THE EFFECTIVENESS OF AUDITORY BIOFEEDBACK ON A TRACKING TASK FOR ANKLE JOINT MOVEMENTS IN REHABILITATION

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ABSTRACT

In the field of physical rehabilitation, fall-prevention programs to improve balance such as bedside ankle motor exercise have been of great importance. Conventional studies indicate that auditory biofeedback can improve tracking movements. In this paper, we investigated the difference in effectiveness between visual and auditory biofeedback during dorsi- and plantarflexion (movement which decreases and increases the angle of ankle) specifically in a tracking exercise. Patients were asked to dorsi- and plantar flex their ankle according to the reference movement. To increase patients' awareness and recognition of lower limb movement, we implemented an interactive sonification system that translated the ankle angle to improve their understanding of movement, and compared the auditory and visual biofeedback characteristics. In this study, we investigated the effects using the following three evaluation criteria: position controllability, timing controllability, and subjective understandability. The experimental results showed that the motor performance of tracking movements with auditory biofeedback (ABF) was not significantly inferior to that with visual biofeedback (VBF) in the scope of rehabilitation exercise. Our results suggest future applications of ABF for rehabilitative exercise of bedridden patients and blind patients for whom VBF cannot be applied.

1. INTRODUCTION

Along with the population aging, the number of elderly patients who stumble or fall in their everyday movement is increasing. Injury caused by falls can severely decrease independence and quality of life. Even without an actual injury, fear of falling after a fall incident restricts an elderly patient's daily activities. Thus, fall prevention programs to improve balance such as bedside ankle motor exercise[1] have been of great importance in the field of physical rehabilitation [1]. Movements in these motor exercises, are initially instructed by physical therapists through verbal cues or passive movement, and then patients practiced on their own. However, these movements may not be reproduced correctly in the absence of physiotherapists because: (1) motor learning in the short instruction time is difficult for patients, and (2) patients with nervous-system damage may have problems in their somatosensory sensation and thus difficulty in sensing movements of the limbs. In particular, during the chronic phase rehabilitation, patients need to practice their motor task at home and have only a limited opportunity to be assessed by physical therapists.

[1](i.e., motor exercise a patient conducts by oneself while still in the bed during recovery from illness).

It would be expected that biofeedback (visual, auditory and/or haptic an informative presentation mapped in real-time from internal biological signals to augment awareness of them) [2, 3] improves the motor performance of patients, and visual biofeedback is most commonly used among the biofeedback modalities. However, visual biofeedback is not appropriate for patients with limited upper-body mobility to perform bedside exercises at home or hospital bedrooms because visual displays require postural challenges such as sitting. Former studies have suggested that auditory biofeedback improves motor performances not only in blind patients [4], but also in healthy people [5, 6, 7, 8]. Conventional studies [9] indicate that auditory biofeedback can improve patients' tracking movements. However other studies shows that visual biofeedback also can support learning and improve movement [10, 11]. Thus, we need to investigate the difference in effectiveness between visual and auditory biofeedback.

In this paper, we investigated the differences in effectiveness of visual and auditory biofeedback during dorsi- and plantarflexion (movement that decreases and increases the angle of ankle) especially in tracking exercises. In this exercise, participants were asked to move their ankle according to the reference movement. To compare the characteristics between auditory and visual biofeedback, we implemented interactive sonification and visualization system that translate the angle of the ankle to improve participants' understanding of movements. We applied this method to healthy participants to explore the future possibility of this application to patients.

Figure 1: *A picture of the experimental set-up and instrumentation. Participants were asked to perform voluntary ankle dorsi-plantarflexion movements.*

2. METHODS

2.1. Participants and general experiment design

Six healthy volunteers (5 males, 1 female; aged 22–31) participated in the study. All gave their informed consent to the experimental procedure. Each participant was asked to perform a tracking motor task of the ankle joint repetitively under two conditions: visual biofeedback (VBF) and auditory biofeedback (ABF). Prior to the start of each task, enough time was spent for practice under the same biofeedback condition used in the following motor task. Figure 1 gives a general description of the experimental set-up.

2.2. Instrumentation

In the study, sitting participants were asked to perform voluntary right ankle dorsi-plantarflexion movements. The angles of the hip and knee joints were 120 and 160 degrees, respectively (Figure 1). In order to limit the degree of freedom in movement direction, participants wore an ankle-foot orthosis (AFO) (TO-230R, Tokuda Ortho Tech, Japan) (Figure 2). The AFO is commonly used for ankle rehabilitation [12, 13, 14]. The angle of the ankle joint was measured by a goniometer (P-00246, Supertech Electronic Co., Ltd., Taiwan) and sent to a computer via Bluetooth serial communication. During the movements, participants were asked to observe a computer screen positioned in front of them and listen to sounds from the headphones (MDR-CD780, Sony Ltd., Japan).

Figure 2: *A picture of the ankle-foot orthosis (AFO). The angle of ankle joint was measured by a goniometer and sent to a PC via Bluetooth serial communication.*

2.3. Protocol

Each participant perform in a 30-minutes session of a lower-limb visuo- or audio-motor tracking task. A physical therapist moved the participant's ankle with AFO to record six reference movements (Figure 3)[2]. Each motor task consisted of a combination of 4–7 movements with different speeds and the total duration was 60–70 sec. Each movement was about 25 degrees of dorsi- and 30 degrees of plantarflexion, and took 6–10 sec. The session consisted of a practice and 20 minutes performing task under two conditions. The order of the two conditions was alternated with-in each movement and randomized across participants. After finishing the motor task, we asked participants to rate the level of understanding how to perform the tasks.

[2]reference data are available in online (see Appendix B)

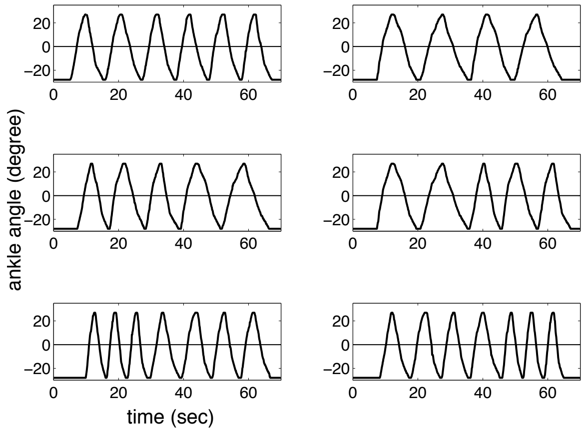

Figure 3: *The 6 reference passive movements were recorded with the help of a physical therapist. Each motor task consisted of 4–7 movements with different speeds and the total duration was 60–70 sec. Each movement took 6–10 sec. The neutral stand position is a degree of zero. A positive angle indicates dorsiflexion.*

2.3.1. Practice session

Prior to performing the task, the participants practiced enough to be able to move their ankle and track the reference movement easily. To learn the relationship between the ankle angle and graph/-sound representations, each participant was given up to 10 minutes non-tracking training at the beginning of the practice. During the training, the participant could observe the display or listen to the sound while changing the angle of his or her ankle. After the training of two biofeedback conditions, the motor tracking tasks were performed. Figure 4 shows an example of movement tracking. A practice reference movement for the actual task was also recorded.

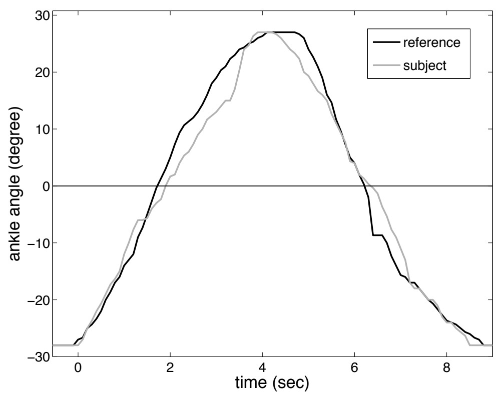

Figure 4: *A plot of single-movement tracking (the reference is an 8 sec. movement).*

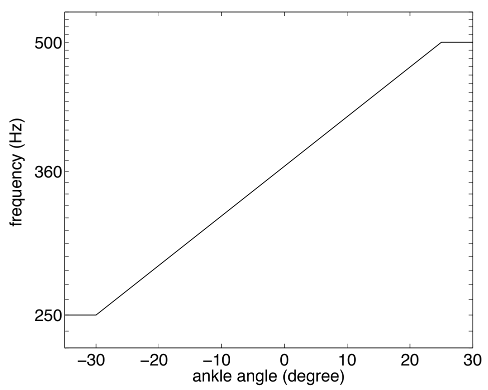

Figure 5: *Parameter mapping between the ankle angle and the sound frequency.*

2.3.2. Visual biofeedback (VBF) and visuo-motor task

Visual biofeedback (VBF) was conducted as follows: The position of the ankle joint (measured by the goniometer in 10 Hz) was represented as a cursor point on the computer screen. The cursor moved automatically from left to right. Participants were able to control the up-and-down movement of the cursor by performing ankle dorsi- and plantarflexions. During dorsiflexion, the cursor moved upward, while during plantarflexion the cursor moved downward. Following Perez et. al. [10], a whole reference movement was statically plotted as a line graph before participants started the performance. In the visuo-motor tracking task, the participants were asked to track the reference movement by moving the cursor so that it tracked the line graph.

We also investigated bar plotting and real-time line plotting [9] for reference representation in the pilot experiment; however, the performance did not show a major difference from the above condition. Since the line-graph presentation of biological signals are commonly used in rehabilitation, we adopted this presentation for the task.

2.3.3. Auditory biofeedback (ABF) and audio-motor task

Auditory biofeedback (ABF) was conducted as follows: in addition to the VBF mentioned above, the angle of the ankle joint was captured and sonified to the sound. We adopted a parameter mapping sonification method [16]. As described by a previous study [8], the frequency of the sinusoidal that corresponding to the participant's movement was continuously varied. In this study we set the maximum dorsiflexion to 500 Hz and the maximum plantarflexion to 250 Hz. During dorsiflexion, the frequency increased, while during plantarflexion the frequency decreased (Figure 5). We also implemented some auditory icons like a finger-snapping sound, which corresponded to the maximum dorsi- and plantarflexion (More details are described in Appendix A).

In the audio-motor tracking task, paricipants were asked to track the reference movement by listening to the sonified sound. As in the Sussman's method [15], in order to increase separated recognition between sounds of reference and participant movements, the two sounds are panned to left and right, and their timbres are pulse (reference) and sinusoidal (participant), respectively. Thus, participants could easily hear the sounds that corresponded to the reference movement from the left ear, and the sounds that corresponded to their movement from the right ear. The sound frequency was varied and corresponded to movement in real-time.

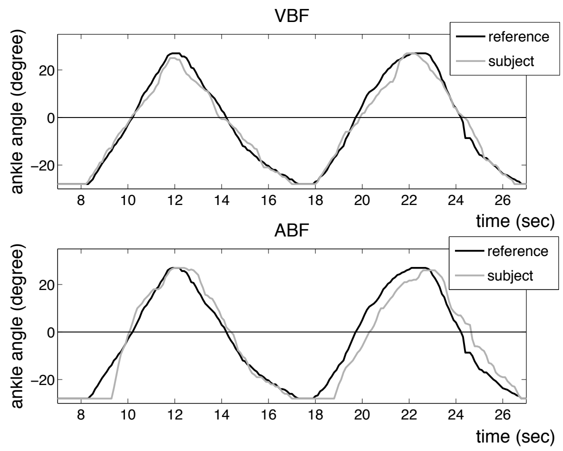

Figure 6: *An example of experimental results in a tracking task with VBF and ABF.*

2.3.4. Subjective understandability rating

After finishing the motor tasks, we asked participants to rate the level of understanding how to perform the tasks. The ratings were as follows: 1 = very difficult, 2 = difficult, 3 = ordinary, 4 = easy and 5 = very easy. Also participants were asked to give free comments about difficulty, enjoyment, and fatigue.

2.4. Angle recording

The angle of the ankle was caputured through the electrical goniometer and recorded (10 Hz) on the computer using MATLAB (version 8.2.0.701, R2013b, Mathworks, Natick, MA, USA) for later analysis.

2.5. Data analysis

To measure the motor performance, the error was calculated as the difference between the reference and the actual movement. The differences of timing and position of the ankle joint at the peaks (maximum dorsi- and plantarflexion) were calculated as the error. These peaks were calculated with MATLAB findpeaks function, which finds the local maximum or minimum point in each movement. A mean absolute error (MAE) was obtained for each movement, which is defined as the following equation:

$$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n}|f_i - y_i| = \frac{1}{n}\sum_{i=1}^{n}|e_i|, \quad (1)$$

where f_i is an actual movement value and y_i is a reference value. Error e_i is calculated by the difference of the actual movements and the reference movements.

In order to investigate how effective these two biofeedback conditions are, we calculated the average and variance of MAE within participants across biofeedback type. A paired Student's T test was performed on significant comparisons (with a significance level of 0.05).

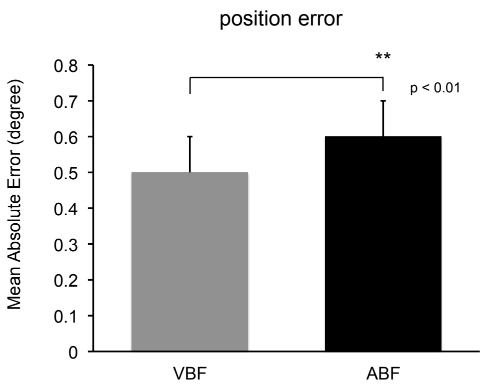

Figure 7: *The bar raph demonstrates average and standard deviation of the mean absolute error of ankle-angle positioning in the tracking tasks with VBF or ABF (n = 6).*

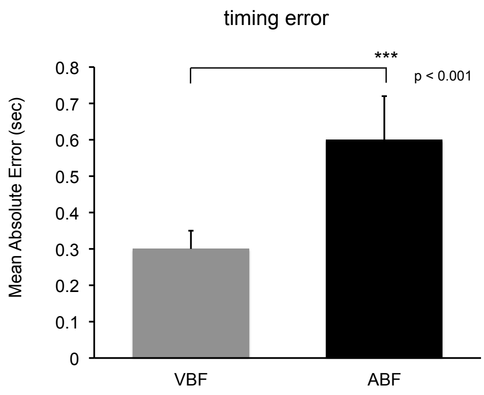

Figure 8: *The bar graph demonstrates average and standard deviation of the mean absolute error of ankle-movement timing in the tracking tasks with VBF or ABF (n = 6).*

3. RESULTS

In this study, we compared the effectiveness of VBF and ABF with the following three evaluation criteria: position controllability, timing controllability, and subjective understandability. Figure 6 shows an example of the experimental results in the tracking task with VBF and ABF.

3.1. Position controllability

Figure 7 shows the average and standard deviation of the ankle-angle positioning MAE in VBF and ABF. There is a significant difference between VBF and ABF ($p = 0.00389$). The maximum MAE position in VBF was 0.9 degree, and the maximum MAE position in ABF was 1 degree. The total degree of movement in the task was about 55 degrees, thus these errors were less than 2% degrees of the movement.

3.2. Timing controllability

Figure 8 shows the average and standard deviation of the ankle-movement timing MAE in VBF and ABF. There is a significant difference between VBF and ABF ($p = 0.00097$). However, the average of MAE timing in VBF was 0.29 sec, and the average of MAE timing in ABF was 0.64 sec. The duration of each movement in the task was more than 6 sec, thus these errors comprised less than about 10% of the total duration.

3.3. Subjective understandability

To achieve effective biofeedback, it should be easy for users to understand how to perform the task. Therefore, a subjective understandability, which has been shown to be important as an objective measure [17], was included in this study. We found no significant difference between VBF and ABF ($p = 0.2955$). As for the difficulty of the tasks, some participants reported that VBF was easier compared with ABF but there was no significant difference between them. In the comments, some participants reported that they enjoyed both ABF and VBF tasks like they were playing video games.

4. DISCUSSION

The timing controllability showed a significant difference between ABF and VBF, in which ABF led to a larger delay than VBF behind the reference movement. However, the delay in timing was 0.64 sec on average. Since sampling frequency of ankle signal is 10 Hz, the consistent delay occurs up to 0.1 sec in both conditions. The consistent delay is possible to be reduced when sampling frequency becomes higher. In physical rehabilitation, a training method are designed depending on what goals the patients would like to accomplish. For example, in an activity such as overarm throwing, skilled throwers can release a ball with an accuracy of a few milliseconds [18]. If a training task requires precise timing, the pitch-modulation sonification method we used in the present study is probably not the best choice. Although the statistical analysis indicated that both the timing and angle errors were greater for the auditory biofeedback compared with the visual biofeedback, the angle of error was very close and all the participants were able to track the target with just ABF only. This means that auditory biofeedback can be used in rehabilitation where repetitive movements are required. Repetitive movements are often used in rehabilitation, for example, when a patient needs to learn a new motor task. Studies have shown that a new task can be learned with visual biofeedback, but whether we can learn a new task through auditory biofeedback would be an interesting topic for further research. Sufficiently appropriate movements were produced under both conditions.

Subjective understandability showed a preference for ABF over VBF, though it was not statistically significant. This was due to the close correspondence between the somatosensory and sound, as reported by many participants. Some participants commented that ABF was more comfortable than VBF because ABF did not cause eye strain when looking at the display. ABF reduces eye fatigue and allows for more variety of positions, which is important for rehabilitation. Some participants commented that they did not feel physical fatigue under both conditions, but felt mental fatigue in VBF. On the other hand, a longer practice session was indispensable for ABF especially participant without professional musical training, because the task could be more challenging when the participants' movements got away from the reference movements.

Modifying the sonification design could increase the effective-

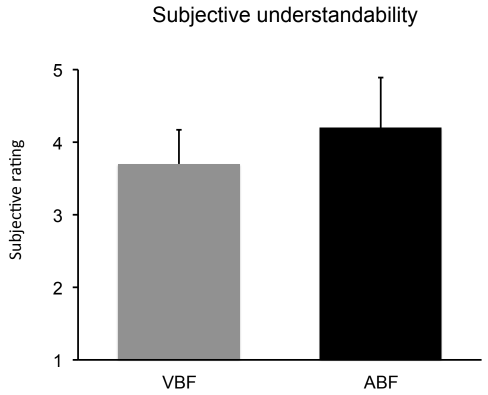

Figure 9: *Bar graph demonstrates average and standard deviation of subjective understandabilty in tracking task between VBF and ABF (n=6). (The ratings were as follows: 1 = very difficult, 2 = difficult, 3 = ordinary, 4 = easy and 5 = very easy)*

ness of biofeedback in rehabilitation yet the design should carefully reflect purpose, scope, expected functionality, and user capability for the task to be conducted. The sonification method employed in this study varied the pitch corresponding to the angle of the ankle with minimal data preprocessing. In general, the degree of data preprocessing defines the sonification as being more analogical or more symbolic [19]. When data preprocessing is minimal, the sonification is more analogical, reflecting the original data more directly and continuously. Analogical sonification is more suitable for exploratory observation of data. Meanwhile, when data preprocessing is heavy, the sonification becomes more symbolic, reflecting the intended perspective of the data analysis. Symbolic sonification is more suitable for the observation of predefined characteristics, such as alarming of an electrocardiogram, auditory icon, earcon, etc. Of these two extremes, our current approach is more analogical, allowing broad applications independent of the type of motor task. With this kind of analogical sonification, users can explore characteristics of their own movements, and reflect an understanding in realizing/reproducing movements. Indeed, there is a successfully applied analogical sonification in the Olympic rower training program, reflecting motion-sensor data onto the pitch of the synthesized sound [8]. Following Tsubouchi et. al. [20], we also need to investigate the comparison among other analogical sonification methods.

5. CONCLUSION

In this paper, we have examined the effectiveness of auditory biofeedback in tracking a motor task for ankle joint rehabilitation. The experimental results showed that motor performance of the tracking movement with ABF was not significantly inferior to that of VBF in the scope of rehabilitation exercise. The study suggests future applications of ABF for rehabilitative exercise of bedridden and blind patients whose visual deprivation prevents VBF. Our future perspective is to explore more engaging sonification method on the aesthetic aspect, such as more selections of sound effects, introducing musical contents in the interaction, etc. We also plan to apply the method to patients under physiotherapeutic treatment as well as blind and elderly patients. Combined with visual and/or haptic biofeedback, the technology of auditory biofeedback described in this study has the potential not only for physical rehabilitation, but also for health care and playful rehabilitation for children.

6. ACKNOWLEDGEMENTS

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Appendix A. SOUND SYNTHESIS

Sound generation and parameter control is realized with Supercollider 3, an open source package for real-time audio synthesis programming available from http://www.audiosynth.com.

A.1. Synthesizer Definition

SynthDef "Clip" is an auditory icon that indicates the maximum dorsi- or plantarflexion. The sound file (snap.wav) was downloaded from Freesound.org[3]. SynthDef "participantABF" and SynthDef "referenceABF" are the auditory biofeedback synthesizer definition of participant movement or reference movement. These sound timbres are sinusoidal or low-pass-filtered pulse waves. Both sounds employ the reverberation effect.

Listing 1: Synthesizer Definition

```
SynthDef("Clip",{
  arg amp = 0.8, speed = 1;
  a = PlayBuf.ar(1, Buffer.read(s, "sounds/snap.wav"),
    speed, doneAction:2);
  OffsetOut.ar(0, (a * amp).dup);
}).load;

SynthDef("participantABF", {
  arg freq = 250, amp = 0.8, pan = 1;
  var src = SinOsc.ar(Lag.kr(freq,1)) * amp;
  OffsetOut.ar(0,FreeVerb.ar(Pan2.ar(
    src,pan),0.4,0.3,0.5));
}).load;

SynthDef("referenceABF", {
  arg freq = 250, amp = 0.8, pan = -1;
  var src = Pulse.ar(Lag.kr(freq,1)) * amp;
  OffsetOut.ar(0,FreeVerb.ar(Pan2.ar(
    LPF.ar(src,400),pan),0.4,0.3,0.5));
}).load;
```

A.2. Open Sound Control Function

Auditory biofeedback is achieved with Open Sound Control (OSC) message. The OSC function, which processes the OSC message, is defined as follows. The OSC functions generate the sinusoidal or pulse wave and their frequency changing corresponds to movement. The difference between the two functions below is that the function for participant movement synthesizes the auditory icon.

Listing 2: OSC function

```
OSCFunc({|msg, time, addr, recvPort|
  var angle = msg[1], freq, amp;

  if(((angle > ~max)&&(~flag != 1)),
    {s.sendMsg("/s_new","Clip",node,0,0,"speed",1);
```

[3] http://www.freesound.org/people/OwlStorm/sounds/151214/

```
      ~flag=1;});
  if(((angle < ~min)&&(~flag != -1)),
    {s.sendMsg("/s_new","Clip",node,0,0,"speed",0.9);
     ~flag=-1;});

  freq = 250 * (2 ** ((angle - ~min) / (~max - ~min)));
  amp = 0.9 - (((angle - ~min) / (~max - ~min)) * 0.2);
  if(freq>500, {freq=500}); if(freq<250, {freq=250});

  s.sendMsg("/n_set",~parNodeID,"freq",freq,"amp",amp);
}, '/participant', nil
);

OSCFunc({|msg, time, addr, recvPort|
  var angle = msg[1], freq, amp;

  freq = 250 * (2 ** ((angle - ~min) / (~max - ~min)));
  amp = 0.9 - (((angle - ~min) / (~max - ~min)) * 0.2);
  if(freq>500, {freq=500}); if(freq<250, {freq=250});

  s.sendMsg("/n_set",~refNodeID,"freq",freq,"amp",amp);
}, '/reference', nil
);
```

A.3. Mappings

- A local variable `angle` represents the ankle joint angle that continuously recieved the OSC message (via Bluetooth) from the lower limb orthosis through the goniometer.
- Local variables `freq` and `amp` represent the sound parameter (frequency and amplitude) of the auditory biofeedback sounds.
- A global variable `max` (maximum dorsiflexion) is stored 20 and `min` (maximum plantarflexion) is stored -30.
- A global variable `flag` shows whether the participant's movement reaches the maximum and minimum angle.

Appendix B. SUPPLEMENTARY DATA

Sound files and supplementary data associated with this article can be found in the online version, at https://db.tt/EtaC5SZd .

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