DEVELOPMENT OF REAL-TIME EMG SONIFICATION SYSTEM FOR GAIT

ABSTRACT

We developed a system that sonifies muscle activity during walking in real time and is aimed at improving the efficiency of treatment in walking rehabilitation and at reducing the burden on physical therapists by exhibiting the coordination of multiple muscles during gait. Our initial goal was to sonify the coordination of multiple muscles in real time. Three healthy adults participated in the experiment. They did not show any significant change in walking speed and stride length depending on sound presentation condition. In addition, an offline listening test was conducted to determine if people could distinguish patterns of muscle activities during gait through the sonified sounds. Results showed that the listeners were able to detect the individual patterns from the sonified sounds (rate, 67%). In summary, the present system does not modify gait with presentation of sound, but can sonify the individual muscle coordination patterns.

1. INTRODUCTION

Walking is one of the most familiar movements to us. Most people can walk without difficulties. However, some people who have walking disabilities because of illness may walk slowly, with small or awkward steps. Those people can undergo walking rehabilitation programs with physical therapists. Physical therapists help them improve their gait through observation, palpation, verbal feedback, etc. Appropriate muscle coordination is needed during walking exercises. However, monitoring of the state of many muscles all at the same time is difficult. Therefore, we constructed a system aimed at multichannel electromyographic (EMG) sonification and easier observation of the coordination of multiple muscles in real time.

2. GAIT AND MUSCLE COORDINATION

Human gait is conducted in cycles. A gait cycle is one cycle from the grounding of the foot on the ipsilateral side to its next grounding. The gait cycle is divided into the stance phase and the swing phase. The stance phase is the period when the foot is on the ground. The swing phase is the period when the foot is away from the ground and is being carried forward.

The lower limbs have three representative joints: the hip joint, the knee joint, and the ankle joint. Each joint can flex

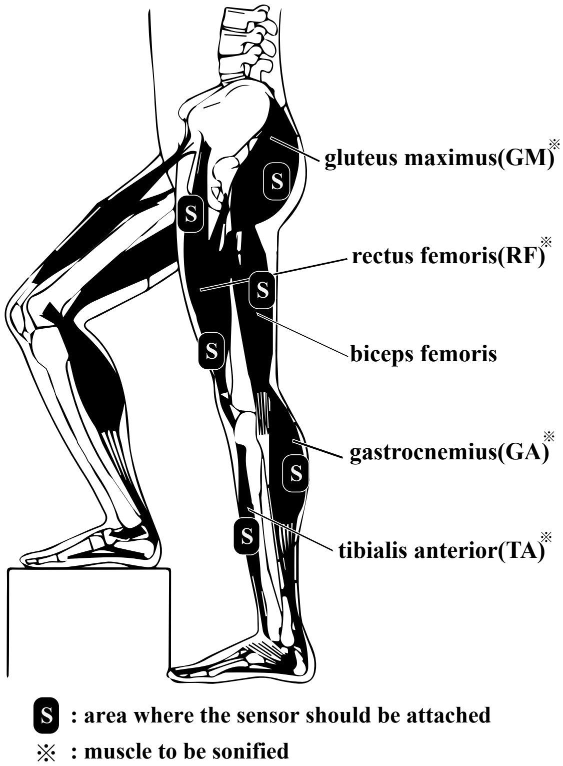

Figure 1: Muscles of the lower limbs (adapted from reference [1]).

and extend through muscle activity. The extension of the ankle joint is called dorsiflexion and the flexion of the ankle joint is called plantarflexion. 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. The tibialis anterior (TA) dorsiflexes the ankle joint. Figure 1 shows the location of these muscles. The functions of each joint in a gait cycle are summarized below.

2.1. Ankle joint

The dorsiflexion muscle group is active at first contact. The TA muscle group contracts centrifugally, and the plantarflexion muscle group starts to act gradually. The activities of the plantarflexion muscle group are maximized, and heel separation is achieved. When the heel begins to lift,

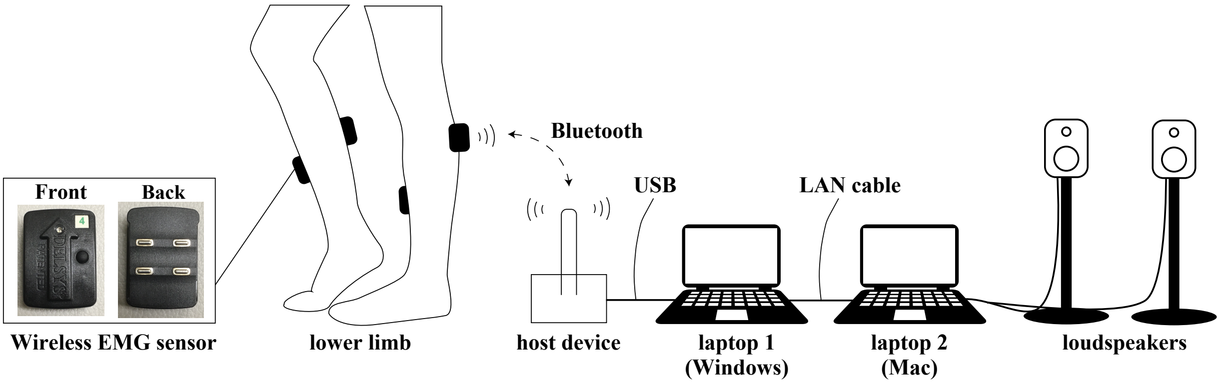

Figure 2: System overview.

the dorsiflexion muscles work and lift the toes. The TA muscles are active while the feet are lifting.

2.2. Knee joint

The quadriceps femoris muscle, which is an extension muscle, continues to work from the swing phase. The quadriceps femoris muscle contracts and absorbs the impact. Within a short time lapse, the quadriceps femoris muscle, excluding the RF, maximally contracts. The activity of the quadriceps femoris muscle gradually decreases. When entering the swing phase, the knee joint flexes passively. If necessary, the short head of the biceps femoris controls the knee joint angle. At the end of the swing phase, the quadriceps muscle contracts and extends the knee joint.

2.3. Hip joint

In the early stance phase, all extension muscles including the GM are active to prepare for shock absorption. Around this time, the GM muscle contracts maximally. The activity of the muscles decreases and disappears at the end of the stance phase. The activities of the flexion muscle group start in the early swing phase.

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 [2]. 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 [3].

Matsubara et al. implemented auditory feedback that helped to understand the movement of multiple muscles [4].

Yang et al. conducted a study to improve the quality of exercise by giving auditory feedback to the exercise [5], [6].

In addition, many studies have been made to sonify EMG signals [7], [8], [9]

As for other methods of auditory biofeedback rehabilitation, 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 [10].

One study showed sufficient rehabilitation of the ankle joint performed on blind persons using auditory feedback [11].

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 [12].

4. SYSTEM

In this study, we implemented a system to sonify the EMG in real time. The system was designed for use during walking.

4.1. Devices

Our sonification system consists of the following devices: a wireless EMG sensor kit, two laptops (Windows and Mac), and two loudspeakers. Figure 2 shows the system overview.

The wireless EMG sensor kit can measure up to 16 EMG signals. The kit had 16 wireless EMG sensors and a host device. The kit is produced by Delsys (Natick, MA, USA). The sensors and the host device communicate through Bluetooth. The sensor's sampling rate is 2000 Hz. The sensors are attached to the user's skin to measure EMG and to send EMG signals to the host device. The host device is connected to a USB port on the Windows laptop.

The Windows laptop receives EMG signals, conducts down-sampling, and sends the processed signals to the Mac laptop, which is connected with a LAN cable.

The Mac laptop receives the processed signals and normalizes and converts them to sound. The produced sound is played through the built-in audio interface.

Two loudspeakers are used to play back the sonified sound to the participants. However, the sonified sound is monaural, and the outputs from the two speakers are identical. During system development, we tried to use Bluetooth earphones to provide sonified sound to the participant. However, the delay time in the transmission of sound from the Mac laptop 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.

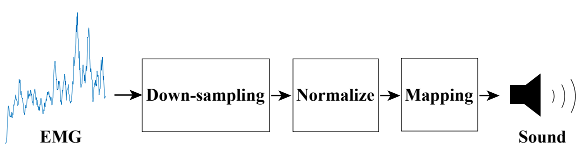

Figure 3: Block diagram of the system.

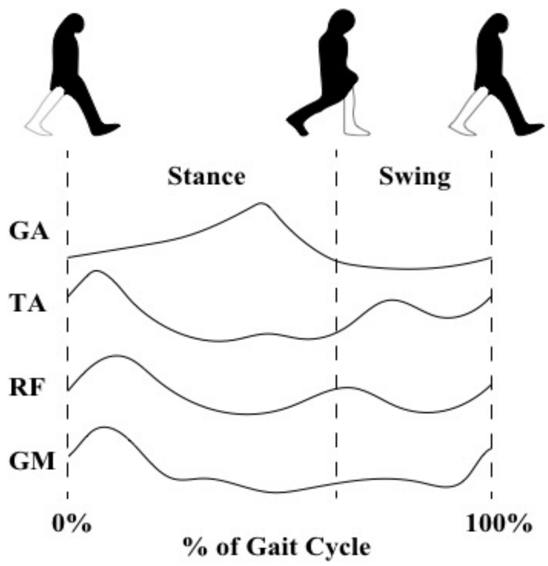

Figure 4. Relative size of EMG during gait cycle (adapted from references [13],[14]).

4.2. Data flow

This section introduces how the system converts measured EMG signals to sound. Figure 3 shows the block diagram of the system's data flow.

The sensors attached to skin acquire the EMG signals and send them to the host device. With the software included in the kit, each sensor's battery and connection condition can be monitored. This software also starts up a server, and the EMG signals are distributed from the server.

The Visual Studio C++ program in the Windows PC receives EMG signals, performs down-sampling, and sends them to the Mac laptop. Because 2000 Hz is too high rate for sonification, Visual Studio C++ carries out down-sampling 1/30 times with respect to the original data. Down-sampling is fulfilled by summing 66 absolute values. Down-sampled EMG signals are sent via the LAN cable using UDP protocol to the Mac laptop.

As for other methods of auditory biofeedback rehabilitation, 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 [10].

MATLAB on the Mac laptop 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.

$$y_i = \arg \max_{10i \le t \le 10i+100} x(t) \quad (1)$$

$$z_i = \arg \min_{10i \le t \le 10i+100} x(t) \quad (2)$$

$$Y = \text{median}\, y_i \quad (3)$$

$$Z = \text{median}\, z_i \quad (4)$$

where $x(t)$ is the down-sampled EMG signal and i denotes the index number for windowing processing. This calibration uses the median of the maximum and minimum values of muscle activities observed in the sliding windows. Typically, maximum muscle activity is used to calibrate the EMG signal. However, in this walking exercise, the maximum muscle activity is rarely observed, and it is desirable to set the upper threshold to a value that is observed more frequently. Furthermore, owing to the ground noise level, it is not desirable to set the lower threshold to 0. The thresholds were calculated from 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. The values between the thresholds are linearized. Values larger than threshold (Y) were rounded to 1, and values smaller than threshold (Z) were rounded to 0. Through calibration processing, the EMG signals are normalized from 0 to 1.

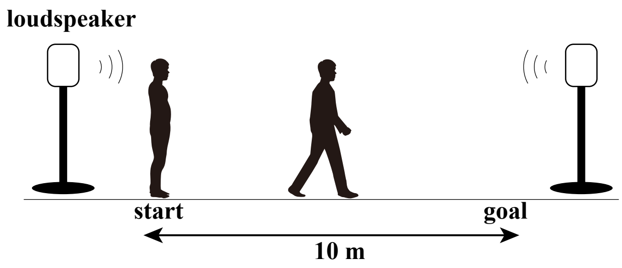

Figure 5: Experimental setup.

As for other methods of auditory biofeedback rehabilitation, 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 [10].

MATLAB sends normalized EMG signals to SuperCollider. SuperCollider is sound synthesis software. It maps each channel of EMG signals to a pitch in a harmony. Synthesized sound is passed to the two speakers.

5. SONIFICATION

We aimed to produce a sound design that can distinguish muscle coordination patterns based on the overtone-mapping technique [15]. 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 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.

Table 1: Mapping between muscle and sound frequency

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

In our implementation, we sonified the activities of four muscles (GM, RF, TA, and GA) on the right side. Table 1 shows the mapping between the muscles and the pitch. During the 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 4 shows the activities of the muscles during the gait cycle. These envelopes of muscle activity

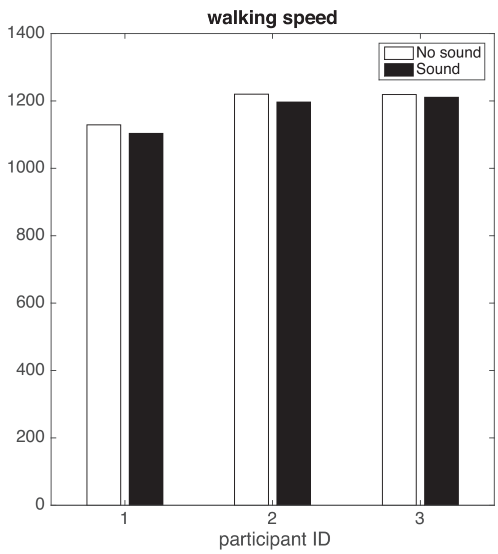

Figure 6: Average walking speed under sound and no-sound conditions.

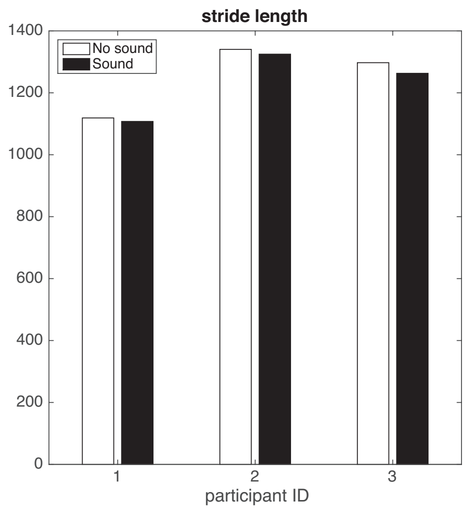

Figure 7: Average stride length under sound and no-sound conditions.

become the envelope of the harmonic sounds. We only sonified four channels because adding another channel can lead to feedback difficulty and would entail more practice.

6. PILOT TEST

6.1. Condition

Three participants (two men and one woman; aged 23-24 years) took part in the experiment. The experiment was conducted in the measurement room of the Center for Innovative Medicine and Engineering in the University of Tsukuba Hospital. Twelve wireless EMG sensors were

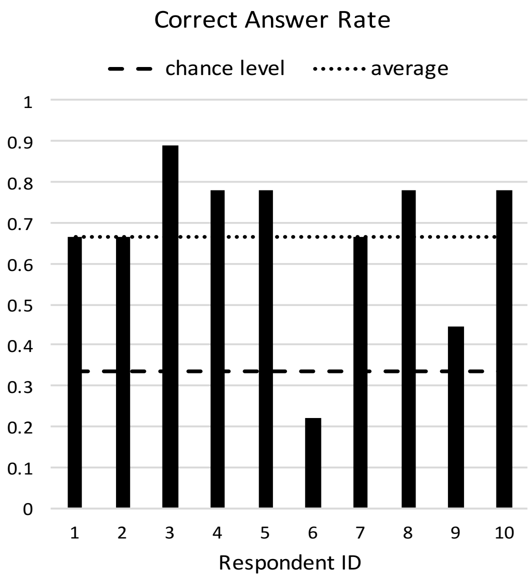

Figure 8: Correct answer rate of the listening test by respondent.

attached to the lower limbs of the participants. Four of the 12 channels of the EMG signal were used for sonification, and the remaining channels were recorded for analytic purposes.

In addition, to analyze their gait, a motion capture system and ground sensors were used. The motion capture system can measure the participants' exercise and calculate their walking speed and stride. The ground sensors attached to the heels of both feet show the time when the heel is grounded.

6.2. Method

In the experiment, they walked approximately 10 m under two conditions: sound condition and no-sound condition. Figure 5 shows the experimental setup. The participants are measured one way, from the start to the goal?.

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 while listening to the sound. The sound was presentation through speakers placed at the walking start point and at the end point. The sounds from the two loudspeakers are the same. They walked ten times under this condition.

6.3. Result

Figures 6 and 7 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.

7. LISTENING TEST

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

7.1. Procedure

An online listening test using Google Form was conducted [16]. The audio files used for the listening test were placed on Google Drive. Ten participants took the test, who first listened to three sample audio files. The three files correspond to the three walkers from the pilot test. The sounds were the sonified EMG signals under the sound condition. Then the participants listened to nine audio files, which were three sonifications for the three walkers randomly presented. They were asked which walker the sonification represents. Participants can listen to the three sample audio files as many times as they want.

7.2. Result

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 8 shows the correct answer rates of each respondent. Only walker 3's correct answer rate fell below the chance level. 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, the p-value was 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; therefore, the trial most likely ended before the influence of the sound appears. A longer walking distance in one trial 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 system measured EMG signals using a wireless EMG sensor kit. The system presented sounds using loudspeakers. The measured EMG signal was converted into sound in real time and fed back to the user of the system. The activity of four muscles was mapped to the volume of the sine wave of a different pitch.

Three healthy adults participated in this pilot test. The result showed no significant difference in the walking speed and stride by conditions, but the sound of the feedback did not interfere with their walking. The joint angle of one participant changed between conditions.

We conducted a listening test to investigate whether it is possible to identify the individual from the sound. The sound used in the listening test was generated from the pilot test data set, and the overall average correct answer rate was 0.67. The possibility of identifying the individual from the sound has been shown.

We intended to analyze the data of the pilot test in terms such as change in joint angle or EMG. We also examined the features of the wrong answer at the listening test.

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