An Objective Index that Substitutes for Subjective Quality of Vibrotactile Material-Like Textures

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Abstract—The presentation of textures is a major application of vibrotactile displays. Lossy data compression is an effective approach for reducing a data size of such textures when delivering them through the Internet. This study developed an objective index that well described material-like textures’ quality changes caused by data compression processes. We introduced a linear combination of the power and amplitude spectra that were weighted by the inverse of a detection threshold curve of vibrotactile stimuli. This combination described the quality deterioration of compressed textures to an accuracy of approximately 80%. These objective indices enhance the development of the lossy data compression algorithms without psychological evaluation tests of subjective quality changes in the textures.

I. INTRODUCTION

The vibrotactile display is one of the most prevalent tactile displays. The presentation of virtual textures of materials such as cloth or paper is a major application of these displays. Several researchers have attempted to present the textures of specific materials such as cloth, paper or metal (e.g., [1], [2], [3], [4], [5]). In the near future, the tactile textures will be delivered on the Internet through vibrotactile displays installed on computer mice or mobiles in our daily lives. Such devices have already commercially been attempted by, for example, iFeel MouseMan from Logitech or a tangible mouse from Fuji Xerox Corp.

In spite of the growing broadband, the data compression of audiovisual data is effective for data reduction especially for mobiles for which communication bands tend to be limited. Data reduction methods are also effective for the delivery of tactile textures. We have proposed lossy data compression algorithms for vibrotactile displays [6]. We developed three types of the algorithms and showed that the linear quantization of vibrotactile amplitudes could reduce data sizes of the textures by approximately 75% while remaining their subjective qualities. In the field of haptics, the data reduction for tactile textures has been rarely attempted while some force/position feedback systems employed such data reduction (e.g., [7], [8], [9]).

Psychological experiments are needed for evaluating the performance of the data compression algorithms. Experimental participants compare uncompressed and compressed vibrotactile textures and rate their quality differences subjectively. At least several participants need to take part in the experiments for such an evaluation. The cost of these psychological experiments is a large burden on developers of the algorithms. An objective index that accounts for the quality changes in the compressed textures is effective for diminishing such costs and enhancing the development of the algorithms.

The objective of the present study is to develop an objective index that accounts for subjective quality in material textures that are deteriorated by data compressions. The objective index predicts the perceptual quality changes in textures from their physical characteristics. Such objective indices for tactile textures have yet to be reported so far. One engineering benefit is that these indices allow us to evaluate the performance of compression algorithms without conducting psychological experiments, which accelerates the development of such algorithms. Further, good indices contribute to understanding of perceptual properties of vibrotactile material-like textures by identifying physical quantities that influence our perception.

In the present article, we focus on the development of the objective index that well describes the results of psychological experiments. As to such experimental results, we use those in our previous report [6]. An experimental setup (Section II), the data compression algorithms (Section III), and procedures and results (Section IV) are briefly overviewed. In Sections V and VI, we describe the development of the objective index and its evaluation, respectively. We apply the index to two types of material-like textures in this study, while the goal of this index is the objective rating of various vibrotactile textures.

II. EQUIPMENT AND MATERIAL

A. Vibrotactile Texture Display

A vibrotactile display composed of one tactor (Fig. 1) was used in this study. As a stimulator, a piezo-stack actuator (NEC/TOKIN, AHB800C801FPOLF, Sendai, Japan) was installed on a frictionless linear slider (SS series, NSK, Tokyo, Japan). The slider’s position on the guide was measured by an optical linear encoder (SR-P1000, Canon, Tokyo, Japan) whose resolution was set to 0.4 μm. When a participant in the experiments placed his/her finger on the vibrator and moved his/her hand along the X-axis, the vibrator slid along the guide and produced displacements along the Z-axis, reproducing the surface profile of the material’s texture. The refresh rate for the voltage output to the vibrator was 3.0 kHz.

The output force of the stimulator was approximately 800 N, which is large enough compared to the force applied...
by the finger that the latter does not cause the output displacements to decay. The maximum output displacement was approximately 80 μm at an applied voltage of 150 V. The displacement changed linearly with the input voltage when the frequency was fixed. The frequency response curve was relatively flat and did not exhibit resonance in the range used for the experiments (up to 400 Hz). The frequency response reached -3 dB at 270 Hz. To compensate for attenuation at high frequencies so that the desired displacements are output, the voltage inputs to the stimulator were multiplied by the inverse function of the frequency response curve. Voltage was applied to the stimulator through a bipolar amplifier (FRA5014, NF, Yokohama, Japan). The contactor was circular with a diameter of 11.6 mm.

B. Material Textures

As material-like textures for the experiments, a board made from the wood of the Judas tree and sandpaper (#1500) were chosen. A non-contact surface measure (NH-3SP, Mitaka Kohki, Mitaka, Japan) was used to measure the surfaces for 10 mm with an interval of 0.5 μm. These two types of textures are perceptually dissimilar and easy for the experimental participants to discriminate them. In section 5, the objective measure is adopted to these textures that are fairly considered to have different characteristics.

III. LOSSY DATA COMPRESSION OF VIBROTACTILE TEXTURES

A. Data Compression using Discrete Cosine Transformation

The two compression algorithms used in this study were originally introduced in [6]. The compressions were performed in frequency space in order to make use of perceptual properties of vibrotactile stimuli, such as detection and differential thresholds. These thresholds are often discussed in frequency space.

Discrete cosine transformation (DCT) was used to convert the texture profile to a frequency spectrum. By computing the DCT of texture height samples $y_n$ ($n = 0, ..., N - 1$), amplitude spectra $C_k$ ($k = 0, 1, ..., N - 1$) were acquired. $C_k$ is given by

$$C_k = \frac{2}{N} \sum_{n=0}^{N-1} y_n \cos \left( \frac{(2n+1)k\pi}{N} \right) \quad k = 1, ..., N' \tag{1}$$
$$C_k = 0 \quad k = 0, N' + 1, ..., N - 1 \tag{2}$$

where $N$ is the number of samples: $N = 20000$. This is type-II DCT with the factor of $2/N$ that makes the DCT indices express the amplitudes of each frequency component. The DC component $C_0$ was not used, since it does not influence perception. The $N$th DCT index corresponds to the amplitude of the 400-Hz component. Because the command refresh rate of the vibrotactile display was 3.0 kHz, elements with a frequency higher than 400 Hz were removed in order to maintain smooth profiles of the texture surface.

The frequency $f_k$ for the $k$th DCT index is determined by

$$f_k = \frac{\text{Sampling frequency} \cdot k}{\text{Number of samples} \cdot N} = \frac{\pi \cdot k}{L} \tag{3}$$

where $L$ and $\pi$ are the distance over which the texture surface was measured (10 mm) and the average velocity of participants’ exploratory hand movements, respectively. The average velocity was set in a range in which natural explorations were not disturbed (50 mm/s). In the experiments described below, participants conducted their exploration following the rhythm of a metronome and used a specified stroke length to achieve this average velocity as far as possible (as described in Section IV-A).

The data-compression algorithms described in the next subsection were applied to $C_k$ and converted it into $C'_k$. The converted DCT indices $C'_k$ were re-converted to texture height profiles $y'_n$ through an inverse DCT. $y'_n$ was acquired from

$$y'_n = \sum_{k=1}^{N'} C'_k \cos \left( \frac{(2n+1)k\pi}{N} \right) \quad n = 0, 1, ..., N - 1. \tag{4}$$

B. Data Compression Algorithms for Vibrotactile Material Textures

1) Linear Quantization: Quantization is one of the most popular strategies for lossy data compression. The quantized amplitude spectrum $L_k$ is determined by

$$L_k = \text{round} \left( \frac{C_k}{\Delta} \right)$$

where $\Delta$ is the quantization step. $\Delta$ is expressed as

$$\Delta = \frac{\max(C_1, ..., C_{N'}) - \min(C_1, ..., C_{N'})}{L - 1} \tag{5}$$

where $L$, the number of quantization steps, determines the compression level. Figs. 2a and 2b show an example of the surface profile and DCT indices, respectively, of the uncompressed and linearly quantized ($L = 4$) wood textures. Given that each DCT index of the uncompressed texture was written in 2 bytes, the data size of the compressed texture in the figure was 12.5% of the size of the uncompressed data.
2) Truncation of Data beneath Shifted Thresholds (Threshold-Cut): Assuming that vibrotactile amplitude elements beneath the detection threshold level can be removed while maintaining subjective quality, we may use the method described here to eliminate vibratory amplitudes smaller than the thresholds. When they are removed, the DCT indices are determined by

\[
T_k = \begin{cases} 
0 & \text{if } \log_{10}|C_k| < \log_{10}b(f_k) + b_0 \\
\frac{20}{C_k} & \text{otherwise}
\end{cases} \tag{7}
\]

where \(b(f_k)\) and \(b_0\) are the detection thresholds at frequency \(f_k\) and a variable for shifting the threshold curve, respectively. \(b_0\) determines the compression level of the method. For example, when \(b_0 = -2\) dB, amplitudes smaller than the -2-dB-shifted threshold curve are truncated.

The function \(b(f_k)\) was preliminarily acquired by a psychophysical method of adjustment involving six participants, using the same equipment as that in this study. For the 12 frequencies, detection thresholds were investigated. The values of the intermediates of the investigated frequencies were determined by linear interpolation. The thresholds were acquired while the hand was still.

Figs. 3a and 3b show the surface profiles and DCT indices, respectively, of the wood textures compressed by this method when \(b_0 = 0\) dB. Fig. 3b shows that the compressed texture does not include vibratory amplitudes smaller than the threshold curve. In this example, since 51.2% of the amplitudes are truncated, the compression ratio is regarded as 48.8%. However, it should be noted that the actual compression ratio depends on encoding algorithms. Hence, this value is a brief estimation.

**IV. EXPERIMENT: SUBJECTIVE COMPARISON OF DATA-COMPRESSED TEXTURES**

**A. Tasks and Participants**

*a) General:* The participants evaluated the subjective similarity between the uncompressed and compressed vibrotactile wood textures and sandpaper. These two types of textures were evaluated by different participants. They rated the similarity on a four-point grading scale. The compression levels of the textures were 6 or 7 grades for both the compression methods.

*b) Tasks:* In a single trial, the participants explored and compared the uncompressed and compressed textures. In the trial, each texture was presented to the participants for 5 s. To adjust the average hand velocity of the participants to 50 mm/s (see Section III-A), the participants moved their hands in strokes of 40 mm in accordance with the rhythm of a metronome (1.25 Hz) in a pattern of one forward stroke for one beat and withdrawal for two beats. Marks on the desk indicated the stroke distance (Fig. 1). During the exploration of two textures in a single trial, the participant was required to attempt to retain the contact status between his/her finger and the stimulator. After exploring the two textures, the participants manually recorded the similarity as “same,” “possibly the same,” “possibly different,” or “different.”

*c) Test Stimuli:* The texture compression levels were fixed to 6 or 7 grades for each compression method. Table I lists the compression levels used in the experiments. In addition to the data-compressed textures, the uncompressed textures were included in the test stimuli. In total, thirteen and fourteen test stimuli were prepared for wood textures.
and sandpaper, respectively. Each test stimulus was presented four times in total. Hence, each participant performed 52 (13 textures × 4 repetitions) or 56 (14 textures × 4 repetitions) trials for wood texture and sandpaper, respectively. The order of presentation of test stimuli was random.

d) Participants: The participants were eight volunteers in their 20s from the authors’ laboratory, excluding the authors. Hence, these experiments are preliminary studies. To shut out the sounds generated by the stimulator, the participants listened to pink noise through noise-cancellation headphones.

B. Results: Changes in Subjective Quality of Compressed Textures

e) Wood texture: Fig. 4 shows the averages and standard deviations of the dissimilarity rates between the uncompressed and compressed vibrotactile wood textures for the two types of data-compression methods. The values in the figure were computed by assigning values of 0, 1, 2, or 3 to “same,” “probably the same,” “probably different,” and “different,” respectively. It should be noted that the value for uncompressed texture—the rightmost circle and diamond in Fig. 4—was not 0. In general, the score increased (similarity decreased) as the data size of the compressed textures decreased. The changes in the scores were not monotonic. For linear quantization, the changes showed a slight plateau around $L = 8$. For small compression rates of linear quantization, the scores increased exponentially.

f) Sandpaper: Fig. 5 shows the dissimilarity rates between the uncompressed and compressed sandpaper textures. Just as for the wood textures, the dissimilarity tended to increase as the compression ratio decreased.

V. Development of Objective Index That Accounts for Subjective Quality Change of Compressed Textures

A. Related Studies: Pacinian-Filtered Power Spectrum

Bensmaïa et al. reported that the power of cutaneous mechanical vibrations can be used to describe the subjective intensity of vibrotactile stimuli or fine textures. The difference in perceived roughness of two fine textures correlated with the difference in the power of high-frequency vibrations of the finger pad when those textures were explored by bare fingers [10]. They weighted the frequency power spectrum of cutaneous vibrations by the square of the inverse quasi-detection threshold curve of Pacinian corpuscles. These Pacinian-filtered power spectra also correlated with the subjective intensities of vibrotactile stimuli at high frequencies [11]. They limited their studies to high-frequency vibrations; however, we need to develop an objective index taking account of the stimuli of low- or middle-frequency bands around tens of hertz, so that the index can be applicable to material-like textures that have frequency components across wide frequency bands.

B. Approach of This Study: Threshold-Filtered Power and Amplitude Spectrum

To develop a new objective index, first, we extend the Pacinian filter used by Bensmaïa et al. to the entire frequency band. Second, in order to properly evaluate the perceptual effects of the vibrotactile stimuli at tens of hertz, we introduce a threshold-filtered amplitude spectrum. These two features are described in the following two subsections.

1) Extension of Weighting Filter across the Entire Vibrotactile Frequency Band: Weighting the power spectrum by the inverse of the detection threshold curve is equal to weighting the vibratory power in accordance with the sensation magnitude of each frequency stimulus. This is because, especially near the detection threshold level, the profiles of equal sensation magnitude curves are similar to those of the detection threshold curves [12]. Following this idea, we extend the Pacinian filter to the entire frequency band. To this end, we use the detection threshold curve for the vibrotactile stimuli of the entire frequency band as a
Fig. 6: Profiles of the psychophysical weighting filters for vibrotactile stimuli

weighting filter of frequency spectra so that the objective index can be available to the vibrations of tens of hertz.

2) Introduction of Amplitude and Power Spectra: The concept of the Pacinian filter was originally introduced by Makous et al. [13]. They attempted to explain the masking effects of noisy vibration stimuli that shift the detection threshold of vibrotactile stimuli as an analogy to the phenomena of auditory critical bands. The Pacinian filters used by Makous and Bensmaïa et al. were the square of the inverse detection threshold curve of Pacinian corpuscles. However, because the detection threshold level of Pacinian corpuscles is much smaller than that of Meissner corpuscles (roughly smaller than one-tenth), weighting by the square of the inverse threshold curve underestimates the effects of the vibratory stimuli of tens of hertz for which Meissner corpuscles are most sensitive. In addition, such weighting by the square function is not valid except by analogy to auditory perception.

In this study, we introduce the amplitude spectrum that is weighted by the inverse of the detection threshold curve in addition to the power spectrum that is weighted by the square of the inverse threshold curve used by Makous and Bensmaïa et al. The threshold-filtered amplitude spectrum is expected to evaluate the perceptual effects of the stimuli of tens of hertz, whereas the threshold-filtered power spectrum tends to underestimate the effects of these stimuli. Fig. 6 shows the weighting values of threshold filters. The squared inverse filter almost neglects the effects of the vibrations of tens of hertz, whereas the inverse filter does not completely diminish them.

C. Equations of the Objective Index

The sum of the power spectrum that is weighted by the square of the inverse detection threshold curve is given by

\[ P = \sum_{k=1}^{N'} \frac{C_k^2}{b(f_k)^2} \quad \text{and} \quad P'_i = \sum_{k=1}^{N'} \frac{C_{ki}^2}{b(f_k)^2}. \] (8)

\[ P \] and \( P'_i \) are the sums of threshold-filtered power spectra for the uncompressed and compressed textures, respectively. The suffix \( i \) denotes the type of compressed texture. The sum of the amplitude spectrum weighted by the inverse of detection threshold curve is determined by

\[ A = \sum_{k=1}^{N'} \frac{|C_k|}{b(f_k)} \quad \text{and} \quad A'_i = \sum_{k=1}^{N'} \frac{|C_{ki}|}{b(f_k)}. \] (9)

\( A \) and \( A'_i \) denote the uncompressed and compressed textures, respectively. The objective index is defined by a linear connection of the relative error of the sum of weighted spectra. The index is

\[ I_{obj,i} = a \frac{|P-P'_i|}{\frac{1}{2}(P+P'_i)} + b \frac{|A-A'_i|}{\frac{1}{2}(A+A'_i)}. \] (10)

where \( a \) and \( b \) are the contribution ratios of the power and amplitude spectra to the subjective quality indices, respectively.

For comparison of the proposed objective index mentioned above, we prepare two types of indices, \( I_p \) and \( I_a \). Each is composed of either the power spectrum or the amplitude spectrum. \( I_p \) is defined by the relative error of the sum of the weighted power spectrum and is given by

\[ I_p,i = \frac{|P-P'_i|}{\frac{1}{2}(P+P'_i)}. \] (11)

\( I_a \) is defined by the relative error of the sum of the weighted amplitude spectrum and is given by

\[ I_a,i = \frac{|A-A'_i|}{\frac{1}{2}(A+A'_i)}. \] (12)

The constant variables in the indices, \( a \) and \( b \) were determined by multiple regression analyses that involved the experimental results of Section IV. The analysis minimized the sum of square residuals between the subjective and objective indices, which is given by

\[ ||S-O|| \] (13)

where \( S \) and \( O \) are the vectors of subjective and objective indices, respectively. They are

\[ S = (I_{obj,j}, I_{obj,j+1}, \ldots, I_{obj,j+M})^T, \]
\[ O = (I_{obj,j}, I_{obj,j+1}, \ldots, I_{obj,j+M})^T \] (14)
(15)

where \( M \) is the number of compressed/uncompressed textures involved in the analysis. \( I_{obj,j} \) is the subjective dissimilarity between the uncompressed and compressed textures specified by \( i \). These subjective dissimilarities are the averages of all participants’ answers acquired in Section IV. We did not use the result of the linearly quantized sandpaper with \( L = 4 \) for the regression analysis. This is because all the participants answered the dissimilarity between this compressed and uncompressed texture as “different” in the experiment. In such case, 4-grading scales were invalid to estimate the subjective dissimilarity.
VI. COMPARISON OF OBJECTIVE AND SUBJECTIVE QUALITY INDICES

A. Wood texture

Figs. 7 and 8 show $I_p$ and $I_a$ for the compressed wood textures, respectively. First, we qualitatively compare $I_p$ (Fig. 7) and the corresponding subjective dissimilarities in Fig. 4. In general, $I_p$ increased as the data size of the compressed textures decreased, which is consistent with the general trend of subjective indices. The change in $I_p$ showed a plateau around the quantized texture of $L = 8$ (diamonds in Fig. 7), which is similar to the trend observed for the subjective indices. On the other hand, $I_p$ values of threshold-cut textures (circles in Fig. 7) were relatively smaller than those of quantized textures (diamonds in the same figure). This feature does not match that of subjective indices. This is because the algorithm of threshold-cut mainly removed low-frequency stimuli in the case of wood texture (see Fig. 3). $I_p$ underestimated the effects of the changes in low-frequency stimuli.

Second, we look at $I_a$ (Fig. 8). As well as $I_p$, $I_a$ also tended to increase as the data size of the textures became smaller. The $I_a$ for the threshold-cut textures (circles in Fig. 8) were larger than those of quantized textures (diamonds in Fig. 8), which shows a trend similar to that of the subjective indices. On the other hand, $I_a$ did not clearly show a plateau around $L = 8$.

Fig. 9 shows $I_{obj}$ and subjective dissimilarities for the wood textures. The subjective dissimilarities are the same as those in Fig. 4. The free variables for $I_{obj}$ were $(a, b) = (0.67, 0.44)$. $R^2$ between $I_{obj}$ and the subjective dissimilarities was 0.851. This value was higher than that between $I_p$ ($R^2 = 0.680$) or $I_a$ ($R^2 = 0.456$) and subjective dissimilarities. $I_{obj}$ described the subjective dissimilarities of compressed wood textures better than $I_p$ and $I_a$ did. These $R^2$ values are shown at the leftmost part in Fig. 10.

B. Sandpaper

Fig. 11 shows $I_p$ for the sandpaper. In general, $I_p$ increased as the data sizes of the textures decreased except for the one quantized with $L = 5$. This is due to the nonlinear changes in the power caused by the quantization. Comparing the $I_p$ values with the trends of subjective dissimilarities in Fig. 5, $I_p$ for threshold-cut textures (circles in Fig. 11) were relatively smaller than those for the quantized textures (diamonds in the same figure). As well as the case of wood textures, this is because $I_p$ is insensitive to the low-frequency vibrations that the threshold-cut algorithm removed from the sandpaper.

Fig. 12 shows $I_a$ for the sandpaper. $I_a$ for threshold-
Fig. 11: $I_p$ for sandpaper

Fig. 12: $I_a$ for sandpaper

Fig. 13: Subjective dissimilarity and $I_{obj}$ for sandpaper
cut textures (circles) were much larger than those for the
quantized textures (diamonds). These differences between
the textures compressed by two types of algorithms were
larger than those for the subjective dissimilarities of them in
Fig. 5.

Fig. 13 shows $I_{obj}$ and the subjective dissimilarities for
sandpaper. The subjective dissimilarities are the same as
those in Fig. 5. The free variables for $I_{obj}$ were $(a, b) =
(0.52, 0.58)$. $R^2$ between $I_{obj}$ and the subjective dissimilarities
was 0.883. This is higher than $R^2$ between $I_p$ or $I_a$ and
the subjective dissimilarities, which were 0.612 and 0.667,
respectively (center of Fig. 10). For sandpaper, as well as
the wood textures, the developed objective index $I_{obj}$ well
described subjective dissimilarities of compressed sandpaper
textures.

C. Gross Analysis: Wood and Sandpaper

Fig. 14 shows $I_{obj}$ vs. the subjective dissimilarities for both
wood textures and sandpaper. $I_{obj}$ was computed using the
experimental results of both textures. The free variables were
$(a, b) = (0.581, 0.464)$ and $R^2 = 0.790$. This value is higher
than those of $I_p$ and $I_a$ indices as shown at the rightmost part
in Fig. 10. The figure shows that in all cases, $I_{obj}$ has higher
$R^2$ values between the subjective indices than $I_p$ and $I_a$.

VII. DISCUSSION: THRESHOLD-WEIGHTED AMPLITUDE
AND POWER SPECTRA CAN BE GOOD OBJECTIVE
INDICES

This study developed an objective index that substitutes
for the subjective quality index for vibrotactile material-
like textures. The objective index is a linear combination of
the power and amplitude spectra of vibratory stimuli. These
spectra were weighted by the inverse of the detection thresh-
old curve. The weighted power spectrum described the vari-
ations of subjective quality indices to an accuracy of approx-
imately 60%, while the linear combination of the weighted
power and amplitude spectra did so by approximately 80%.
Bensmaïa et al. [10], [11] found that the Pacinian-filtered
power spectrum of vibrotactile stimuli or cutaneous me-
chanical vibrations correlated with the perceptual intensities
of high-frequency vibrations or perceived roughness of fine
textures. On the other hand, the experimental results of the
present study suggest that for vibrotactile material textures
that are composed of low or intermediate frequencies of
around tens of hertz, the combination of threshold-filtered
power and amplitude spectra well describes the subjective differences in the textures, although its application is currently limited to two types of textures. We speculate that the developed index well described the material textures because the combination of threshold-filtered amplitude and power spectra properly evaluated the perceptual effects of the stimuli at tens of hertz in which Meissner corpuscles are sensitive and the stimuli at high frequency around hundreds of hertz in which Pacinian corpuscles are sensitive. In other words, \( I_p \) functions for high-frequency range and \( I_a \) functions for both high and low frequency ranges, however, it is inadequate for describing the quality changes alone. \( I_p \) and \( I_a \) work for vibrotactile material-like textures in a mutually complementary manner.

VIII. Conclusions

This study developed an objective index that substitutes for subjective quality indices for vibrotactile material-like textures. We found that a linear combination of power and amplitude spectra of vibrotactile stimuli weighted by a detection threshold curve well describes the quality changes in textures. We applied this objective index to two types of vibrotactile material-like textures that come from the surfaces of wood and sandpaper, respectively. The subjective qualities of these textures were manipulated by two types of lossy data compression algorithms. The index described the changes in the subjective quality of data-compressed textures to an accuracy of approximately 80%. The index was shown to be a good predictor of quality changes in vibrotactile material textures. The developed objective index should be applied to the various type of textures, not just to two types in this study for its validation. Good objective indices are expected to lower the costs of psychological experiments needed for the enhancement of data-compression algorithms and contribute to understanding human perceptual properties by clarifying the effective physical quantities.

References