Sonification of Muscular Activity in Human Movements Using the Temporal Patterns in EMG

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***Abstract*—Biofeedback is currently considered as an effective method for medical rehabilitation. It aims to increase the awareness and recognition of the body's motion by feeding back the physiological information to the patients in real time. Our goal is to create an auditory biofeedback that aids understanding of the dynamic motion involving multiple muscular parts, with the ultimate aim of clinical rehabilitation use. In this paper, we report the development of a real-time sonification system using EMG, and we propose three sonification methods that represent the data in pitch, timbre, and the combination of polyphonic timbre and loudness. Our user evaluation test involves the task of timing and order identification and a questionnaire about the subjective comprehensibility and the preferences, leading to a discussion of the task performance and usability. The results show that the subjects can understand the order of the muscular activities at 63.7% accuracy on average. And the sonification method with polyphonic timbre and loudness provides an 85.2% accuracy score on average, showing its effectiveness. Regarding the preference of the sound design, we found that there is not a direct relationship between the task performance accuracy and the preference of sound in the proposed implementations.**

I. Introduction

In a medical rehabilitation of motor dysfunction, patients often have trouble accomplishing the desired motion because the synchronous (or asynchronous) control of multiple muscular parts in accordance with their intention is difficult. In order to overcome this difficulty, *biofeedback* aims to increase the awareness and recognition of the body motion by feeding back the physiological information to the patients in real time. In biofeedback, the physiological information is typically captured using sensors, such as electromyography (EMG), and visually fed back to the patients [1], [2]. However, some problems have been pointed out with visual EMG biofeedback: improper posture due to eye distraction, and simultaneous presentation of multiple-sensor data.

A potential solution to these problems with visual biofeedback is auditory biofeedback, in which the physiological information is fed back to the users with sound. Auditory biofeedback typically employs data sonification, which transforms non-audio data into audio information using sound synthesis. The advantages of auditory biofeedback are (1) there is no distraction for eyesight, which improves concentration on the gestural task; (2) audition is more accurate in the sense of timing than vision and thus serves as a better medium to represent dynamic data; and (3) the cost for the sound synthesis and audio setup is usually cheaper than that for the computer graphics with visual displays. Good examples of EMG sonification have been proposed for elite sports training [3]; for rehabilitation [4], [5], [6]; and for interactive music performance [7], [8]. The current issues in sonification, including the above-mentioned studies, are (1) the evaluation test by users is often missing; (2) the simultaneous presentation of multiple data streams needs to be investigated, in which auditory gestalt perception plays the key role; and (3) the use of multidimensionality of timbre should be exploited in representing multidimensional data [9].

In our project, the goal is to create an auditory biofeedback that aids understanding of the dynamic motion involving multiple muscular parts (i.e., muscular activity), with the ultimate aim of clinical rehabilitation use. In the paper, we report the development of a real-time sonification system using EMG, and we propose three sonification methods that represent the data in pitch, timbre, and the combination of polyphonic timbre and loudness. Our user evaluation test involves the task of timing and order identification and a questionnaire about the subjective comprehensibility and the preference, leading to a discussion of the task performance and usability.

II. EMG Sonification

The proposed system configuration is shown in Fig. 1. The system consists of three steps: EMG measurement, muscular

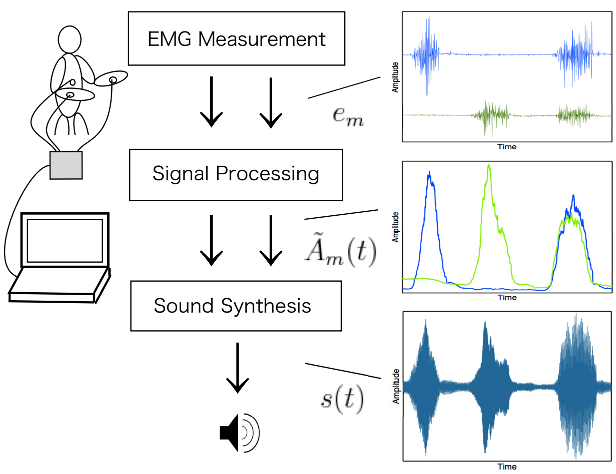

Fig. 1. Proposed sonification system overview.

activity extraction with signal processing techniques, and a sound synthesis using a parameter-mapping approach [9]. To keep the system flexible for a future implementation in real time, the current approach is in a frame-based processing design.

A. EMG Measurement

The EMG signals are usually measured using wired or wireless electrodes. In this study, we employed the wired measurement technique because of its higher signal-to-noise ratio, which is well suited to our goal, which is based on EMG sonification. In the experiments reported in this paper, we used the g.USBamp biosignal amplifier by g.Tec Inc.(Berryville, VA). The bus active g.LADYbird electrodes were connected in bipolar settings on the surface area of the right and left brachioradialis muscles. The EMG signals were sampled at 1,200 Hz, captured, and stored using the Data Acquisition toolbox in MATLAB.

B. Signal Processing

The EMG signals contain noise of slow drifts of the direct-current (DC) component, and they are observed as a series of pulses. Thus, the raw EMG signals are not suitable for direct analysis of human movements. In order to extract muscular activity features, the system removes the DC component, and filters the signals.

Next, the system calculates features for data sonification. The purpose of the DC removal is to isolate the signal of a muscle contraction. After the DC removal, resting states are treated as 0% contractions, and maximum voluntary contractions (MVC) states are treated as 100%. Although the DC component removal is commonly performed with high-pass filtering, in this study we employed subtraction of an average potential in the resting states from the measured EMG signals. Let $e_m(n)$ be an EMG signal, n the sample, and E_{0_m} and E_{max_m} the mean muscle potentials of the resting and MVC states at the body part m, respectively. A muscle potential amplitude $A_m(n)$ is calculated by the following equation:

$$A_m(n) = \frac{|e_m(n) - E_{0_m}|}{E_{max_m} - E_{0_m}}. \quad (1)$$

Next, the $\tilde{A}_m(t)$ is yielded by smoothing the $A_m(n)$ with a moving-average filter and upsampling to the same frequency as the sound output. $\tilde{A}_m(t)$ ranges from 0 to 1, but it usually falls in the range 0.006 to 0.9 due to the smoothing noise side effect. The resulting $\tilde{A}_m(t)$ is treated as a feature of muscular activity in the sound synthesis step described in next sections.

TABLE I
METHOD FEATURE

Method	Perceived Dynamic Parameter	Segregation
A	Pitch	Yes
B	Loudness, Polyphonic Timbre	Yes
C	Timbre	No

C. Sound Synthesis

For the sound synthesis, the acoustic parameters (i.e., amplitude, frequency, and harmonic structure) vary correspondingly to the muscular activity $\tilde{A}_m(t)$. We implemented three sonification methods—A, B, and C—and Table I shows the features of each method.

Method A is a typical technique in sonification studies [9]. It changes the frequency of a basic sound when the muscular activity changes, and the body motions are perceived as changing in sound pitch. Method B relates the muscular activity to a combination of loudness and polyphonic timbre, and Method C relates it to timbre transition.

Because of our goal, all methods synthesize the sound objects in multiple form from each muscle. According to a perspective on the auditory scene [10], sounds are heard as integrated or segregated auditory objects, even though they reach the ear as a whole. In methods A and B, the sonified sounds are heard as segregated into individual components corresponding to each muscular part. However, in method C the sonified sounds are heard all together as a balance between multiple muscular parts. We describe the details of each method below.

Method A: This Method relates the muscular activity to an instantaneous frequency of a sine wave

$$S(t) = K \sum_{m=1}^{M} \sin(2\pi f_m(t)), \quad (2)$$

where K is a coefficient of sound amplitude ($K = 0.45$) and M is the number of EMG channels. The pitch varies according to the human movement. When the EMG amplitude becomes higher, pitch becomes higher, and vice versa. Instantaneous frequency $f_m(t)$ is determined by the muscular activity $\tilde{A}_m(t)$, which is calculated by the signal-processing step:

$$f_m(t) = K_m \log_2(1,000\ \tilde{A}_m(t)) + T_m. \quad (3)$$

In this study, we set $M = 2$ and use the following constants: $K_1 = 50, T_1 = 120, K_2 = 40$, and $T_2 = 20$. These coefficient constants were adjusted in the preparation phase in order to change the frequency approximately one octave from 250 Hz for $m = 1$ and 125 Hz for $m = 2$ (because the muscular activity $A_m(t)$ ranges from 0.006 to 0.9 in our configuration). We used the SuperCollider for the implementation and the Lag function to change pitch smoothly.

Method B: In this method, we relate the muscular activity to a combination of loudness and polyphonic timbre. The sounds are composed by mixing two modulated sounds corresponding to each muscular part. The muscular activity $\tilde{A}_m(t)$ is regarded as the weights of the modulated sounds in mixing. The combination of loudness and polyphonic timbre is gradually changed, as follows:

$$s(t) = \sum_{m=1}^{M} \tilde{A}_m(t) W_m(t). \quad (4)$$

The modulated sounds are different in fundamental frequency and timbre, so they are heard easily as segregated into individual components. These two sounds $W_1(t)$ and $W_2(t)$ are calculated by additive synthesis using the following formula:

$$W_1(t) = \sum_{i=1}^{5} \frac{1}{(2i-1)} \sin((2i-1)f_1\pi t), \tag{5}$$

$$W_2(t) = \sum_{i=1}^{5} \frac{1}{2i} \sin(2if_2\pi t). \tag{6}$$

In order to differentiate the timbre of both two sounds, W_1 is composed of only odd number harmonics corresponding to the first body part, and W_2 is composed of only even number harmonics corresponding to the second body part. In this study, we set the fundamental frequencies $f_1 = 300$ Hz and $f_2 = 120$ Hz, respectively. The frequency ratio is the same as 5:2, so that these two sounds form a major third interval. We implemented this method in MATLAB.

Method C: This method represents a balance of muscular activity by timbre transition without pitch changing. In order to realize the timbre transition, the two modulated sounds that have the same fundamental frequency but different spectral structures are mixed. This implementation is mostly the same as method B, but the fundamental frequencies of the both two sounds are set at $f_1 = f_2 = 120$ Hz. The sonified sound timbre is gradually changed. When a potential of one body part becomes higher, the sonified sound timbre becomes like a clarinet, and when a potential of the other body part becomes higher, its timbre becomes like the brass instruments.

III. Experiment

We conducted a listening experiment to verify whether subjects can understand the muscular activity by listening to the sonified sounds. As mentioned earlier, the experimental test involved the task of timing and order identification and a questionnaire about the subjective comprehensibility and the preference in case of methods A, B, and C.

A. Experiment Conditions

Participants: Nine subjects (four females and five males) between 18 and 30 years old (mean 22.7) successfully completed the listening tests. Five of them reported having at least eight years of experience in performing with musical instruments.

Stimuli: We composed acoustic stimuli artificially, which represent multiple muscular activities. First, we captured an EMG signal of a motion that involved one muscle contraction. Second, we duplicated the captured EMG signal with τ seconds of shifting. These two EMG signals could be regarded as muscular activity of the α and β body parts. The EMG envelopes for stimuli are shown in Fig. 2. Finally, we synthesized the sounds from these envelopes with above-mentioned sonification method in $\tau = \{-0.5, -0.2, 0, 0.2, 0.5\}$. We also sonified the sounds from the α and β parts as dummy stimuli.

Environments: All subjects were asked to listen to the sound stimuli via headphones in their usual living spaces.

B. Experiment Procedure

The listening experiment consisted of three parts—instruction, training, and testing—it lasted approximately 15 minutes. In the instruction phase, all subjects read a detailed description of the task and the purpose of the experiment. In the training phase, the subjects listened to sample stimuli, and familiarized themselves with the sonification method and the task, adjusted the volume, and further clarified the test goals as needed.

In the testing phase, the subjects were asked to identify the order of the muscular activity and to choose from the following five statements by listening to the stimuli.

1) Only the α part moves.
2) Only the β part moves.
3) Both the α and β parts move synchronously.
4) The α part moves before the β part moves.
5) The β part moves before the α part moves.

This identification task used three sets of stimuli corresponding to the three sonification methods. Each set consisted of 12 stimuli—two times for stimuli with the shifting parameter $\tau = \{-0.5, -0.2, 0, 0.2, 0.5\}$ and once each of two dummy stimuli, which were sequenced in random order. To avoid the unfairness in each method due to the learning effect of the task, each set was also presented in random order. The subjects were allowed to listen repeatedly to the stimuli that were hard to answer, although they were asked to answer intuitively.

After the testing session, the subjects were asked to describe the process of understanding and their impression about each method, and they were also asked to complete a questionnaire survey with the following questions about comprehension and preference:

A. How comprehensible was the sonification sound?
B. What is your preference of the sonification sound?

The evaluation was done with a five-point scale, where 1 corresponded to "bad" and 5 corresponded to "good."

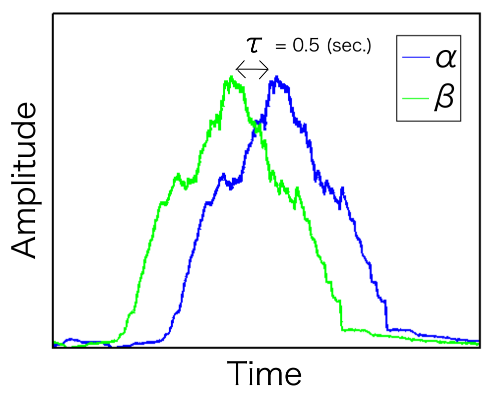

Fig. 2. EMG envelope for stimuli

TABLE II

AVERAGE OF ACCURACY, COMPREHENSION, AND PREFERENCE IN EACH METHOD (1:BAD, 5:GOOD)

Method	Accuracy(%)	Comprehension	Preference
A	62.0(±15.1)	3.0(±0.4)	3.9(±1.1)
B	85.2(±11.0)	4.3(±0.4)	3.7(±0.8)
C	44.4(±20.5)	1.3(±0.4)	1.4(±1.0)

TABLE III

AVERAGE OF ACCURACY IN MUSICIANS AND NON-MUSICIANS

Accuracy(%)	Whole	A	B	C
Non-musician	55.6	52.1	77.1	37.5
Musician	70.6	70.0	91.7	50.0

C. Experiment Results

The experimental results are shown in Tables II and III and Fig. 3. The average value of accuracy with the confidence interval, comprehensibility (degree of subjective understanding), and preference in each method are shown in Fig. 2. Table III shows the mean accuracy of subjects who had musical experience and of those who did not have it. Fig. 3 provides a bar graph of mean accuracy depending on τ in each method (error bars indicate 95% confidence interval).

IV. DISCUSSION

A. Comparing the Methods

As shown in Table II, the average of accuracy in method B marked the highest score at 85.2%, so most subjects could understand the muscular activity by hearing sounds. As shown in Fig. 3, the accuracies were consistently higher in all cases of τ in method B than in the others, especially with short delay time (± 0.2). In particular, as shown in Table III, the subject who had musical experience identified the timing of the sounds with different pitches more accurately, so that the accuracy of method B was 91.7%.

In the interview after the experiment, the subjects were asked to describe their comprehensibility and preference about each method. In method A, many subjects felt that their body was being moved spontaneously up and down and described it as "feeling like a rollercoaster ride." In contrast, in method B the subjects seemed to interpret the sonified sounds like reading a musical score.

In method C, the subjects had difficulty in distinguishing sounds, whether the sonified sounds were mixed or not. For that reason, the subjective comprehensibility declined, and the scores for accuracy were low. At this time, the range of timbre transition was small, so that identifying the order of muscular activities was difficult. We can increase the comprehensibility in method C by expanding the difference between the two sounds.

This time, there were two measurement points. However, when the number of body parts increased many pitches would be mixed, and the sounds might be too complex in methods A and B. In such cases, method C has a potential advantage because timbre transition is suitable to represent multidimensional information.

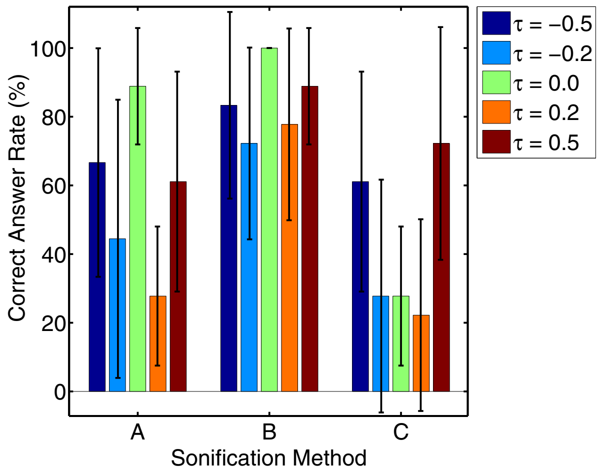

Fig. 3. The relationship between the accuracy and delay time, in each method

B. Comprehensibility and Preference

As shown in Table II, there is a relationship between accuracy and comprehensibility, but there is no direct relationship between accuracy and the preference of sounds. Among the nine subjects, five preferred method A, three preferred method B, and one preferred method C. Four of the five subjects who preferred method A scored their highest accuracies in method B. Accuracy is considered the highest priority factor for understanding the data feature correctly. However, considering the perspective of usability, it is difficult for long-term use with low preference even comprehensibility is high. For practical, long-term use in the future, it is necessary to satisfy both of the following conditions: sounds must be friendly and clear for users to understand precisely, and sound familiarity is also a considerable factor. One of the subjects with musical background said, "I do not prefer any sound, because it is like a sound made from a machine, not a musical instrument." The solution to this problem is not only using a familiar timbre such as an instrument but also examining the suitableness between sonified sounds and data features.

V. CONCLUSIONS

In this study, we implemented a real-time sonification of muscular activity, proposed three sonification methods, and conducted the listening experiments with subjects from the perspective of subjective comprehensibility and the preference in each method. The results show that the subjects can understand the order of the muscular activities at 63.7 % accuracy on average, and the sonification with polyphonic timbre and loudness produced an 85.2% accuracy score on average, demonstrating its effectiveness. Regarding the preference of the sound design, we found that there is not a direct relationship between the task performance accuracy and the preference of sound in the proposed implementations. This causes an interesting future research question, on the trade-off or balance between preference and efficiency factors.

In our future work, we plan to examine other muscular activity patterns, such as moving to alternating-pattern and rhythmical-pattern behavior. We also plan to investigate the effects of increasing the number of body parts, to three or more. The perception of the sound can be very different in an interactive setting, in the same way that a simplistic sound effect in a video game can be highly effective. For that reason, we would like to move onto an interactive, real-time user evaluation in the future.

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