REAL-TIME EMG SONIFICATION SYSTEM FOR GAIT

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ABSTRACT

We developed a system that sonifies muscle activity during walking in real time. We aim at improving the efficiency and quality of walking rehabilitation by exhibiting the coordination of multiple muscles during gait. Our initial goal is to sonify the coordination of multiple muscles in real time, and we conducted two pilot tests: (1) gait experiment to monitor the gait pattern change with auditory biofeedback, and (2) listening test to verify if the individual gait patterns are successfully sonified. Three healthy adults participated in the gait experiment. They did not show any significant change in walking speed and stride length depending in the biofeedback condition. The listening test showed that listeners can distinguish individual patterns of muscle activities during gait with the sonification at a statistically significant level.

1. INTRODUCTION

Walking is one of the most familiar movements to us, often conducted unconsciously. However, people with walking disabilities due to illness may walk slowly, with small or awkward steps. When walking rehabilitation programs with physical therapists are chosen, the therapists help them improve their gait through observation, palpation, and verbal feedback, etc., in order to accomplish appropriate muscle coordination during walking. Yet, concurrent observation of multiple muscles is uneasy. Therefore, we constructed a real-time system to sonify multichannel electromyographic (EMG) signals that facilitates the observation of the coordination of multiple muscles. We are particularly interested (1) if the presence of the auditory biofeedback would change the gait patterns, and (2) if the individual patterns in the muscular coordination can be sonified.

2. GAIT AND MUSCLE COORDINATION

Human gait is conducted in cycles: A gait cycle is one cycle from the grounding of the foot on one side of the body to its next grounding. The gait cycle is divided into the stance phase (i.e., the period when the foot is on the ground) and the swing phase (i.e., the period when the foot is away from the ground and carried forward).

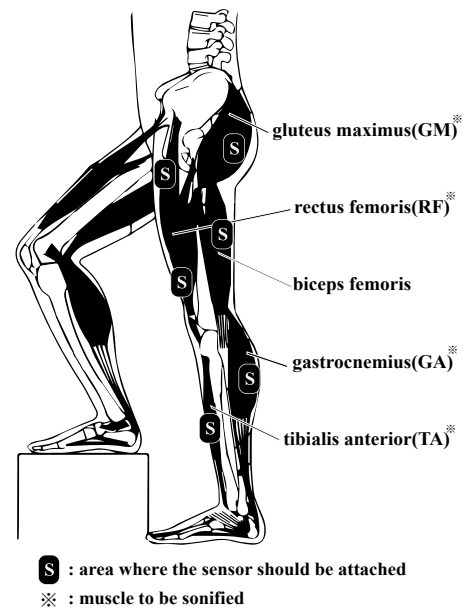: area where the sensor should be attached
※ : muscle to be sonified

Figure 1: Muscles of the lower limbs.

The lower limbs have three representative joints: the hip joint, the knee joint, and the ankle joint. The extension (i.e., dorsiflexion) and flexion (i.e., plantarflexion) of these joints involves the activities of four major muscles as described in Figure 1: The gluteus maximus (GM) extends the hip joint; The rectus femoris (RF), which is one of quadriceps femoris muscles, flexes the hip joint and extends the knee joint; The gastrocnemius (GA) plantarflexes the ankle joint; And the tibialis anterior (TA) dorsiflexes the ankle joint.

3. RELATED RESEARCH

Much research has been conducted on rehabilitation using EMG biofeedback. Intiso et al. used EMG biofeedback in a group of patients to improve foot-drop after stroke, who showed recovery of foot-drop in the swing phase [1]. Morris et al. applied EMG biofeedback combined with contemporary physical therapy to stroke patients with genu recurvatum and determined that the combination enhanced the effectiveness of the treatment [2]. Matsubara et al. implemented auditory feedback that helped to understand the movement of multiple muscles [3]. Yang et al. conducted a study to improve the quality of exercise by giving auditory feedback to the exercise
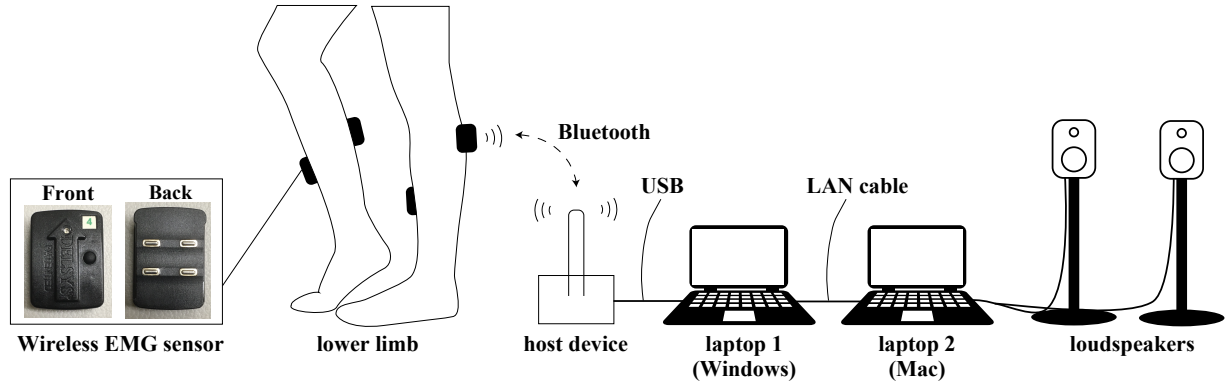
Figure 2: System overview.

[4, 5]. In addition, many studies have been made to sonify EMG signals [6, 7, 8].

As for the other methods of auditory biofeedback rehabilitation than EMG, Aruin et al. conducted an experiment on patients with narrow width between their legs and showed that patients who used audio feedback were able to widen the width, compared with those who did not receive audio feedback [9]. One study showed sufficient rehabilitation of the ankle joint performed on blind persons using auditory feedback [10]. Claude et al. reported feedback of joint motion with sound may be a substitute for an ability to sense positions, locations, orientations, and movements of the body and its parts [11].

4. DEVELOPMENT OF REAL-TIME SYSTEM

4.1. Devices

Our sonification system consists of the following devices: a wireless EMG sensor kit made by Delsys (Natick, MA, USA), two laptop PCs (Windows and Mac), and two loudspeakers. Figure 2 shows the system overview.

The Windows PC receives EMG signals via Bluetooth, conducts data-preprocessing, and sends them to the Mac, which is connected with a LAN cable. The Mac normalizes the signals and converts them to sound. Two loudspeakers are used to play back the sonified sound to the participants.

During system development, we tried to use Bluetooth earphones instead of loudspeakers. However, the delay time in the transmission of sound from the Mac to the Bluetooth earphones was too long (approximately 1 second), and we decided that Bluetooth earphones were not suitable for the real-time sonification system.

4.2. Data pre-processing, normalization, and synthesis

In the preprocessing, the original EMG signal at 2000 Hz sampling rate is processed by windowing with length of 66 samples. Within a window, we first calculate the absolute values of the signal, then a mean value to represent the window. (Note this is essentially same as taking the RMS value and moving average, which is the standard way to process EMG signals.) The pre-processed EMG signals are sent via the LAN cable using UDP protocol to the Mac.

MATLAB on the Mac normalizes the received data. A walking exercise was measured beforehand to calculate the appropriate thresholds within a channel. The following equations were used for calibration:

$$y_i = \max_{10i \leq t \leq 10i+100} x(t) \quad (1)$$
$$z_i = \min_{10i \leq t \leq 10i+100} x(t) \quad (2)$$
$$Y = \text{median } y_i \quad (3)$$
$$Z = \text{median } z_i \quad (4)$$

where $x(t)$ is the pre-processed EMG signal at and i denotes the index number for the window. This normalization uses the median of the maximum and minimum values of muscle activities observed in the sliding windows. Typically, maximum muscle activity is used to normalize the EMG signal. However, in this walking exercise, the maximum muscle activity appears as a sharp spike in a gait cycle. In order to sonify the state between spikes, it is desirable to set the upper threshold to a value that is observed more frequently. In addition, owing to the ground noise level, it is not desirable to set the lower threshold to 0. If we want to hear the states between sharp spikes, normalization should be based on a threshold calculated from middle-values but not from maximum values.

The thresholds were calculated for each person with the EMG data of 5 seconds of steady gait, excluding the start and end, where the walking speed and stride were unstable. In this calibration stage, the maximum and minimum values are detected in the window of 100 samples for each channel with a shifting-step width of 10 samples. The values in the window are stored in arrays. The median of the values of the two arrays was taken as the threshold. In the normalization, the values between the thresholds are linearly normalized. The values larger than threshold (Y) were rounded to 1, and the values smaller than threshold (Z) were rounded to 0, resulting in the normalized EMG signals ranging from 0 to 1.

The normalized EMG signals are then sent to SuperCollider, a sound synthesis software. It maps each channel of EMG to a pitch in a harmony, and the amplitude of the normalized signal of the channel is mapped to the volume of the tone, as described in the next section. Synthesized sound is played with the two speakers.

5. SONIFICATION DESIGN

We aimed to produce a sound design that can distinguish muscle coordination patterns based on the overtone-mapping technique [12]. Each channel of EMG signals is mapped to the amplitude of a sinusoid, and the pitches of multiple sinusoids comprise a harmony. When a certain muscle is used, the
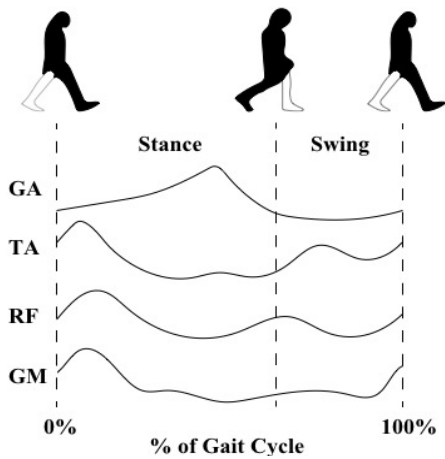
Figure 3. Relative size of EMG during gait cycle.

amplitude of the corresponding sine wave increases, making that tone louder than the other in the harmony. When multiple muscles are active in a synchronized manner, the corresponding tones in a harmony overlap and comprise a harmonic sound object.

In our implementation, we sonified the activities of four muscles (GM, RF, TA, and GA) on the right side of the body. Table 1 shows the mapping between the muscles and the pitch. During a gait cycle, a coordinated transition of the muscle activity across the four muscles exists, resulting in a rhythmic pattern in the harmony. At the beginning and end of the gait cycle, GM, RF, and TA are active. GA becomes active at 40% to 60% of the gait cycle. Figure 3 shows the activities of the muscles during the gait cycle. These envelopes of muscle activity become the envelope of the harmonic sounds. We only sonified four channels because adding another channel can lead to difficulty in comprehending the feedback and would require more practice to the users.

Table 1: Mapping between muscle and sound's frequency.

Channel	Muscle	Note	Frequency (Hz)
1	GA	C5	523
2	TA	G4	392
3	RF	E4	330
4	GM	C4	262

6. GAIT EXPERIMENT

We conducted a gait experiment to monitor if the presence of sonification changes the gait behavior of healthy people.

6.1. Condition

Three participants (two men and one woman; aged 23-24 years) participated in the gait experiment. It was conducted in the measurement room of the Center for Innovative Medicine and Engineering in the University of Tsukuba Hospital, with the approval by university IRB. Twelve wireless EMG sensors were attached to the lower limbs of the participants. Four of them were used for sonification, and the remaining channels were recorded for analytic purposes. We also used a motion capture system and ground sensors to measure the walking speed, stride, and heel grounding timing.
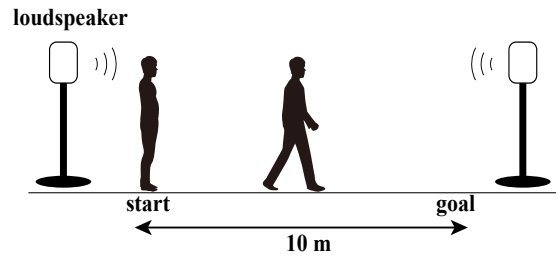

Figure 4: Experimental setup.

6.2. Method

In the experiment, they walked approximately 10 m under two conditions: sound and no-sound conditions. Figure 4 shows the experimental setup.

Under the no-sound condition, the system provides no sound and the participants only had to walk. They walked three times under this condition. In the sound condition, four channels (right GM, TA, GA, and QF) of the lower limb muscles are sonified in real time. Participants walked ten times while listening to the sound, which is played from the speakers.

In both conditions, participants were asked to walk normally, without paying particular attention to the sounds.

6.3. Results

Figures 5 and 6 show the average walking speed and stride length, respectively, of the three participants for each condition. There were no significant differences in walking speed and stride length between the two conditions.

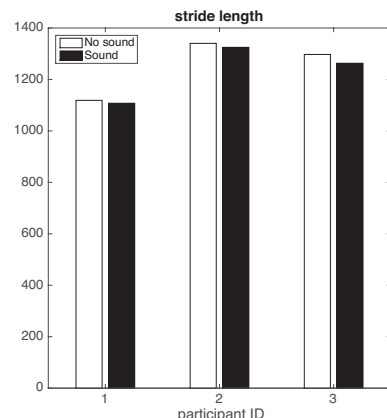Figure 5: Average walking speed under sound and no-sound conditions.

Figure 6: Average stride length under sound and no-sound conditions.

7. LISTENING TEST

We conducted a listening test to verify whether individual walking patterns can be identified from gait sonification.

7.1. Method

An online listening test using Google Form was conducted. Ten participants took the test. They first listened to three sample audio files. The three files are sonification of three walkers from the gait experiment. Then the participants listened to nine audio files, three sonifications for the three walkers randomly presented. They were asked to identify the walker by listening to the sonification. Participants can listen to the three sample audio files as many times as they want.

7.2. Results

The results of the listening test are shown in Table 2. The numbers in each element shows the distribution of the correct and incorrect responses to the identification task. Figure 7 shows the correct answer rates of each respondent (listener). The overall correct answer rate was 0.67. When χ^2 test was conducted with the correct answers of each walker and the expected number from the chance level, they were significantly different ($p = 0.00001$).

Table 2: Result of the listening test.

		Source data of sonification		
	Walker ID	1	2	3
Listener's response in the identification task	1	0.67	0.07	0.33
	2	0.20	0.77	0.10
	3	0.13	0.17	0.57

8. DISCUSSION

The present system did not change walking speed or step speed, but the sound feedback was considered not to interfere with their walking.

One participant's hip joint extension and knee joint extension increased under the sound condition. The walking distance in this test was as short as 10 m in one trial. The trial most likely ended before the influence of the sound appears. We did not ask to pay attention to the sonification either. A longer walking distance in one trial, and more specific instruction may cause some changes on the gait pattern.

Based on the results of the listening test, individual gait patterns can be identified from the sound. Some listening test respondents had difficulties in identifying the walker, but they can recognize the difference in sounds. From the post-test interview, we determined that the speed of the attack and the timing of the sound appearance within one cycle were the clues for the identification.

9. CONCLUSION

This study developed a real-time EMG sonification system during walking. The activity of four major muscles was mapped to the amplitude of the sine wave of a different pitch to comprise a harmonic chord. Three healthy adults walked with auditory biofeedback. They walked with no significant difference in the walking speed and stride with and without the biofeedback, showing that the sonification did not interfere
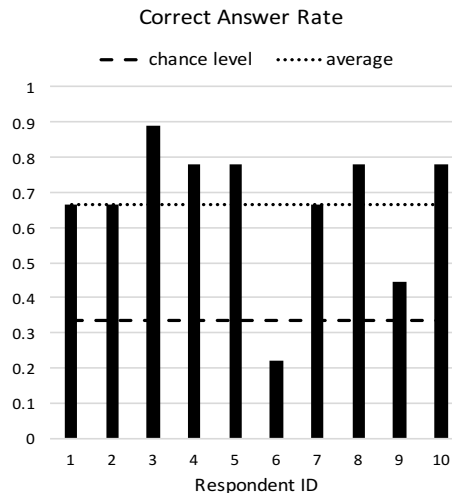
Correct Answer Rate

Figure 7: Correct answer rate of the listening test by respondent.

with their walking at least. One of three participants showed more extended joint with auditory biofeedback.

A listening test was conducted to investigate whether it is possible to identify the individual from the sound. Ten people tried to identify the three walkers. The overall average correct answer rate was 0.67. The possibility of identifying the individual from the sound has been shown.

10. REFERENCES

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