Wearable Auditory Biofeedback Device for Blind and Sighted Individuals

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GaitEcho is a wearable auditory biofeedback device that uses an instrumented ankle-foot orthosis for gait rehabilitation. Experimental results suggest it offers similarly adequate functionality for blind and sighted participants.

As a population ages, elderly people increasingly fall and injure themselves. Such falls make them hesitant to move actively and thus severely decrease their independence and quality of life. Preventing falls is therefore critical in maintaining the wellness of elderly people.[1]

In physiotherapy, a tracking task for an ankle-joint exercise can be used to facilitate motor learning of the ankle.[2] For such tasks, a physiotherapist teaches a movement pattern that is optimally designed for the patient (reference), and the patient practices the pattern (tracking). However, Masaki Iguchi, our physiotherapist researcher (the second author) suggests that in practice such tasks tend to bore patients, who as a result may discontinue rehabilitation. Making the task effective, yet enjoyable would therefore encourage better exercise participation, resulting in fall prevention over the long term.

Biofeedback has been successfully used in physical rehabilitation for approximately 40 years,[3] but visual biofeedback (VBF) examples greatly outnumber auditory biofeedback (ABF) examples.[4–6] Earlier work examined the effectiveness of VBF in a tracking task using real-time visualization of ankle-joint movement,[2] however, the effectiveness of ABF in an ankle-joint tracking task has not been investigated. Because ABF does not require visual attention, it provides a much broader possible range of postures and gestures than VBF. Unattended use of vision is beneficial in physical exercise such as gait training.[7] Therefore ABF can overcome some drawbacks of VBF in rehabilitation. In addition to such physical advantages, ABF can widen the user population because visually impaired and blind individuals can benefit greatly from such a system.[6] Furthermore, since music can encourage accurate motor activities with positive emotional effects in physical therapy,[8] we expect similar effects by introducing a sonic interaction with rhythmic and melodic aspects. To address this issue, we developed a wearable auditory-biofeedback device called GaitEcho that can be used in fall prevention programs for sighted and blind individuals and examined the effects of interactive sonification on an ankle-joint exercise.

This study discusses the feasibility of a reference-tracking task of ankle-joint exercise with interactive sonification for sighted and blind individuals in terms of both objective and subjective evaluations via our wearable auditory biofeedback device using the instrumented ankle-foot orthosis (AFO) we call GaitEcho. Our experimental results suggest it offers similarly adequate functionality for both blind and sighted participants.

System Configuration

GaitEcho measures the instantaneous angle at the ankle joint (the ankle-angle signal) with a goniometer (Supertech Electronic P-00246) mounted on a custom-made plastic AFO (Kowagishi Laboratory) and sends it to a tablet PC (Acer Iconia W3-810) with Bluetooth serial communication at 500 Hz. To add sonification, a server program on the PC smoothes the received ankle-angle signal with a moving-average filter and sends it to a sound synthesis

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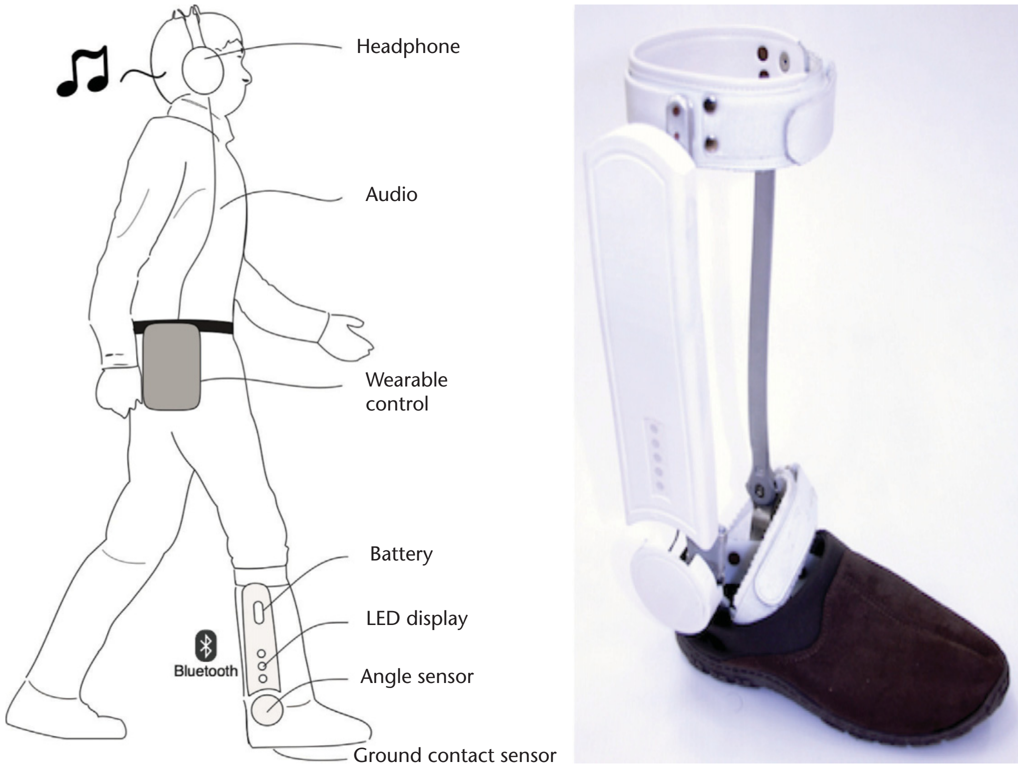

Figure 1. Overview of GaitEcho. The wearable auditory biofeedback device uses an instrumented ankle-foot orthosis for gait rehabilitation.

server with Open Sound Control protocol (at 25 Hz). A reference movement pattern is prerecorded and stored on the synthesis system. The sound generated by the reference emanates from the right channel of a headphone (Sony MDR-CD780), and the reference generated by the ankle angle emanates from the left channel. Figures 1 and 2 show the overview and specifications of GaitEcho.

Previous sonification research on continuous human movement in rehabilitation showed that continuous mapping approaches are suitable for motor learning.[9–12] We employed a mixture of continuous and discrete mapping: a sinusoid whose frequency is swept according to the ankle angle is mixed with a finger-snap sound to indicate the designated maximum and minimum peak angles.

We determined the sinusoid frequency was 500 Hz at maximum dorsiflexion (toe-pointing upward, ankle-bending direction) and 250 Hz at maximum plantarflexion (toe-pointing downward, ankle-extended direction). In dorsiflexion, the muscles at the shin (such as the tibialis anterior) are contracted with increasing pitch that is meant to be analogous to increasing tension. In plantarflexion, the muscles are actively lengthened, with the decreasing pitch analogous to decreasing tension.

A finger-snapping sound was added to the continuously sweeping sinusoid so that a patient can notice when the required movement is accomplished. This sound is generated when the angle at the ankle joint reaches the maximum dorsiflexion and plantarflexion angles.

We implemented this sonification using SuperCollider. (Supplementary files and source code are available in an online appendix at https://db.tt/qwvSdGxe.)

Experiments

Six sighted participants (five males and one female, aged 22 to 31) and six blind participants (four males and two females, aged 20 to 25) participated in our experiments. All participants gave their informed consent to the experimental procedure, which was approved by the local ethics committee. Sighted participants performed the task with both ABF and VBF and blind participants with ABF only.

Tracking Task and Its Evaluation

In the tracking task, participants performed a movement pattern as closely as possible to the

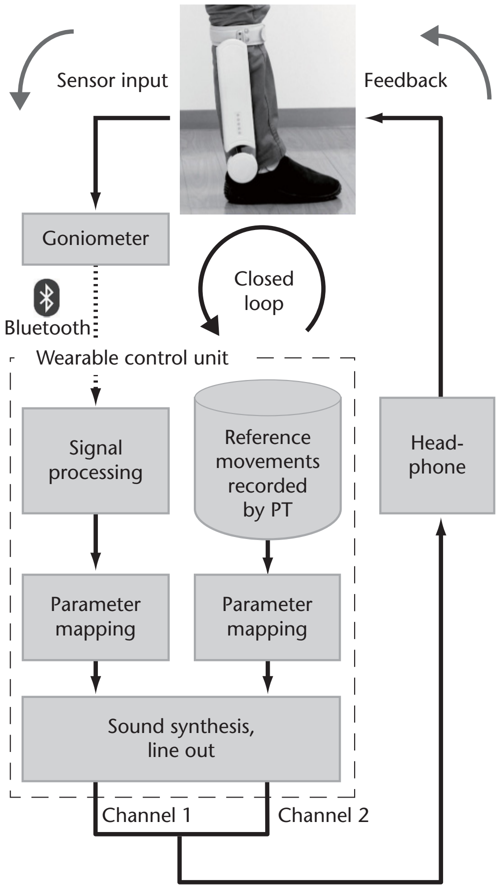

Figure 2. GaitEcho system scheme. GaitEcho sends the ankle-angle signal to a server program that in turn forwards it to a sound synthesis server to generate a variable-frequency sinusoid that reflects the ankle-angle and a click sound when the ankle joint reaches the maximum dorsiflexion and plantarflexion angles. Mixing these two sounds helps the user simultaneously understand both the current ankle-angle and the target angle.

reference using ABF or VBF. For the reference, a physiotherapist (PT) moved one participant's ankle with AFO to record six movement patterns of 60 to 70 seconds. Each pattern comprised a combination of four to seven movements with different speeds. Each movement was about 25 degrees of dorsiflexion and 30 degrees of plantarflexion, taking 6 to 10 s. The dorsiflexion angle was adjusted for some participants because of their limited range of motion.

The evaluation of our system has some exploratory character. Because the framework of the reference-tracking task requires a feedback, we cannot test the "no feedback" control condition. However, we aimed for a comparison with the standard system practically tested in the medical research, instead of a purely theoretical comparison as described in the discussion section.

Procedure of the Experiment

The participants first performed a practice task and then the main performance task. The latter took about 10 minutes for blind participants and 20 minutes for sighted participants. The order of the movements and that of the two conditions (ABF and VBF) were both randomized for each participant.

Throughout the practice and main tasks, participants sat up straight in a chair with their leg slightly raised on a stool and performed the ankle-joint tracking task in that sitting position. We recorded the entire waveform of the ankle-angle signal and used it for the analysis. After finishing the main task, we asked participants to answer a questionnaire.

For the practice task, the participants performed up to 10 minutes of free movement with the visual/sonic representations until they felt confident, and they then performed a sample reference-tracking task. Blind participants performed with ABF only, whereas sighted participants performed with both ABF and VBF.

For VBF, the reference was plotted as a waveform on a computer screen, replicating the system developed by Monica Perez, Jesper Lundbye-Jensen, and Jens Nielsen.[2] Participants traced the reference waveform with their own waveform, using a cursor-point that moves automatically from left to right and changes its vertical position according to the participant's ankle angle. The cursor moved upward during dorsiflexion and downward during plantarflexion.

For ABF, the sonification of the reference emanated from the headphone's left side and that of the participant's movement emanated from the right. Participants traced the reference movement by synchronizing two sounds. The sound design was basically identical for both sounds, but to facilitate auditory segregation, the reference sonification used pulse waves instead of sinusoids. Participants could therefore easily distinguish reference movements from their own by hearing left/right sounds. The delay time between sensor measurement and sonification was less than 0.04 s.

After the main task, participants rated on a scale from one to five three questionnaire items:

- subjective understandability (Was the sonification hard/easy to understand?),
- task difficulty (Was the motor task difficult/easy?), and
- enjoyment (Was the task enjoyable/boring?).

Finally, they gave free comments.

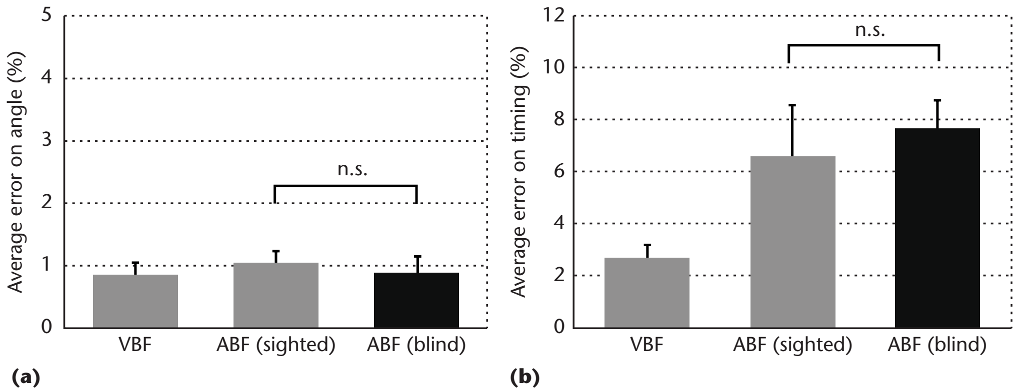

Figure 3. Average and standard deviation of the average error on (a) angle and (b) timing in tracking tasks with VBF and ABF (sighted) and ABF (blind) ($n = 6$).

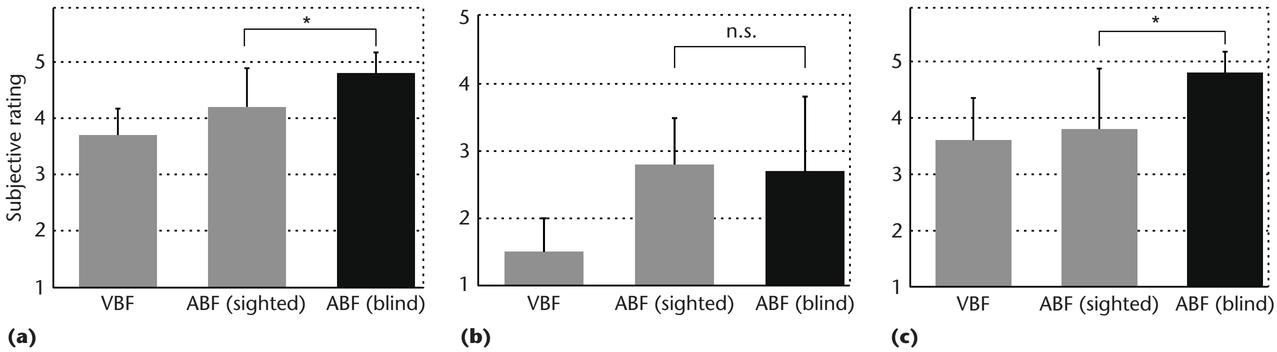

Figure 4. Average and standard deviation of subjective (a) understandability, (b) difficulty, and (c) enjoyment in tracking tasks with VBF and ABF (sighted) and ABF (blind) ($n = 6$). For the ratings, 1 indicated hard to understand, easy to perform, or boring; 3 denoted ordinary; and 5 indicated easy to understand, difficult to perform, or enjoyable, for the respective questions on understandability, difficulty, and enjoyment.

Results

The error between the reference and participants' movements was calculated using the differences of angle and timing at maximum dorsiflexion and plantarflexion. For each movement, we obtained average error on angle (AEA) and average error on timing (AET):

$$\mathrm{AEA} = \frac{100}{N}\sum_{i=1}^{N}\frac{|a_{r_i} - a_{s_i}|}{A},$$

where a_{r_i} and a_{s_i} are the reference and participants' angles at the ith peak ($i = 1\ldots N$), respectively, and A is the physiotherapist-instructed range of the ankle-joint angle in the task.

$$\mathrm{AET} = \frac{100}{N}\sum_{i=1}^{N}\frac{|t_{r_i} - t_{s_i}|}{T},$$

where t_{r_i} and t_{s_i} are the reference and participants' timing at the ith peak ($i = 1\ldots N$), respectively, and T is the reference-instructed duration of a movement.

Figure 3 shows the mean and standard deviation of the AEA and AET. AEA showed no significant difference between ABF (sighted) and ABF (blind) ($p = 0.2732$, unpaired student's t-test). The maximum AEA was less than 2 percent, equivalent to less than 1 degree of movement. AET showed no significant difference between ABF (sighted) and ABF (blind) ($p = 0.3228$, unpaired student's t-test). The mean AET with VBF was 0.30 s, and that with ABF (sighted and blind) was 0.66 s. The duration of each movement in the task exceeded 6 s, so these errors comprised less than about 10 percent of the total duration.

As Figure 4 shows, under the ABF condition, blind participants gave higher understandability and enjoyment scores ($p = 0.0428$ and 0.0380, respectively) than sighted participants, while their difficulty scores ($p = 0.7805$) were not significantly different. Both sighted and blind participants commented that for both conditions they enjoyed the tasks, comparing the experience to playing a game.

Most blind participants expressed delight through facial expression when using GaitEcho, while some reported that their foot became like a musical instrument.

Discussion

Our physiotherapist determined that both sighted and blind participants appropriately performed the ankle-joint exercise under both ABF and VBF conditions. The AEA with ABF was only 1 degree, within the acceptable error range. The 0.66 s AET with ABF is also acceptable because the ankle-joint exercise does not usually require precise timing.

In physical rehabilitation, training methods and rehabilitation programs are personally designed for the patient's needs. If an exercise requires precise timing, rhythm-based sonification can be used instead of pitch-modulation sonification. The relationship between movement types in various context and sonification methods has been investigated in the field of sonification for locomotion.[12]

The difference between VBF and ABF in sighted participants, especially for timing controllability, comes about because the system design employs different kinds of tasks for ABF and VBF. The VBF shows the entire reference waveform and thus enables the participant to predict the subsequent movement, while the ABF provides only the instantaneous ankle angle. In our prototype, we tried using VBF that shows the instantaneous ankle angle only, and in that case, the timing error was actually bigger than that with ABF. However, in this study, we employed the current VBF design (proposed earlier[2]) as a standard representative for visual biofeedback tested in the medical research.

The questionnaire scores showed significant differences between blind and sighted participants. Blind participants gave higher enjoyment and understandability scores, while the task performance difficulty ratings were similar. During the experiment, most blind participants expressed delight through facial expression when using GaitEcho, while some blind participants reported that their foot became like a musical instrument. For angle and timing controllability, no significant difference between the participants was seen with ABF. This implies that ABF offers equivalent functionality for blind and sighted participants, yet provides better emotional effect for blind people.

Some sighted participants commented they felt more comfortable with ABF than VBF because they felt no eyestrain with the former while watching the display. ABF reduces eye fatigue and allows for more varied position and posture. Some participants commented they felt no physical fatigue under either condition, but felt mental fatigue with VBF.

Conclusion

With ABF, both the sighted and blind groups performed the exercise appropriately, and blind participants reported higher understandability and enjoyment. Yet, the future applications are to be explored. GaitEcho is a fully equipped wearable system, and people can use it wherever they want, outside the typical rehabilitation venues. GaitEcho would be suitable for bedside rehabilitations or everyday rehabilitation at home. We also plan to apply GaitEcho for gait training at home, or anywhere outside hospitals. Exploring emotionally engaging sound design remains our future problem, such as employing more musical framework.

Demo video, sound files, supplementary data, and source code for sonification (SuperCollider) associated with this article are available online at https://db.tt/qwvSdGxe. **MM**

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