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Psychoacoustic Characteristics of Fibers

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Abstract : In order to investigate psychoacoustic characteristics of fibers, and to compare them with sound physical parameters, each sound of 25 different fabrics consisted of a single fiber such as wool, cotton, silk, polyester, and nylon was recorded. Sounds of specimens were transformed into critical band diagram and psychoacoustic characteristics including loudness and sharpness for each sound were calculated based on Zwicker's models. Physical parameters such as the level pressure of total sound (LPT), level ranges (ΔL), frequency differences (Δf), AR coefficients (ARC, ARF, ARE) were obtained in fast fourier transform (FFT) spectrum. Nylon taffeta showed higher values for loudness than 2.5 sone corresponding to human low conversation, while most silk fibers generated less louder showing lower values for loudness than 1.0 sone. Wool fibers had higher loudness mean value than that of cotton, while the two fibers didn't differ in LPT. Loudness showed high positive correlation coefficients with both LPT and ARC. Sharpness values were higher for wool fiber group than other fibers. Sharpness was not concerned with loudness, LPT, and ARC, but the fabrics with higher values for sharpness tended to show higher ΔL.

Introduction

There has been a growing demand for fibers and textiles to have sensory effects related with their end uses. Tactile and visual aesthetic performance of textiles is already common requirements. Sound from textiles is recently focused in both fields of research and industry to develop textile products providing consumers auditory satisfaction. A modification was applied to polyester fibers to imitate silk-scrooping. The silky polyester fiber was reported to introduce the silk-scrooping and the pleasant cloth-rustling sound when two edges of a micro-slit of a trilobal shaped cross-section are touched and rubbed. Its silk-scrooping was compared with the sound of natural silk by investigating sonic wave forms in real time analysis[1].

Subjective qualities frequently used to describe sound are loudness, pitch, timbre, and duration[2]. Each of these attributes depends on one or more physical parameters that can be measured. Loudness and pitch are most chosen to characterize sound and identified to be related mainly with sound pressure corresponding to amplitude, and frequency respectively. Loudness, pitch, and timbre should be considered to characterize fabric sound. Sound spectrum shape determines timbre. Therefore sound spectrum by Fast Fourier Transform (FFT)[2] analysis we assumed can be used to characterize fabric sound.

Complex sound such as textile sound can be decomposed into a family of simple sine-waves, each of which is characterized by its frequency, amplitude, and phase. These are called as the partials, and the collection of all the partials can be transformed to a spectrum by FFT. Spectrum analysis by FFT is required in physical analysis of complex sound to specify sound-pressure-level means, and other variables characterizing spectral shapes. Yi and Cho have discussed the physical sound parameters of fibers such as the level pressure of total sound (LPT), level differences (ΔL), frequency differences (Δf), and AR coefficients in a previous work[3]. Pollard[4] pointed out that two other levels of analysis as well as physical analysis adopted for complex sound like music may be psychophysical analysis and feature analysis. The former provides information relating to the properties of human hearing such as mean loudness by spectral weighting, and the latter involves perception and subjective assessment of sound including sharpness, roughness, and other cues.

Considering auditory effects of fibers on garments wearer's sensation, it should be undertaken to observe the sound characteristics of fibers concerned with the two analyses mentioned above. Psychoacoustic models established by Zwicker[5] have been utilized widely as measurable sound parameters reflecting human auditory sensation. Sensory attributes including loudness, sharpness, roughness, rhythm, sensory pleasantness, and tone to noise can be quantified by the models. Loudness and sharpness calculations were adopted as most reliable and predictable for sound sensation. Therefore it is necessary to investigate psychoacoustic characteristics of fibers such as loudness and sharpness by Zwicker's models for identifying sound dimensions of fibers relating to human hearing.

The purpose of this study is to examine psychoacoustic characteristics of five different singular fiber-constituted fabrics including wool, cotton, silk, polyester, and nylon fabrics, based on Zwicker's models, and to compare them

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with physical sound parameters quantified from FFT spectrum.

Experimental

Specimen

Test specimens were commercially available woven fabrics. The total number of specimens was 25 and the component fibers contents of the specimens were wool, cotton, silk, polyester, and nylon. In each fiber group, 5 different fabrics were sampled. Characteristics of specimens are summarized in Table 1.

Sound Generation and Recording

Two pieces of each specimen were rubbed against each other using the instrument[3] designed to generate the sound of the fabrics reproducibly without any noise which may disturb fabric sound. The sound generator enabled the fabrics to rub by making a piece of fabric mounted on the other fabric move with a constant velocity by controlling both the accelerated velocity by gravity and energy loss due to oil flowing in the piston connected with the upper fabric. The principle of the instrument The sound generator enabled that is picked up by a microphone (Type 4145, B & K) and recorded by a DAT (Digital Audio Tape) recorder (TEAC RD-145T). Calibration data were obtained at a level of 113.6 dB and 1 kHz before recording the sound. Sound recording was performed in an anechoic chamber in which the loudness of the background noise and the cutoff frequency were below 10 dB and 63 Hz, respectively.

Psychoacoustic Parameters

Loudness and sharpness in Zwicker's models were selected as psychoacoustic parameters for the sound from fibers. From prerecorded sound of each specimen, loudness and sharpness were calculated using a software (SDRC-based Sound Quality System Type 3800, B & K). The calculations were based on the following functions.

(1) Sound Transformation

The recorded sounds were analyzed with a FFT analyzer (Model 35670A, HP). A sound spectrum was obtained for each specimen under the conditions that the frequency interval (Δf) is 16 Hz and the maximum frequency (f_{max}) is 25,600 Hz. For the calculation of psychoacoustic parameters, the FFT spectrum of the sound from each specimen was converted into critical band diagram in terms of bark unit.

Table 1. Characteristics of specimens

Specimens	Fiber Component	Yarn Type	Construction	Fabric Type	Thickness (mm)	Weight (g/m^2)
W1	wool 100%	staple	twill	gabardine	0.44	192.4
W2			plain	saxony	0.46	232.4
W3			plain	melton	0.68	405.2
W4			twill	gabardine	0.62	244.3
W5			plain	tropical	0.28	154.6
C1	cotton 100%	staple	satin	sateen	0.19	131.8
C2			plain	waffle cloth	0.32	163.7
C3			plain	dobby	0.23	128.9
C4			plain	muslin	0.25	108.1
C5			plain	pique	0.23	137.9
S1	silk 100%	filament (S4: warp-staple)	plain	crepe de chine	0.18	65.1
S2			plain	chiffon	0.19	55.3
S3			plain	geogette	0.24	71.0
S4			satin	satin	0.18	90.0
S5			plain	shantung	0.36	140.4
P1	polyester 100%	filament (P2 : staple)	twill	crepe	0.57	235.8
P2			twill	peach skin	0.30	142.8
P3			satin	satin	0.17	85.8
P4*			plain	taffeta	0.28	163.5
P5			plain	taffeta	0.08	48.7
N1	nylon 100%	filament	plain	taffeta	0.31	188.9
N2*			plain	taffeta	0.10	65.5
N3			plain	taffeta	0.20	101.8
N4*			plain	taffeta	0.14	106.1
N5			twill	peach skin	0.23	131.3

*means polyurethane coated.

(2) Loudness

Loudness, N, is the integral of specific loudness, N', over critical band rate. The unit of critical band rate is bark. The unit 'bark' is the one critical band in frequency ranges. The 24 bark corresponds to 15,500 Hz, approximately.

$$N = \int_0^{24Bark} N' dz \tag{1}$$

N : loudness
N' : specific loudness
z : bark

$$N' = 0.08\left(\frac{E_{TQ}}{E_0}\right)^{0.23}\left[\left(0.5 + \frac{E}{2E_{TQ}}\right)^{0.23} - 1\right]\frac{sone_G}{Bark}$$

E_{TQ} : excitation at threshold in quiet
E_0 : excitation corresponding to the reference intensity $I_0 = 10^{-12}$ W/m^2
G : a hint for the user that the loudness is produced using the critical-band levels

(3) sharpness

$$S = 0.11\frac{\int_{0Bark}^{24Bark} N' g(z) dz}{\int_{0Bark}^{24Bark} N' dz} acum \tag{2}$$

S : sharpness
N' : specific loudness
N : loudness
$g'(z)$: weighting factor as a function of critical band-rate, $e^{0.171z/bark}$
z : bark

Physical Parameters

As physical parameters of sound from fibers, LPT, ΔL, Δf, and three AR coefficients (ARC, ARF, ARE) were obtained from FFT spectrum in terms of amplitude and frequency.

(1) LPT

The value of the Level Pressure of Total Sound (LPT) is a physical parameter for loudness. LPT for each specimen was calculated in the range of 16~20,000 Hz considering human hearing range. The equation was as follows:

$$\mathrm{LPT(dB)} = 10 \log 10^{\frac{BL_1}{10} + \cdots + \frac{BL_n}{10}} \tag{3}$$

where, BL : Broadband Level

(2) Level Range (ΔL)

$$\Delta L(\mathrm{dB}) = \text{maximum amplitude } (\mathrm{dB}_2) - \text{minimum amplitude } (\mathrm{dB}_1) \tag{4}$$

(3) Frequency Differences (Δf)

$$\Delta f(\mathrm{Hz}) = \text{frequency}_{\text{at maximum amplitude}}\,(f_1) - \text{frequency}_{\text{at minimum amplitude}}\,(f_2) \tag{5}$$

(4) AR coefficients (ARC, ARF, ARE)

Linear trends in frequency with autoregressive (AR) error were fitted to amplitude. The AR functions were applied to frequencies in the range of 16~20,000 Hz as well as LPT. The AR functions developed for this study were as follows;

$$\tilde{y}_1 = \hat{y}_1, t = 1 \tag{6}$$

$$\tilde{y}_t = \hat{\alpha} + \hat{\beta}x_t + \tilde{\phi}\varepsilon_{t-1}, t = 2, \cdots, n \tag{7}$$

where $\tilde{\varepsilon}_{t-1} = y_{t-1} - \hat{y}_{t-1}, \hat{y}_{t-1} = \hat{\alpha} + \hat{\beta}x_{t-1}$.

$\tilde{y}_t$: estimated value of y (amplitude)
$\hat{y}_1$: estimated value of y (amplitude), when $t = 1$
t : frequency order
(when $t = 1$, frequency value is 16 Hz, when $t = 2$, frequency is 32 Hz)
x_t : value of tth frequency
(when $t = 1$, frequency is 16 Hz,)
$\hat{\alpha}$: constant, named as ARC
$\hat{\beta}$: coefficient of x_t term, named as ARF
$\hat{\phi}$: coefficient of ε_{t-1} term (error term), named as ARE

The ARC, ARF, and ARE were considered to characterize the spectral shapes of fabric sounds and were investigated for their relationship with mechanical properties.

Results and Discussion

Psychoacoustic characteristics of fibers

(1) Loudness

Psychoacoustic parameters of the specimens were given in Table 2. Loudness ranged from 0.21 sone (S4) to 3.43 sone (N1). Subjective loudness for pure tone of 40 dB and 1000 Hz corresponds to 1 sone. Loudness value for S4 was similar to that for rustling leaves (0.2 sone), while the value for N1 to that for low conversation (2~5 sone). This means that the silk satin generated less noise, while nylon taffeta could border both wearers and others due to its considerably louder sound.

To investigate the distribution of sound parameters with a variation with fiber contents, mean values were obtained for each parameters of five different fiber groups. Figure 1 illustrates mean value and standard error for loudness of each fiber group. Silk fibers showed the lowest mean value for loudness. As presented in Table 2, all of silk fibers generated sounds of which loudness values were below 1 sone. This means that sound from silk would not be perceived as considerable noise. As predicted, nylon group showed the highest mean value of loudness corresponding to human speech, which implies that wearers could accept nylon sound as uncomfortable. Polyester fibers showed a variety of loudness values according to their fabric types, which similar to LPT values

Table 2. Values for physical sound parameters of specimens

Specimens	psychoacoustic parameters		physical parameters					
	loudness (sone)	sharpness (acum)	LPT (dB)	ΔL (dB)	Δf (Hz)	ARC	ARF	ARE
W1	1.20	4.27	52.96	31.54	-5936	38.60	-0.0025	0.9984
W2	2.02	4.52	54.97	21.42	-4704	37.88	-0.0023	0.9984
W3	2.22	4.23	52.86	22.95	-19872	38.88	-0.0024	0.9979
W4	0.98	4.82	48.74	24.64	-4736	38.45	-0.0027	0.9982
W5	0.68	4.50	50.04	34.48	-6832	39.61	-0.0028	0.9986
C1	1.11	3.56	50.41	26.26	-7408	36.29	-0.0026	0.9983
C2	0.76	3.76	50.15	33.87	-6240	36.98	-0.0028	0.9985
C3	1.12	3.41	51.16	28.64	-7184	35.31	-0.0025	0.9977
C4	0.71	3.40	52.03	40.19	-7200	40.93	-0.0031	0.9988
C5	0.63	3.14	49.33	36.91	-7056	36.31	-0.0029	0.9987
S1	0.32	3.67	52.49	52.37	-7424	27.04	-0.0024	0.9981
S2	0.47	4.87	41.16	25.81	-4096	29.60	-0.0025	0.9983
S3	0.68	4.35	44.10	23.60	-4848	31.12	-0.0025	0.9983
S4	0.21	3.70	36.62	37.35	-9024	25.78	-0.0027	0.9982
S5	0.49	4.12	47.50	34.41	-7424	37.80	-0.0029	0.9988
P1	1.05	5.07	52.71	33.72	-4688	38.55	-0.0024	0.9986
P2	0.28	3.99	42.37	41.13	-5728	30.88	-0.0029	0.9985
P3	0.22	3.70	34.22	39.08	-8560	23.32	-0.0027	0.9982
P4	2.99	4.70	62.30	21.08	-3920	46.55	-0.0023	0.9986
P5	2.14	2.45	61.30	47.75	-8528	40.86	-0.0026	0.9968
N1	3.43	4.42	61.91	18.65	-2592	47.77	-0.0024	0.9985
N2	2.65	2.92	44.87	41.01	-19872	24.12	-0.0018	0.9955
N3	2.40	4.52	61.43	35.99	-8256	43.16	-0.0023	0.9979
N4	2.54	3.60	56.39	19.11	-2944	39.56	-0.0020	0.9984
N5	1.47	4.11	49.62	25.10	-19904	35.10	-0.0020	0.9975

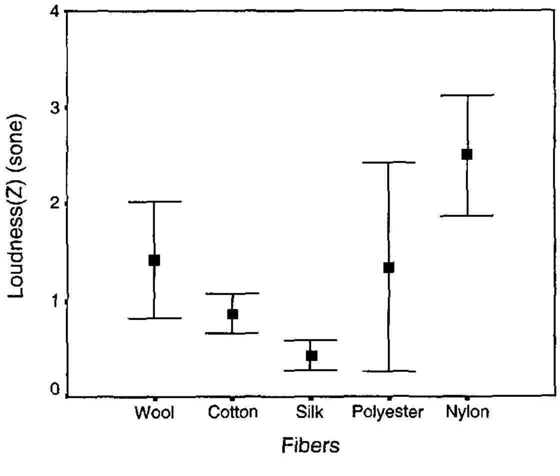

Figure 1. Distribution of loudness Values for Specimens.

previously reported[3] as that polyester fabrics generated sound similar to that of fabrics which polyesters try to resemble.

(2) Sharpness

As given in Table 2, the highest values for sharpness of fibers was 5.07 acum (P1), while the lowest 2.45 acum (P5). The values were higher than those for woodwinds reported as 0.5~2.0 acum[6]. Sharpness is a measure of the amount of high frequency content in the FFT spectrum[7]. Polyester, crepe (P1) seemed to have higher amplitude values in higher frequency ranges than the other specimens. Sharpness can be calculated on the basis of the loudness calculation, however sharpness has been reported not to be much related with sound level, particularly in range of 30~90 dB[8]. Therefore sharpness seemed not to be correlated with the parameters such as LPT and loudness in this study. Distribution of sharpness values according to fiber component is given in Figure 2. As expected from Table 2, wool fiber group showed the highest mean value of sharpness, while cotton the lowest value. Nylon which showed the highest mean value for loudness had lower sharpness than any other fiber group except cotton. This result suggests that sound from nylon fibers was not so sharper than other fibers even though it was the loudest by Zwicker's theory. However it needs to identify the relationship between Zwicker's sensory attributes such as loudness and sharpness and sensory scales by subjective evaluation.

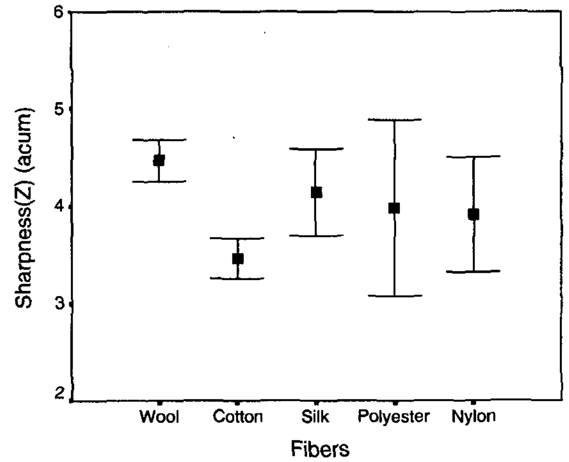

Figure 2. Distribution of sharpnesss (Z) Values for Specimens.

Physical sound parameters of fibers

Physical sound parameters including LPT, ΔL, Δf, three AR coefficients (ARC, ARF, and ARE) were obtained from FFT spectra. The values are presented in Table 2. The LPT values of specimens ranged from 34.22 dB (P3) to 62.30 dB (P4). These are the values corresponding to those of office (40~50 dB) and normal conversation (50~60 dB). Level Range (ΔL) was from 18.65 dB (N1) to 52.37 dB (S1). Through FFT analysis, the details of which was in the previous work[3], silk crepe de chine (S1) had 48.72 dB for the maximum amplitude at 96 Hz and -3.64 dB for the minimum amplitude at 7520 Hz, and nylon taffeta (N1) rarely showed a curved shape in its spectrum so that the difference of the minimum amplitude from the maximum one was very small. Frequency differences (Δf) were ranged from -19904 Hz (N5) to -2592 Hz (N1). Sound spectra of fabrics were described with three coefficients of AR functions (ARC, ARF, and ARE). The ARC, a constant of the AR functions, corresponds to the amplitude value at 16 Hz. The values of ARC ranged from 23.32 (P3) to 47.77 (N1). The ARF and ARE values of specimens are given in Table 2. Their values were ranged from -0.002 to -0.003, and from 0.996 to 0.999, respectively. Even though the values of both ARF and ARE were not varied among the specimens as shown in Table 2, they were significant because they were related to the shape of the spectrum.

(1) LPT

Figure 3 presents mean values and standard error for LPT values of each fiber group. Means for LPT of wool, cotton, and polyester fiber group were not quite different. Especially wool and cotton fabrics were expected to generate sounds of similar levels. Wider range of the standard error for polyester group indicated that LPT values vary very much with their fabric types. Silk fiber group showed the lowest mean value for LPT as expected as the least loud in terms of spectral shapes of fabrics. The loudest fabrics were nylon fabrics.

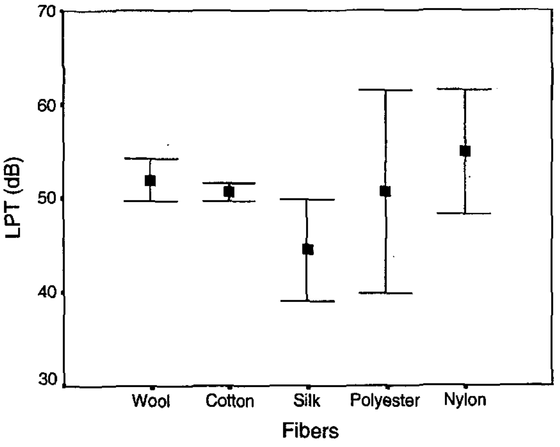

Figure 3. Distribution of LPT Values for Specimens.

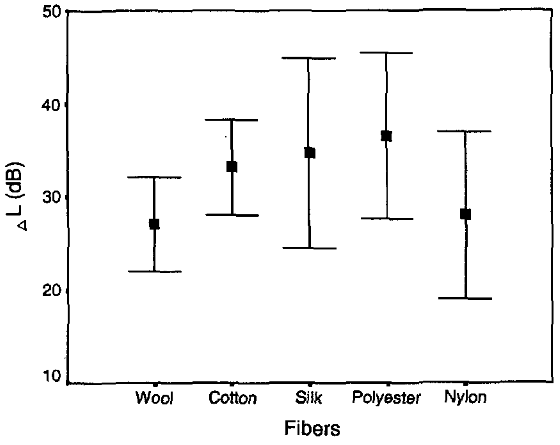

Figure 4. Distribution of ΔL Values for Specimens.

(2) ΔL and Δf

Figure 4 is for the mean value and standard error for level range (ΔL) of each fiber group. The mean value of ΔL was the highest for polyester group while the lowest for wool and nylon. As discussed in the previous study[3], peach skin (P2), satin (P3), and taffeta (P5) had deep curves in their spectra so that the differences between maximum amplitude and minimum amplitude were higher than other fabrics. On the other hand, the spectra for wool fabrics and nylon fabrics were more flat and less curved than those of other fiber groups.

Figure 5 presents the mean values and standard errors for frequency differences (Δf) of five different fiber groups. Every fiber group had negative values for Δf, which means that the frequency values with maximum amplitudes were lower than those with minimum amplitudes. Cotton, silk, and polyester fiber groups showed similar mean values for Δf to one another. The mean

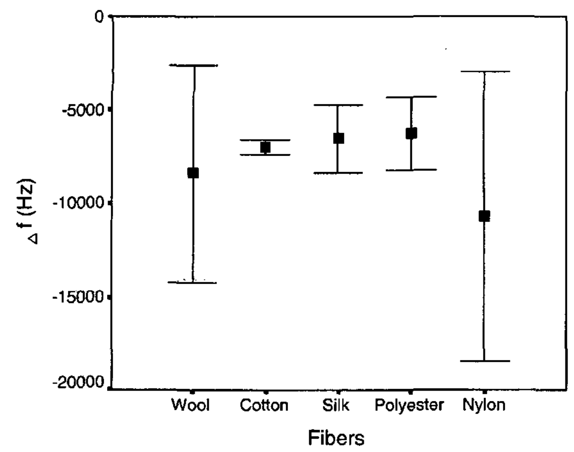

Figure 5. Distribution of Δf Values for Specimens.

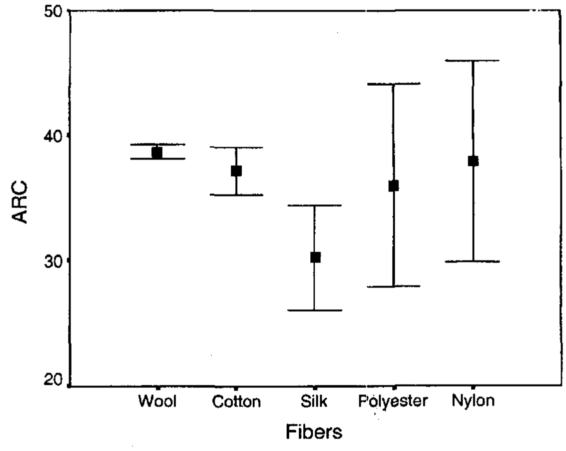

Figure 6. Distribution of ARC Values for Specimens.

value for Δf of nylon fiber group was lower than those for any other fibers. This indicates that the distances between frequency values of minimum amplitudes and of maximum amplitudes for nylon fabrics were generally longer in spectra than those of other fabrics. However standard error for nylon fiber group suggests that Δf values for the fiber group varied. N1 (taffeta) and N4 (polyurethane coated taffeta) showed higher Δf values than any other fabrics in other fiber groups, while N2 (polyurethane coated taffeta) and N5 (peach skin) did the lowest values among all of specimens. Distribution pattern of ΔL and Δf among fiber groups were different from those of LPT.

(3) AR coefficients

Among the three AR coefficients (ARC, ARF, ARE), distributions of ARC with fiber groups were investigated because ARC values had a variety among specimens. Figure 6 gives the mean value and standard error for ARC of each fiber group. Silk fiber group had the lowest mean values for ARC while nylon fiber and wool fiber group showed the highest ones. It was reported that ARC values were correlated positively with LPT values of fabrics[3]. Mean values of silk fiber group supported that results. Furthermore wider range of standard error for ARC of polyester fiber group was identical to that for LPT of that fiber. However both of wool and cotton which were lower in mean values for LPT showed similar mean values for ARC to that of nylon fiber group. This means that the amplitude values at 16 Hz of the three fiber groups were similar to one another while LPT values for wool and cotton fiber were lower than those for nylon fibers.

Relationship between psychoacoustic characteristics and physical sound parameters of fibers

Relationship between psychoacoustic characteristics and physical sound parameters of fibers were examined by using Pearson's correlation coefficients[9]. Table 3 summarizes the results of correlation analysis among the parameters. Similar to the result of the previous study[3], LPT and ARC showed the highest correlation coefficient value ($r = 0.869$). In this study, loudness was found to be highly positively correlated with LPT ($r = 0.861$) and ARC ($r = 0.813$), respectively. This means that the physical and psychoacoustic parameters describing sound loudness were highly correlated to one another. A significant correlation was found between loudness and ARF, and loudness and ΔL, respectively. loudness had a tendency to increase with higher ARF ($r = 0.626$). This

Table 3. Correlation coefficients among psychoacoustic and physical sound parameters of fibers

	loudness	sharpness	LPT	ΔL	Δf	ARC	ARF
loudness							
sharpness	0.022						
LPT	0.861**	-0.141					
ΔL	-0.444*	-0.539**	-0.164				
Δf	-0.131	0.318	-0.037	-0.168			
ARC	0.813**	0.017	0.869**	-0.410*	0.070		
ARF	0.626**	0.278	0.436*	-0.349	-0.312	0.214	
ARE	-0.263	0.386	-0.243	-0.182	0.517**	0.014	-0.403*

*means $p<0.05$.
**means $p<0.01$.

implies that the amplitude values having positive influence on loudness seemed to increase with higher values for x term in AR functions. On the other hand, ΔL showed a negative correlation with loudness, which means that the loudness values increased with lower level ranges. Sharpness showed a significant correlation with ΔL. Correlation coefficient value ($r = 0.539$) indicated that the sharpness decreases with higher level ranges. Since the fabrics with lower level ranges tended to have higher amplitudes in high frequency ranges, their sharpness were thought to be higher than other fabrics.

From these results, psychoacoustic characteristics of fibers could be correlated partly with physical sound parameters. It is noted that sharpness values of fibers by Zwicker's model were concerned with the level ranges in spectral analysis.

Conclusions

This study was carried out to examine psychoacoustic characteristics of five different fibers, and to identify their relationship with physical sound parameters. Sound from each of 25 fabrics, constituted of singular fibers including wool, cotton, silk, polyester, and nylon was recorded and transformed to FFT spectrum for the physical analysis and critical band diagram for psychoacoustic examination, respectively. As psychoacoustic characteristics, loudness and sharpness, defined in Zwicker's models, were calculated for each sound of fibers. Silk fibers showed the loudness lower than 1.0 sone, while nylon taffeta fabrics had 2.5~3.4 sone for loudness which is sufficiently loud to make wearers uncomfortable. Wool fibers had higher loudness values than cotton, while the two fibers were not different in LPT, a physical sound parameter. This implies that wool and cotton may be different in psychoacoustic loudness, even though they were similar to each other in physical measurement for loudness. Sharpnessrange was from 2.45 to 5.07 acum, which were much higher than those of woodwinds instruments. The values for sharpness of fibers were not concerned with loudness and LPT. Because LPT for most of fibers were between 30 and 60 dB, the sharpness reported to be affected by level pressure higher than 90 dB was not related to loudness and LPT in this study. This results enabled us to expect subjective sensation for sound from fibers, however the relationship between the psychoacoustic characteristics and sound sensation by subjective evaluation should be identified in a further study.

This study has strong implication for informing both of wearers and manufacturers on psycho-physical characteristics of sound from fibers. Further study is required to examine the relationship between psychoacoustic characteristics and subjective sound sensation of fibers, and to investigate other models for psychoacoustic characteristics of fibers.

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