such as pleasant sound color as scrooping sound of silk or annoying sound like frictional sound of coated fabric. In recent years, there are several research about fabric sound along with consumer's increasing need for auditory aspects of fabric as an essential factor affecting clothing comfort.

The sound color of various woven fabrics has been quantified using physical sound parameters and their relationship with the mechanical properties has been studied [1,2]. Effects of sound properties according to weaves, yarn types, and cross-sectional shapes were analyzed [3,4]. Also, researches [5-7] carried out subjective evaluation of fabric sound and estimated sound color from physical and sound properties of fabrics, which led to objective factor affecting sound color.

On the other hand, the descriptors used for subjective evaluation might be understood differently by each person or psychological state of a person [8]. However, physiological responses mainly controlled by autonomic nervous system is difficult to change on purpose [9]. Therefore, physiological responses can be used as objective indices of human sensation. In these days, researches generally measured physiological responses such as the electroencephalogram (EEG), electrocardiogram (ECG), electrodermal activity (EDA), or photoplethysmograph (PPG) to quantify human sensation in a more accurate and objective way. Accordingly, it is necessary to investigate not only objective properties of fabric sounds but also physiological responses evoked by them. Cho *et al.* [10] reported that the increment of loudness(Z) and sharpness(Z) influence negative sensations, causing the increment of SCL and LF/HF with the decrement of slow alpha and PPG. Like these, database for fabric sound of woven fabric has been established, but that of knitted fabric has rarely been investigated even though its need is increasing due to the latest casual trends in fashion.

A knitted fabric consists of interlacing loops which give better performance in stretchiness, flexibility, winkle resistance, and air permeability than woven fabric. In particular, warp knitted fabrics has a dimensional stability almost equal to that of a woven cloth or an elasticity comparable with that of a weft knitted fabric [11]. However, warp knitted fabrics differ from both woven and weft knitted fabrics in that a function of their structure greatly influences their physical properties [12]. The factors affecting the characteristics of warp knitted fabrics are the run-in ratio, pillar-lapping movement, the direction of mutual guide bar movement (parallel or counter), and lap form (closed or open) [13]. A construction type of warp knitted fabrics is also important in affecting the fabric sound, as sounds of woven fabrics are related to their weaving types [14].

The purpose of this study is to analyze the sound properties and physiological responses evoked by frictional sound of warp knitted fabrics according to their construction, lap form, and the direction of the mutual guide bar movement, and to investigate the relationship between sound properties and physiological responses for providing information to design auditory-sensible knitted fabrics.

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Table 1. Characteristics of specimens

Specimen	Fabric name	Bar	Pattern	Lap form	Direction of mutual guide bar movement
RL1	Reverse locknit	B2[a]	2-3 / 1-0	closed	counter
		B1[b]	1-0 / 1-2		
RL2	Reverse locknit	B2	3-2 / 0-1	open	counter
		B1	0-1 / 2-1		
RL3	Reverse locknit	B2	1-0 / 2-3	closed	parallel
		B1	1-0 / 1-2		
DD1	Double lenbigh	B2	1-0 / 1-2	closed	counter
		B1	1-2 / 1-0		
DD2	Double denbigh	B2	0-1 / 2-1	open	counter
		B1	2-1 / 0-1		
SS1	Sharkskin	B2	3-4 / 1-0	closed	counter
		B1	1-0 / 1-2		
SS2	Sharkskin	B2	1-0 / 3-4	closed	parallel
		B1	1-0 / 1-2		

[a]: back bar, [b]: front bar.

Experimental

Specimens

Seven warp knitted fabrics including three reverse locknit stitches, two double denbigh stitches, and two sharkskin stitches were produced using an electronic guide bar controlled warp knitting machine (Karl Mayer) under same density with 100 % polyester filament yarn. They were then heat-set in a laboratory drying and curing machine CH-815 (Swiss Werner Mathis AG) at 180 °C for 30 seconds. The characteristics of the specimens are given in Table 1.

Sound Recording and Analysis

The frictional sounds of the specimens were generated and recorded by a Measuring Apparatus for Fabric Noise (MAFN, patent no. 2001-0073360) [15] and a Sound Quality System (Type 7698, B&K). The sound spectra were analyzed by the fast Fourier transform (FFT) at frequencies ranging from 0 to 18,750 Hz. The Zwicker's psychoacoustic parameters [16] such as loudness(Z), sharpness(Z), roughness(Z), and fluctuation strength(Z) were calculated using BZ5652 software [17].

$$Loudness(Z) = \sum_{i=0}^{24} N'(i)\Delta z_i \quad \text{sone}$$

where, Δz_i = 1 bark
N': specific loudness

$$Sharpness(Z) = \frac{\int_l^{24} N'(z)g(z)z\,dz}{\int_l^{24} N'(z)\,dz}\, acum$$

$$\text{where, } g(z) = \begin{bmatrix} 1 & \text{for } z \le 16 \\ 0.066e^{0.171z} & \text{for } z > 16 \end{bmatrix}$$

$$Roughness(Z) = \sum^{24} R'(z)\, asper$$

where, $R'(z) = 0.0003 f_{\text{mod}}(z)\Delta L_E(z)\Delta z\ asper$
$\Delta L_E = 20\log(N'(1)/N'(99))$
f_{mod}: modulation frequency

$$Fluctuation\ Strength(Z) = \sum^{24} F'(z)\, vacil$$

$$\text{where, } F'(z) = \frac{0.032\Delta L(z)}{f_{\text{mod}}(z)/4 + 4/f_{\text{mod}}(z)}\, vacil$$

$\Delta L = 20\log(N'(1)/N'(99))$
f_{mod}: modulation frequency

Measurements of Physiological Responses

Participants

Participants were consisted of fourteen female students aged from 18 to 26. They were screened for normal hearing by a Houghson-Westlake, and a "5 dB up, 10 dB down" procedure [18] using an audiometer (Grason-Stadler, Inc.).

Physiological Signal Data Acquisition

Four physiological signals, the electroencephalogram (EEG), electrocardiogram (ECG), skin conductance level (SCL), and photoplethysmograph (PPG) were recorded simultaneously. The EEG was measured as an electric potential generated from the cerebrum using a Neurodata Acquisition System (Grass Co.), and the others were acquired by MP100WS (Biopac systems, Inc.) in a soundproof chamber. These signals were analyzed with Acqknowledge III software (Biopac systems, Inc.)

Monopolar leads of EEG were recorded from frontal (F3, F4), temporal (T3, T4), and occipital (O1, O2) sites according to the international 10/20 electrode system [19]. EEG signals were analyzed by FFT, and then relative powers of alpha (8-13 Hz) and beta (13-20 Hz) were calculated. Low frequency (LF, 0.04-0.15 Hz) and high frequency (HF, 0.15-0.4 Hz) were obtained from the power spectra of HRV. Measures of changes in HRV as a function of stimulus presentation are usually based on the identification of successive R waves and the calculation of interbeat interval for later conversion into beats per minute. RESP was measured in beats per minute, too. SCL was recorded as changes in electrical resistance in the skin, and PPG was also recorded for assessing peripheral microcirculation caused by periodic pulsation of arterial blood.

Experimental Procedure

Participants were instructed to sit on a reclining chair in a soundproof chamber and have adaptation period for 10 minutes. The physiological responses were recorded in a baseline and in stimulus state for 60 seconds respectively. After 90 seconds rest, the next fabric sound was presented to the participant and the same experimental protocol was repeated. The recorded fabric sounds were presented in random order.

Statistical Analysis

The data was analyzed using ANOVA and t-test to compare differences of physiological responses among specimens. Also, the data was analyzed using the stepwise regression to extract the factors of physiological responses predicted from the physical sound parameters and the psychoacoustics parameters of warp knitted fabrics with the SPSS package.

Results and Discussion

Sound Properties of Warp Knitted Fabrics

Psychoacouaic parameters of specimens were investigated according to the constrution, lapform, and direction of mutual guide bar movement. Comparing with polyester woven fabrics [4], the loudness(Z) of the warp knitted fabric was lower than that of the polyester woven twill fabric. This showed that woven fabrics make more noise than knitted fabrics [20].

Among the construction with the counter direction of the mutual guide bar movement and the closed lap (Figure 1), the SS1 (sharkskin) had the highest loudness(Z) (4.49 sone) and fluctuation strength(Z) (2.09 vacil), followed by the DD1 (double denbigh, 3.65 sone, 1.36 vacil) and the RL1 (reverse locknit, 2.01 sone, 0.56 vacil). However, the sharpness(Z) of the SS1 (2.84 acum) was lower than that of the DD1 (3.65 acum). The roughness(Z) of RL1 and DD1 exhibited similar values about 2 asper but that of SS1 showed a little higher value (2.44 asper) than the others. Sharkskin is considered to make the loudest and the most fluctuating sound because it is extremely stable and irregular owing to the rigid control of the front bar threads over the large floats of the back bar threads [10], while reverse locknit made a quiet and steady sound.

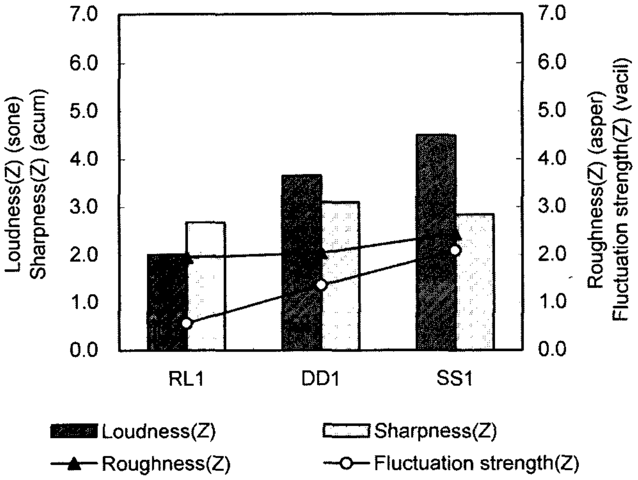


Figure 1. Psychoacoustic characteristics according to construction.

In case of the lap form (Figure 2), loudness(Z) and fluctuation strength(Z) of RL2 (2.76 sone, 1.40 vacil) and DD2 (4.64 sone, 1.82 vacil) were higher than those for RL1 (2.01 sone, 0.56 vacil) and DD1 (3.65 sone, 1.36 vacil). However, sharpness (Z) and roughness(Z) showed similar values between RL1 (2.68 acum, 1.95 asper) and RL2 (2.87 acum, 2.00 asper) or DD1 (3.10 acum, 2.04 asper) and DD2 (3.28 acum, 2.21 asper). Thus, we found that the open lap made the louder and larger fluctuating sound than the closed lap, but lap form type didn't affect a sharp and rough sound.

In the direction of mutual guide bar movement, the loudness (Z), roughness(Z), and fluctuation strength(Z) of RL3 (3.84 sone, 5.54 asper, 1.72 vacil) and SS2 (6.14 sone, 6.56 asper, 2.54 vacil) were higher than those of RL1 (2.01 sone, 1.95 asper, 0.56 vacil) and SS1 (4.49 sone, 2.44 asper, 2.09 vacil) as shown in Figure 3. But the sharpness(Z) of SS2 (2.30 acum) was much lower than the others. Therefore, the parallel direction of the mutual guide bar movement showed loud, rough, and

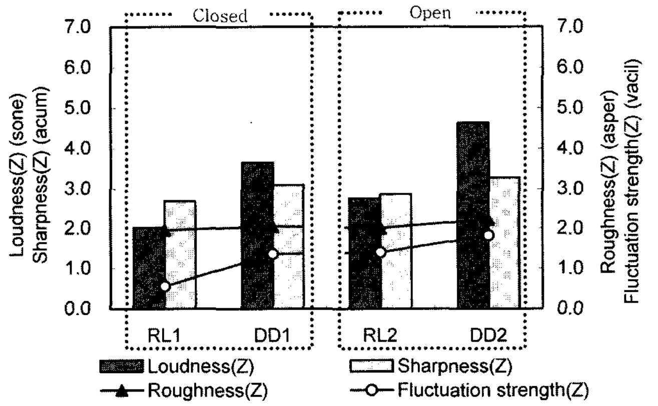


Figure 2. Psychoacoustic characteristics according to lap form.

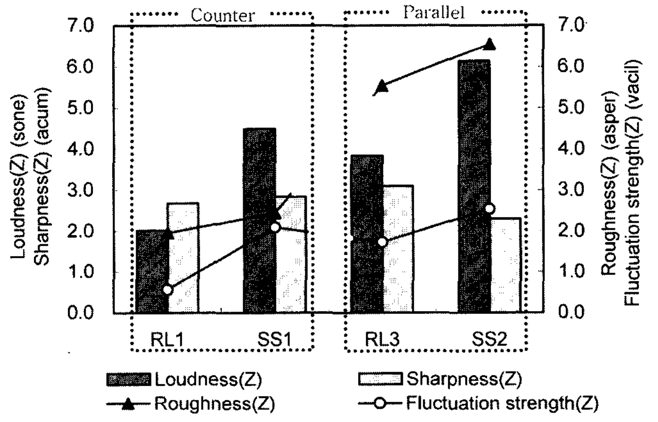


Figure 3. Psychoacoustic characteristics according to direction of mutual guide bar movement.

Table 2. Difference of physiological responses to frictional sound

Specimen	Alpha (%)	Beta (%)	HF/LF (-)	RESP (BPM)	SCL (μS)	PPG (%)
RL1	0.130	–0.149	0.096	0.833	–0.273	-0.021
RL2	-0.205	–0.108	0.061	1.000	–0.219	-0.026
RL3	0.015	0.269	–0.200	1.333	–0.531	-0.055
DD1	–0.554	–0.319	0.138	1.333	–0.163	–0.025
DD2	–0.182	–0.221	–0.238	1.500	–0.239	-0.024
SS1	–0.482	0.004	–0.245	2.250	–0.437	-0.055
SS2	–0.334	0.587	–0.255	1.583	–0.133	-0.023

fluctuating sound as opposed to the counter direction, because the effect of putting the bar in phase greatly increased the internal mobility [3,12]. Roughness(Z) largely increased about 4 asper due to the change from counter to parallel, while it had similar values due to the change of construction type and lap form.

Physiological Responses to Frictional Sound of Warp Knitted Fabric

Table 2 shows the differences of physiological responses from their baselines. According to EEG, alpha wave to almost all the frictional sounds of warp knitted fabrics decreased from their baselines, so frictional sounds of specimens evoked arousal because alpha wave were increased by physiological relaxation and comfort [21]. But beta wave didn't increase in all specimens so that it was agreed with Whang *et al.* [22] that they had reported the increase of the alpha wave is not accompanied with the reduction of the beta wave.

As for ANS signals, PPG decreased especially in RL3 and SS1, but RESP increased because these signals are caused by the constriction of the blood vessel and by increasing respiratory. So, they mean that its sound also evoked negative sensation because of activating the sympathetic nervous system [23]. The difference of HF/LF value, the index of positive sensation or activation of the parasympathetic nervous system, increased in RL1, RL2, and DD1. But, SCL, index of negative sensation, decreased because frictional sounds of warp knitted fabrics didn't cause great excitement because of SCL reflects vigilance and sustained attention as well as heightened arousal [24].

To investigate differences of physiological responses among construction, one-way ANOVA analysis was conducted and then post-hoc test was carried out with Duncan test. RESP showed significant differences among constructions (F=3.89, p<0.05) but the others didn't. Figure 4 appeared changes of RESP according to constructions. SS1 had significantly high RESP, but significant difference between RL1 and DD1 wasn't shown. Therefore, frictional sound of sharkskin having loud and fluctuating sound evoked more negative sensation than that of reverse locknit or double denbigh.

We carried out t-test to analyze differences of physiological responses between closed and open lap or counter and parallel direction,. In lap form, all physiological responses didn't have significant differences. Thus, it means that changes of frictional sound by lap form couldn't be perceived different even though open lap made louder and a larger fluctuating sound than the closed lap type.

In the direction of mutual guide bar movement, physiological

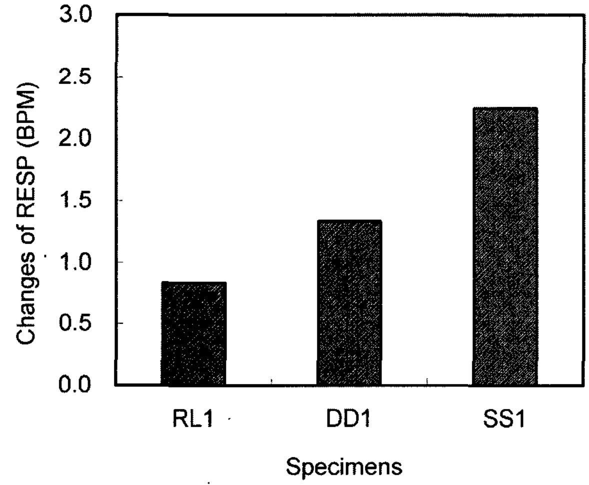


Figure 4. Changes of RESP according to construction.

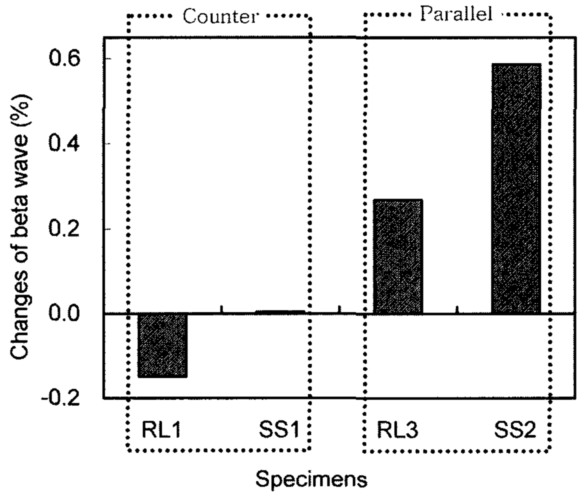
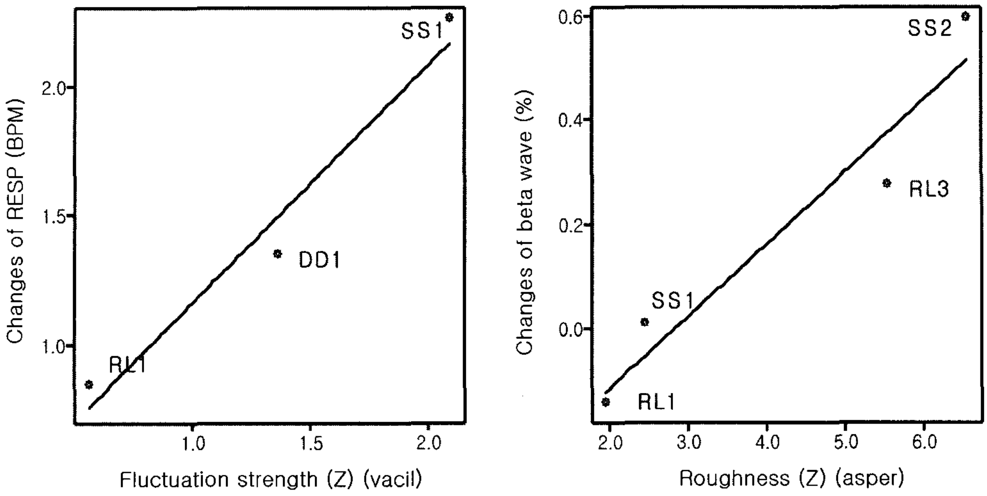


Figure 5. Changes of beta wave according to direction of mutual guide bar movement.



(a) Fluctuation strength(Z) vs. RESP

(b) Roughness(Z) vs. Beta wave

Figure 6. Relationship between sound parameter and physiological response.

responses didn't have significant differences between counter and parallel direction except beta wave. Figure 5 shows changes of beta wave according to direction of mutual guide bar movement. Beta waves of the RL3 and SS2 (parallel direction) were significantly higher than those of the RL1 and SS1 (counter direction) ($t=1.81$, $p<0.1$). As a result, the parallel direction of the mutual guide bar movement evoked the negative sensation because parallel direction made louder and rougher sound than counter direction type.

Effect of Sound Parameters on Physiological Responses

We carried out multiple stepwise regressions to figure out the key sound parameters affecting physiological responses with significant differences according to the structural parameters as mentioned above.

In construction, RESP was regressed by fluctuation strength (Z) ($RESP = 2.71{*}Fluctuation\ strength(Z) - 4.33$, $R^2 = 0.97$). RESP increased wiht fluctuation strength(Z) as given in Figure 6(a). Fluctuation strength(Z) and RESP increased about 0.75 vacil and 0.7 BPM according to construction, respectively.

In case of mutual guide bar movement, changes of beta wave were mainly explained by roughness(Z) ($beta\ wave = 0.14{*}Roughness(Z) - 0.39$, $R^2 = 0.94$). The higher beta wave, the higher roughness(Z) as presented in Figure 6(b). Roughness (Z) and beta wave of parallel direction was about 4 asper and 0.5 % higher than those of counter direction type.

From these results, roughness(Z) and fluctuation strength(Z) were found to be important factors among acoustic parameters of warp knitted fabrics in predicting physiological responses.

Conclusions

In this study, we have investigated the acoustical characteristics of fabric sound according to the structural parameters of warp knitted fabrics and physiological responses evoked by the sounds to find out the factors affecting human auditory sensation. In addition, we analyzed the relationships of sound parameters with physiological responses.

Among the constructions such as reverse locknit, double denbigh, and sharkskin, the sharkskin stitch showed the highest loudness(Z), roughness(Z), and fluctuation strength(Z) values, followed by the double denbigh and reverse locknit stitches. Also, sharkskin had the highest value of RESP than reverse locknit and double dength. Then frictional sound of sharkskin having the highest loudness(Z) and fluctuation strength(Z) values evoked less pleasant sensation than that of reverse locknit or double denbigh.

In regards of the lap form, it was found that loudness(Z), sharpness(Z), and fluctuation strength(Z) of the open lap have higher values than those of the closed lap. Also, all physiological responses didn't have significant differences among specimens. For this reason, sound changes by lap form didn't evoke physiological responses even though open lap was louder and higher fluctuating sound than the closed lap.

In the direction of mutual guide bar movement, loudness(Z), roughness(Z), and fluctuation strength(Z) of the parallel direction were higher values than those of the counter direction. Beta waves of parallel direction were significantly higher than that of counter direction. So, the parallel direction evokes the negative sensation because of its louder and rougher sound than counter direction. Moreover, we found out roughness(Z) and fluctuation strength(Z) were the important factors for prediction of physiological responses. From these results, we have extracted some structural parameters and sound properties as the determinants of human sensations.

Therefore, it can be suggested that designing pleasant sound of warp knitted fabrics will be possible by decreasing roughness and fluctuation strength in sound of warp knitted fabrics through controlling constructions and direction of mutual guide bar movement.

Acknowledgments

This work was supported by Korea Research Foundation Grant (KRF-2002-041-D00580).

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