Regular Paper

Posture-based Golf Swing Instruction using Multi-modal Feedback

Yuka Tanaka[1,a) Takuto Nakamura[1,2,b)] Hideki Koike[1,c)]

Received: May 4, 2021, Accepted: November 2, 2021

Abstract: Beginners must learn correct swing motion in golf. Systems are available that provide visual, auditory, or haptic feedback to the user. Such systems, however are only one modality and do not explore combinations of different modalities. We developed a wearable device using vibro-transducers that can provide auditory and haptic feedback separately or simultaneously. We also conducted user studies to compare how each modality improves the common flaws in golf swings, such as sway, separated elbow, and head lift. The results demonstrated that the combination of auditory and haptic feedback is significantly effective in correcting these faults.

Keywords: multimodal feedback, golf, sonification, haptic feedback

1. Introduction

In many sports, learning a particular posture or motion correctly is vital for improvement. To support such learning processes, designers have proposed several systems [1].

In golf, for example, reproducing a good swinging motion is strongly related to improving one's skills, and commercial products like as Gears [*1] and M-Tracer [*2] aim to meet this need. These products analyze and visualize the posture and trajectory of golf swings to help people achieve the correct posture. After the swing, such devices examine the learner's swinging motion, however, Wiggins [2] stated that immediacy or immediate follow-up is a necessary factor for effective feedback.

Based on this concept, several researchers have proposed employing visual [3], auditory [4], or multimodal feedback [5] to provide real-time feedback on "differences between experts and beginners" and "how to adjust your posture" for golf swings.

Most studies and products provide real-time feedback feature visual signals. However, visual feedback does not always work best for golf swing practice because golfers must keep their eyes on the ball during the swing. Thus, seeing visual feedback during the swing disturbs the golfer's posture.

Providing swing feedback using an auditory signal, on the other hand, allows users to receive feedback while maintaining their posture. Products and studies, such as the SALTED Smart Insole [*3], have been proposed as a method of providing real-time auditory feedback. During the swing, this feedback device records the position of the user's center of gravity or head movement. Practicing with auditory feedback enables users to pay attention without diverting their gaze.

In general, novice golfers should be aware of several aspects of their golf swings, most real-time auditory feedback devices however only focus on one point. This limitation stems from the fact that assigning auditory feedback for all of the many items would be difficult in the short time that a golf swing occurs since the user would have to listen to different sounds almost simultaneously to determine the meaning of the feedback. Thus, conventional auditory feedback systems tend to focus on a single caution point so that the user can immediately understand what auditory feedback means.

This study proposes a feedback method that uses auditory, tactile, and audio-haptic feedback (a combination of auditory and tactile feedbacks) to achieve the goal of simultaneously improving the user's multiple caution points that need to be taken care of during the swing. To provide auditory and tactile information to the user simultaneously, we developed a device using a vibration transducer (hereafter vibro transducer) that functions as a loudspeaker and transducer. The proposed method was compared with a conventional practice method in the user study, namely, using a mirror. In addition, three feedback methods using the developed device were compared: auditory feedback, tactile feedback, and combined auditory and tactile feedback. In the experiments, we examined the impact of each method on users' learning and their impressions of the proposed method and we verified the usefulness of the proposed method.

2. Related Works

2.1 Feedback for Motion Acquisition

With the development of high-precision movement-measurement devices, many products and studies have been proposed to

1 School of Computing, Tokyo Institude of Technology, Meguro, Tokyo 152–8550, Japan
2 Japan Society for the Promotion of Science
a) tanaka.y.ci@m.tiech.ac.jp
b) nakamura.t.by@m.titech.ac.jp
c) koike@acm.org

*1 https://www.gearssports.com
*2 https://www.epson.jp/products/msensor/golf/
*3 https://www.salted.ltd/golf

© 2022 Information Processing Society of Japan

assist in the acquisition of the correct posture for various activities. In particular, researchers have employed several methods of instruction and feedback to assist in the acquisition of postures and motions during sports or exercise.

There are two kinds of feedback available to help with posture acquisition. One method compares and contrasts the difference between an expert's and the user's movement, assisting the user in imitating the expert's movements. As an example of the former, some assist the user in imitating the movements of a role model. My Tai-Chi course coaches have displayed the expert avatar from multiple angles next to the user's avatar in an augmented reality environment [6]. One body is displayed an an avatar or human-like shape performing the correct posture, and the expert image motion is superimposed over the user image motion [7].

The other method is to provide instruction or feedback on movements based on learning theory, which is widely known in the target sport. One example of this method is a device that provides feedback based on the ideal order of moving the back and knees in oar rowing [8]. In golf, a visual feedback system based on the ideal center of gravity position theory has been proposed [9].

In the current study that focuses on golf swings, there is a significant difference between novice and expert golfers in the range of motion (ROM) of body joints. In most cases, it is impossible for novices to reproduce the movements of expert players. Therefore, the proposed system provides feedback based on widely known theories about the golf swing.

2.2 Auditory Feedback (Sonification)

Auditory feedback is a common method for assisting with the acquisition of movements and techniques when visual feedback is difficult or impossible to obtain. According to Tajadura-Jiménez et al. [10], sounds that correspond to movements help people perceive their posture more clearly, and the researchers used auditory feedback for chronic pain rehabilitation. Ghai et al. [11] discovered that auditory feedback transmits specific postural instructions such as knee angles. In sports, particularly in movement acquisition, auditory feedback has been used to improve swing speeds in baseball [12], and backward leaning in skiing [1].

Due to the difficulty of seeing visual feedback during movement in the golf swing, auditory feedback has been widely used to aid training. The change in the center of gravity [13], the movement of the head during the swing [14], and the timing of the club's acceleration [15] are among the characteristics of auditory feedback that are considered essential during the swing.

These types of auditory feedback are limited in their ability to convey a small amount of information in a short time. It is worthwhile to play back complex feedback sounds for applications where the user can listen to the feedback sounds repeatedly over time [16]. However, users often struggle to understand the meaning of complex feedback sounds in a short time (e.g., during a golf swing). To therefore provide a simple sound to the user, the conventional auditory feedback used for golf swings targets only one of the several notes that the learner must be aware of during the swing.

In addition, the Vi-HaB [17] stated that when the user is not looking directly at the vibrator and the tactile feedback is provided, the accuracy in discriminating the vibrating parts increases. Implying that the vibration feedback is useful for learning the golf swing.

To avoid overloading a single human sense with feedback, several researchers have combined visual, and auditory or tactile feedback. It has been demonstrated that there are positive changes in performance when visual feedback is combined with haptic feedback [18] or when visual feedback is combined with auditory feedback [19]. Sigrist et al. also investigated visual, tactile, and auditory feedback for the acquisition of correct rowing behavior [20]. All of these examples demonstrate the advantages of providing feedback from multiple modalities. However, because the direction of the gaze is fixed on the ball during a golf swing, looking at such visual feedback during the swing can disrupt the user's posture. Therefore, in this study, we presented auditory and haptic feedback to the user to supply feedback on multiple caution points to the user in a more understandable manner than auditory feedback alone.

2.3 Haptic Feedback

Subtletee [21], compared the modalities of visual, auditory, and haptic feedback to determine which was more appropriate for the golf swing, and it was determined that haptic feedback was more appropriate. On the other hand, the feedback presented by Subtletee requires the user to recognize multiple channels of feedback during operation (the position and intensity of vibration, as well as changes in sound). As a result, the system is considered to have a high cognitive feedback load and such a system makes it difficult for the user to change a motion based on all of the feedback.

Some studies on haptic feedback about the golf swing involve moving the club's center of gravity with an attached actuator and a weight [22], using cables to correct the club's trajectory [23], and applying torque via the golf club device to correct the user's posture [24]. In contrast, we aimed to improve the user's posture by delivering or applying vibration feedback directly to the user's body rather than through the golf club.

There are numerous approaches to making haptic feedback interact with the user's movements and posture.

The Pumanact [25] flexes and extends the user's arm using pneumatic actuators. In one study, artificial muscles attached to the entire hand were used to move the fingerprint [26]. These are devices that use force presentation to move the joints of the user's body.

As a different example, a method for providing information about the direction of motion to the user's body using haptic illusions has been proposed [27]. Some systems provide instruction on snowboarding turns by conveying the direction by illusion [28]. In addition, other than using illusions, effective methods for conveying the direction of motion with tactile information have been investigated [29].

GymSole [30] uses multiple vibrators attached to the shoes to display the user's center of gravity position during squats and deadlifts using multiple vibrators attached to the shoes. The ClimbingAssist [31] also indicates whether enough force is be-

© 2022 Information Processing Society of Japan

ing applied to the feet while climbing. These are systems that use vibration to reinforce awareness of one's posture.

Other devices have also been proposed that use vibration as a signal to encourage the user to move. MusicJacket [32] assists violinists in learning proper posture for violin playing by activating the vibrator when an error in posture occurs or when a movement should occur.

The purpose of this study is to enable users to detect and correct any errors in their posture spontaneously. Since the directional conveying of movement via tactile illusions takes time for the user to perceive the direction, we adopted a feedback method that encourages movement by using vibrations as signals. In the proposed system, the direction of motion is not included in the feedback, thus allowing the user to easily distinguish the feedback in a short time.

3. Implementation

To present feedback to the user about multiple locations during the swing, we implemented a feedback device using a Vibro-transducer Vp210 [*4], which is a loudspeaker-type transducer.

When low-frequency sounds are played from the speaker, the speaker vibrates to convey tactile feedback, and when high-frequency sounds are played, the speaker can present auditory feedback where vibration is not perceived. By presenting high-frequency and low-frequency sounds simultaneously, auditory and tactile feedback can also be presented simultaneously.

3.1 Feedback Methods

We selected three of the most important points a novice golfer should take concerning posture during the golf swing: (1) avoiding abduction and extension of the right shoulder in the swing (Separating elbow), (2) avoiding upper body sway to the right during the swing (Sway), and (3) avoiding moving the position of the head during the swing (Head lift). Our system presents feedback on the separating elbow, sway, and head lift. These caution points were chosen based on points frequently raised by beginners, using the results of instructional books, and interviews with experienced players. Other candidates included wrist and waist rotation angles during a golf swing. However, these were rejected because these were too close to selected points and there were too many points to correct. Finally, we selected these three points that are far apart and easy to handle because three points are not so hard to deal with. The errors at the selected locations differ in the timing, at which they are likely to occur. For the elbow angle, errors tend to occur during the backswing at the beginning of the swing; for the sway (waist position), errors tend to occur from the middle to the end of the backswing; and for the head position, and errors tend to occur throughout the swing. Of course, multiple errors may occur simultaneously depending on the user, but by reducing the probability of a simultaneous occurrence, we believe this arrangement will prevent confusion in the user's information processing.

The proposed system calculates parameters representing the degree of abduction and extension of the right shoulder, sway, and head movement in the manner described below and assumes that a value closer to 0 for all these parameters is closer to the ideal swing form. Based on this assumption, we presented the user feedback on posture errors by presenting sounds and vibrations from the corresponding transducers when the parameters exceed a set threshold. The threshold value was the average value of each parameter obtained from the 10 swings performed before practice. The parameters are as follows:

(1) Separating elbow—the angle between the right arm and torso (**Fig. 2** (b))
(2) Upper body sway—based on the position of the hips at the start of the swing, the distance the hips move to the right during the swing (Fig. 2 (a)); and
(3) Head lift—based on the position of the head at the beginning of the swing, the distance the head moves up and down during the swing (Fig. 2 (c)).

Humans are able to recognize and discriminate an average of 2.6 bits of information with a standard deviation of 0.6 bits [33]. Based on this information, we designed the feedback system to present 1 bit information, "presence or absence of sound or vibration," at three locations on the body, giving the user 3 bits of information. We designed the feedback so that the total information presented to the user in the system would be 3 bits. We hoped that by doing so, the user would be able to accurately identify all of the information presented without causing perceptual conflicts.

Scalera et al. [29] found that when the feedback is closer to the vibration, the user's reaction speed is faster than when feedback is avoided. On the other hand, the feedback in the proposed system only presented information about the posture's correctness. This did not include information on the direction of body movement. As a result, the transducer was placed closest to the point where the posture error occurred.

When sound or vibration is presented during an action such as exercise, learners generally find the presented sound or vibration unpleasant. Therefore, we thought that continuously providing sounds and vibrations when the posture is correct would interfere with the user's learning. On the other hand, we expected that presenting a sound or vibration when a posture error occurred would motivate the learner to avoid the unpleasant sensation. For this reason, we designed the feedback as negative reinforcement learning.

3.2 Device Configuration

Figure 1 shows the configuration of the device. The user mounted the device on the body by carrying a backpack containing the audio amplifier and battery.

The stereo audio output from the personal computer (PC) is connected to two vibro transducers via a stereo plug and amplifiers (**Fig. 3**). These two vibro transducers can present independent sound and vibration by playing the audio output from the PC. To use the three vibro transducers in the experimental environment, the audio amplifier was connected to the PC via an audio interface with two 3.5 mm stereo plugs. The vibro transducers were attached to the backpack's right shoulder belt, right waist belt, and cap.

The user study was performed with three Vibro-transducers

[*4] http://www.acouve.co.jp/product/pd_vp2.html

© 2022 Information Processing Society of Japan

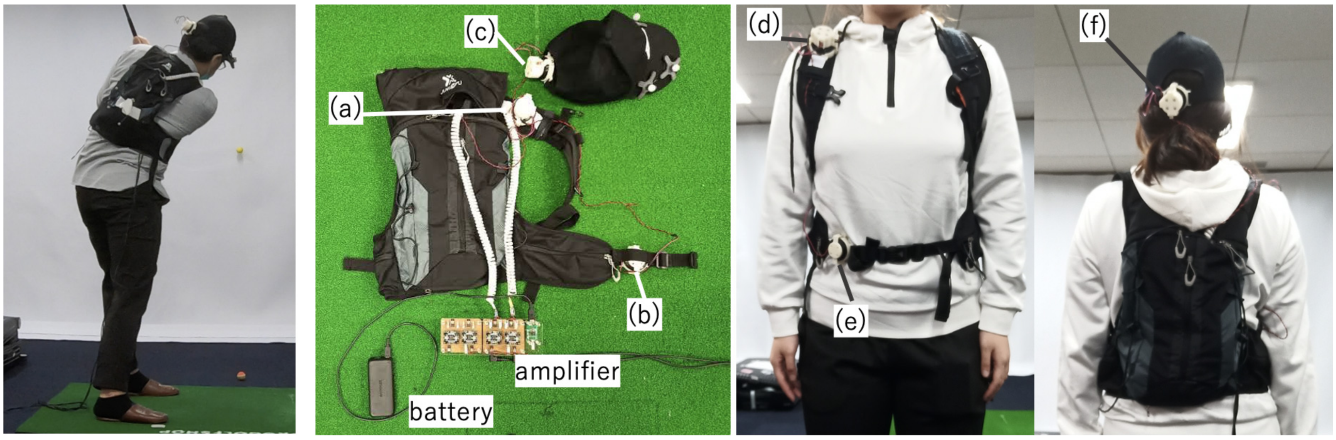


Fig. 1 The proposed device and an example of how it was worn in user study. The user study was performed with three loudspeaker-type transducers attached to (a), (d) the user's right shoulder, (b), (e) right waist, and (c), (f) back of the head.

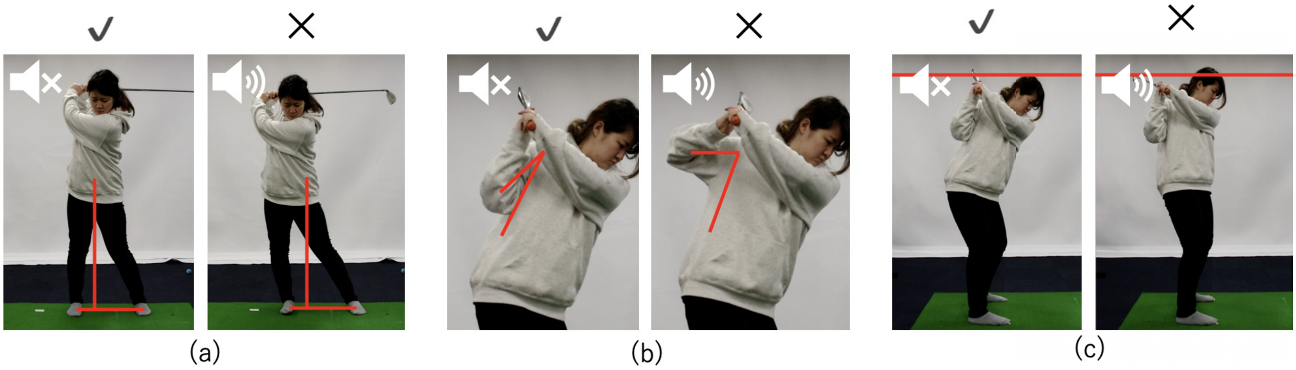


Fig. 2 Three parameters used to provide feedback: (a) Sway, (b) Separating elbow, and (c) Head lift.

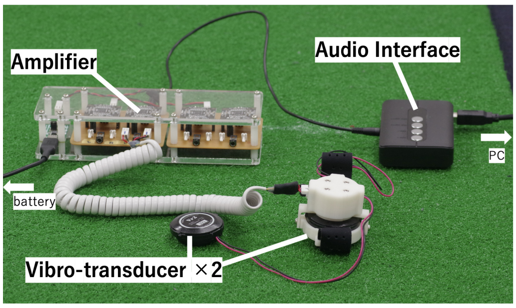


Fig. 3 Device configuration.

attached to the user's right shoulder (Fig. 1 (a)), right waist (Fig. 1 (b)), and back of the head (Fig. 1 (c)). The transducers in Fig. 1 (a), Fig. 1 (b), and Fig. 1 (c) were used for separating the elbow, sway, and head lift, respectively.

To provide auditory feedback, a sinusoidal wave was played back from the Vibro-transducer. A sinusoidal waveform was used for the auditory feedback, and the feedback sound presented was played at different frequencies from Vibro-transducers attached to the waist, elbow, and head. The respective frequencies were 1,046.5 Hz (waist), 1,318.5 Hz (elbow), and 1,568.0 Hz (head).

To provide haptic feedback, a square wave was played back, which could present the vibration more clearly. The waveform of the tactile feedback was a square wave, and a wave with the same frequency of 130.8 Hz was presented as tactile information from all vibro-transducers.

To provide audio-haptic feedback, the waveforms for sound feedback and haptic feedback are input to the transducer and played back simultaneously to provide feedback. High frequencies were used for auditory feedback so that the user would not feel any vibration from the Vibro-transducer. These frequency values were set so that the feedback sounds and vibrations would not be dissonant when presented simultaneously.

These sounds and vibrations were presented when the user's posture deviated from the allowance and stopped when the user's posture was in the tolerance range. Regardless of the degree of the user's postural error, the feedback was always of constant frequency and amplitude when it was conveyed.

The acceleration amplitude of the vibration used in the haptic feedback was measured by attaching an accelerometer (MMA7361, Bosch Corporation) to the Vibro-transducer while the user was wearing the device. An oscilloscope was used to read the accelerometers' output voltage, and the acceleration amplitude was calculated based on the peak-to-peak voltage of the output voltage, and the sensitivity of the accelerometer (206 mV/G in ± 6 G mode, 1 G = 9.8 m/s^2). The volume of the auditory feedback was measured using a smartphone sound level meter application, Sound Mater [*5]. The sound volume was measured at a distance of 1 m from the user wearing the device. The volume of the auditory feedback was approximately 64.3 dB when all three feedback sounds were played simultaneously.

[*5] https://play.google.com/store/apps/details?id=com.ktwapps.soundmeter

© 2022 Information Processing Society of Japan

To ensure the same conditions within a group in the experiment, the waveforms, and frequencies used for auditory and tactile feedback were identical among the subjects in the group.

4. User Study

To further investigate our proposed technique we conducted a user study to:

- compare the effect and usability of the proposed device against a conventional method of visual feedback with a mirror in a practice to improve multiple notes and
- confirm the effect and usability of auditory feedback alone, tactile feedback alone, and combined auditory and tactile feedback in a practice session to improve multiple notes.

4.1 Experimental Environment

The experiment environment is displayed in **Fig. 4**. A camera and a short-focus projector were installed in front of the user, and the image from the camera was flipped left and right onto the wall in front of the user as a substitute for a full-length mirror (commonly used in golf practice). Eight OptiTrack prime 13 W units were set up as shown in Fig. 4 to perform motion tracking of the user's head, waist, and right upper arm. Retroreflective markers

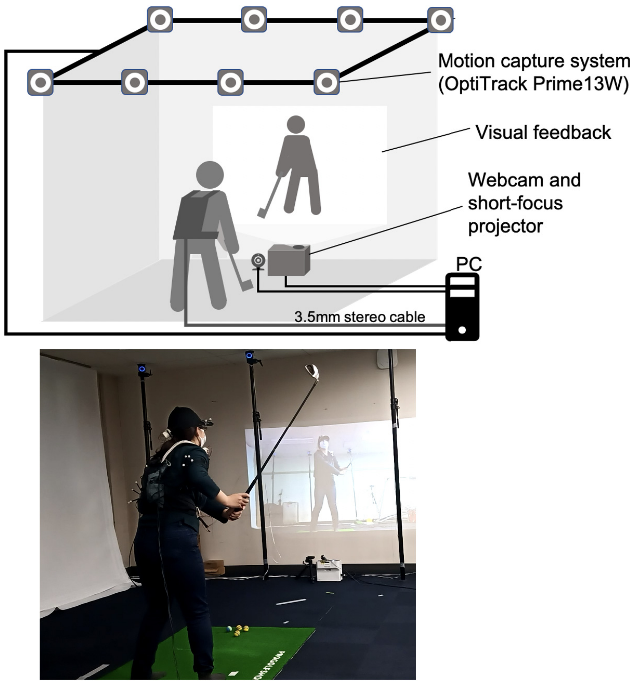


Fig. 4 Environment in which the experiment was conducted.

were attached to three locations on the user's cap, backpack, and right arm to obtain their respective three-dimensional positions and rotation angles. Three retroreflective markers (**Fig. 5** (c)) were attached to the hat to perform motion tracking of the head. For the right upper arm and waist, four retroreflective markers were attached to the 3D printed parts (Fig. 5 (a), (b)).

OptiTrack Motive:Body2.0 software was used to process the tracking data. The sampling frequency of the motion data from the camera and software was 240 Hz. Using the Optitrack Unity Plugin, the processed data was streamed to the developed Unity program. The feedback based on the motion data was generated as 3 channel audio data using Unity2020.1.5f, and the sound and vibration were conveyed to the user through a vibro transducer.

4.2 Procedure

Before beginning the user study, participants were instructed on the golf swing and the experimental procedure. In the instruction on the golf swing, the beginners were told how to grip and swing a golf club, as well as the three points to pay attention to during the swing (example: the separating elbow, sway, and head lift). The participants were instructed to perform a swing in 4 seconds to a metronome tempo of 60 bpm. The participants practiced swinging to the metronome's tempo several times after the instruction phase. Following the prepractice instruction, the participants participated in a four-phase user study that includes: (1) prepractice, (2) visual feedback (mirror), (3) feedback using the proposed method, and (4) post-practice.

(1) Prepractice phase

The participants took 10 swings without feedback during the prepractice phase, which were recorded and used to calculate the thresholds.

(2) First practice phase

The participants practiced swinging 15 times while looking at a mirror image of themselves projected onto the wall in front of them during the first practice phase. The first five swings were practiced to allow the participants to get acquainted with the conditions, and the next 10 swings were recorded as practice swings using the conventional method of visual feedback with a mirror. Following these swings, the participants were asked to fill out a questionnaire about the practice. After completing the questionnaire, the participants took a 5 minute break.

(3) Second practice phase

The participants practiced their swings with the proposed device in the second phase. The participants were divided into four

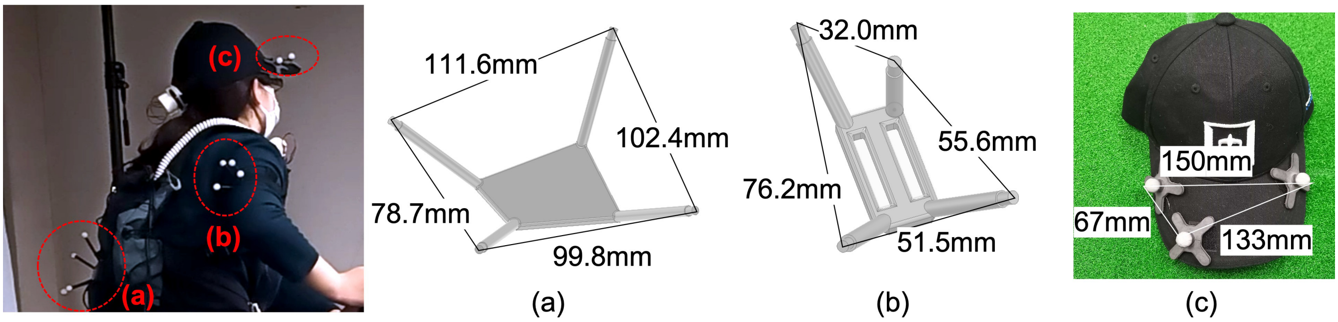


Fig. 5 Markers used for motion tracking and their dimensions. (a) Marker attached to the user's waist (b) Marker attached to the user's right arm (c) Marker attached to the cap worn by the user.

© 2022 Information Processing Society of Japan

groups of four people each. Each group practiced under different conditions: auditory feedback only, haptic feedback only, combined (auditory and haptic) feedback, and visual feedback which was the same as the first practice phase. The threshold used for feedback was the average of 10 swings before practice (i.e., the data obtained in the prepractice phase) set for each participant. In this phase, 15 swings were taken—the first five for practice and the next 10 for recording. After completing the swings, the participants were asked to fill in a questionnaire about their experiences with the device.

(4) Post-practice phase

The participants took 10 swings without feedback in the post-practice phase, which were recorded as post-practice swings. They also filled in an open-ended questionnaire about the entire experiment.

4.3 Participants

A total of 16 subjects participated in the experiment (age 20–31, 14 males and 2 females). All of them were beginners in golf. There were a total of 16 participants in the experiment, 12 of whom received feedback using the proposed device. Eleven of the participants who used the proposed device were right-handed. One participant was not able to provide an answer about the dominant hand. Four participants received only visual feedback without the proposed device; three were right-handed and one was left-handed. In addition, all participants experimented using a right-handed golf club.

4.4 Experimental Conditions

The 16 participants were randomly divided into four groups of four people each. Participants in each of the three types of feedback were conveyed to participants in three of the groups. The feedback types were: auditory feedback only, haptic feedback only, and combined (auditory and haptic) feedback during the feedback phase of the proposed method. Each group experimented under the condition of only one assigned feedback. The participants in the group presented with haptic feedback practiced with the proposed device while wearing noise-canceling earphones (Sony WI-1000X) that played white noise at a comfortable volume for each participant to block the sound coming from the vibro transducers. All swings during the experiment were done to the tempo of the metronome. On average, it took the participants 60 minutes to complete the experiment.

4.5 Questionnaire

The questionnaire that the participants were asked after each of the two practice sessions consisted of the following seven questions Q1–Q7, and a free comment section. Q1 to Q7 were questions in the form of a five-point Likert scale (5 meaning strongly agree, 1 meaning strongly disagree). In the experiments in this study, one of the final objectives was to evaluate the impression of the system as a whole depending on the type of feedback. To avoid arbitrary questions in the questionnaire, we designed the questionnaire using existing questionnaires. For this reason, we adopted the System Usability Scale (SUS) as a questionnaire to evaluate the usability of the interface. We used questions from Q1 to Q5 of the questionnaire in the subject experiment, which is particularly relevant to the proposed system.

Q1 I think that I would like to use this system frequently.
Q2 I found the system unnecessarily complex.
Q3 I thought the system was easy to use.
Q4 I would imagine that most people would learn to use this system very quickly.
Q5 I felt very confident using this system.
Q6 I was able to practice being aware of all three points to note (i.e., right elbow, waist, and head).
Q7 I feel that the three points to note (i.e., right elbow, waist, and head) could be improved.

5. Results

A two-factor analysis of variance (two-way analysis of variance) was conducted to compare the effects of practice between experimental phases with those between types of feedback on the proposed method.

The independent variables

The two independent variables and their levels were set as follows:

- Three practice phases p1, p2, and p3.
  - **p1** The first practice phase
  - **p2** The second practice phase
  - **p3** Post-practice phase
- Four groups divided by the type of feedback used in the second practice phases $\mathbf{g}_a$, $\mathbf{g}_h$, $\mathbf{g}_m$, and $\mathbf{g}_v$
  - $\mathbf{g}_a$ Group using auditory feedback
  - $\mathbf{g}_h$ Group using haptic feedback
  - $\mathbf{g}_m$ Group using auditory and haptic multimodal feedback
  - $\mathbf{g}_v$ Group using visual feedback

Comparisons were not made for the prepractice phase because it was used to determine the feedback threshold.

In this experiment, comparing error rates among groups made it difficult to verify the effectiveness of the proposed system. The reason for this is that each group had four participants, and there were differences in subjects' original motor abilities. As a result, we focused on the differences between practice phases when analyzing the experimental results.

The three dependent variables were as follows:

- right elbow error rate — ratio of time the right arm angle was above the threshold and time of one swing;
- sway error rate — ratio of time that the sway to the right of the hips exceeded the threshold and time of one swing;
- head error rate — ratio of time that the head movement was above the threshold and time of one swing, and

The threshold was calculated by using the average of the maximum values of the parameter during each of the 10 swings in the prepractice phase. When the dependent variable was close to 0, a swing was rated "good" due to the short amount of time that postural errors had occurred during the swing.

Before the analysis by two-way analysis of variance, normality was tested by the Kolmogorov-Smirnov test. As a result, normality was confirmed in each group. The changes in error rates for each group divided by the type of feedback given in the second practice phase are shown in **Fig. 6**, and their statistics are shown

© 2022 Information Processing Society of Japan

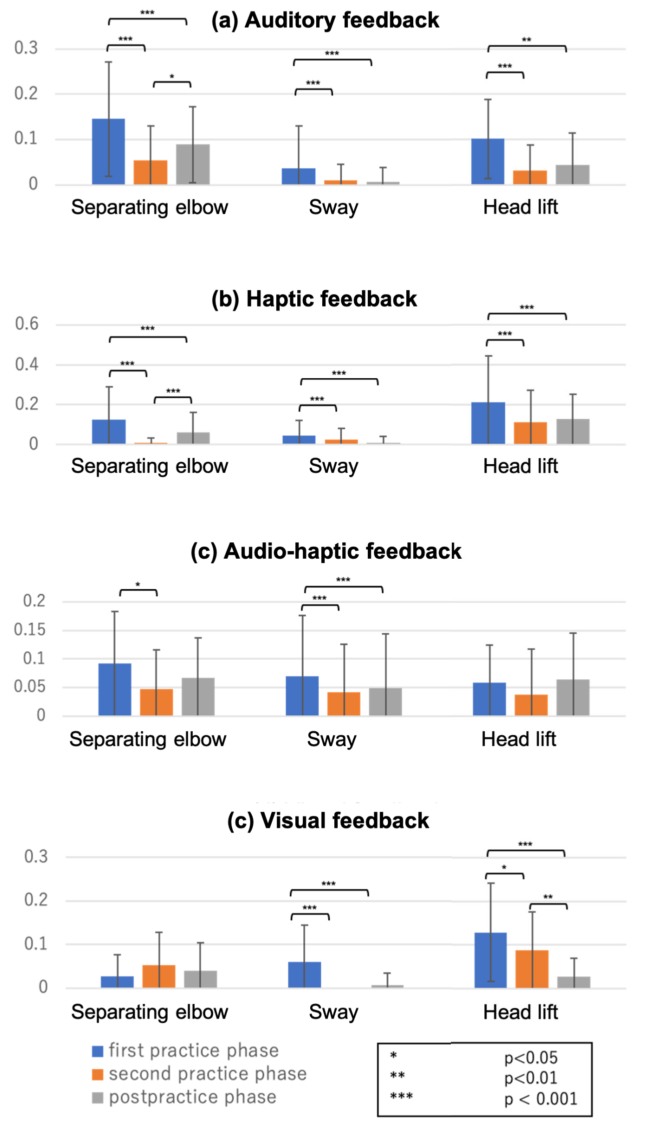


Fig. 6 Error rate in practice phases for each group divided by the type of feedback given in the second practice phase.

in **Table 1**.

The right elbow error rate

Since the sphericity assumption was rejected, the degree of freedom was adjusted by Huynh-Feldt-Lecoutre's epsilon. A two-factor analysis of variance was conducted on the practice phases and feedback methods, and significant interactions were found for each independent variable ($F(5.098,312) = 6.845$, $p < .001$). Tests for simple main effects between each feedback method showed a simple main effect of error rates between practice phases for $\mathbf{g}_a$, $\mathbf{g}_h$, and $\mathbf{g}_m$ ($F(2,312) = 25.28$, $p < .001$; $F(2,312) = 23.64$, $p < .001$; $F(2,312) = 3.38$, $p < .05$, respectively). The results of Bonferroni's multiple comparison test for $\mathbf{g}_a$ showed significant differences between p1 and p2 ($p < .001$), p1 and p3 ($p < .001$), and p2 and p3 ($p < .05$) (Fig. 6 (a) left). The results of Bonferroni's multiple comparison test for $\mathbf{g}_h$ showed significant differences between p1 and p2 ($p < .001$), p1 and p3 ($p < .001$), and p2 and p3 ($p < .001$) (Fig. 6 (b) left). The results of Bonferroni's multiple comparison test for $\mathbf{g}_m$ showed a significant difference between p1 and p2 ($p < .05$) (Fig. 6 (c) left).

Table 1 Means of the error rates (standard deviation in parentheses).

		Practice phase first	second	post
Auditory feedback	Separating elbow	.15 (.13)	.054 (.076)	.088 (.084)
	Sway	.036 (.095)	.0096 (.035)	.0070 (.031)
	Head lift	.10 (.087)	.031 (.057)	.044 (.070)
Haptic feedback	Separating elbow	.12 (.17)	.0092 (.025)	.062 (.098)
	Sway	.043 (.077)	.024 (.058)	.0086 (.034)
	Head lift	.21 (.23)	.11 (.16)	.13 (.12)
Audio-haptic feedback	Separating elbow	.092 (.092)	.048 (.067)	.067 (.071)
	Sway	.070 (.11)	.043 (.083)	.049 (.096)
	Head lift	.058 (.066)	.038 (.079)	.065 (.080)
Visual feedback	Separating elbow	.028 (.049)	.053 (.076)	.039 (.065)
	Sway	.060 (.085)	.00 (.00)	.0072 (.027)
	Head lift	.13 (.11)	.088 (.089)	.028 (.042)

Sway error rate

Since the sphericity assumption was rejected, the degree of freedom was adjusted by Huynh-Feldt-Lecoutre's epsilon. A two-factor analysis of variance was conducted on the practice phases and feedback methods, and no significant interactions were found. The main effect between each feedback method was significant, $F(3,156) = 5.373$, $p < 0.01$. The results of Bonferroni's multiple comparison test showed a significant difference between p1 and p2 ($p < .001$), and p1 and p3 ($p < .001$) (Fig. 6 (a, b, c, d) center).

Head error rate

A two-factor analysis of variance was conducted on the practice phases and feedback methods, and significant interactions were found for each independent variable ($F(6,312) = 4.721$, $p < .001$). Tests for simple main effects between each feedback method showed a simple main effect of error rates between practice phases for $\mathbf{g}_a$, $\mathbf{g}_h$, and $\mathbf{g}_v$ ($F(2,312) = 7.85$, $p < .001$; $F(2,312) = 16.63$, $p < .001$; $F(2,312) = 14.54$, $p < .001$, respectively). The results of Bonferroni's multiple comparison test for $\mathbf{g}_a$ showed significant differences between p1 and p2 ($p < .001$), and p1 and p3 ($p < .01$) (Fig. 6 (a) right). The results of Bonferroni's multiple comparison test for $\mathbf{g}_h$ showed significant differences between p1 and p2 ($p < .001$), and p1 and p3 ($p < .001$) (Fig. 6 (b) right). The results of Bonferroni's multiple comparison test for $\mathbf{g}_m$ showed significant differences between p1 and p2 ($p < .05$), p1 and p3 ($p < .001$), and p2 and p3 ($p < .01$) (Fig. 6 (d) right).

Questionnaire results

The questionnaire results are shown in **Fig. 7**, and the average values of the questionnaire are listed in **Table 2**. The participants commented on the questionnaire after the first practice phase, that "the mirror was useful for initial posture adjustment, but it was difficult to see it during the swing" and that they were "able to check the posture at the moment of the top of the swing, but it was difficult to check both the hitting motion and the posture."

© 2022 Information Processing Society of Japan

Fig. 7 Questionnaire results.

Table 2 Mean values of the questionnaire results.

	auditory	haptic	audio-haptic	visual
Q1	4	3	4.25	3
Q2	2.75	2.75	1.75	2.5
Q3	3.75	3.25	4.25	3.75
Q4	4.25	3	5	2.75
Q5	3.75	3.25	3.75	2.25
Q6	4.5	4.25	4.75	2
Q7	4.75	3.5	3.75	2.5

Participants in the tactile feedback stated that the vibrations were unpleasant and that attempting to avoid the vibrations motivated them to practice. Participants commented that "it was difficult to distinguish whether the sound was coming from the shoulder or the waist" after receiving auditory feedback. A participant who received both auditory and haptic feedback said, "I didn't care much about the sound because I was able to identify the area to be corrected by vibration alone."

Several participants commented on the second practice phase with the feedback via the proposed device: "I knew I was doing it wrong but I didn't know how to correct myself"; "it would have been nice to have feedback on how the previous swing went after each swing."

6. Discussion

6.1 Effect and Usability of the Proposed Device

The participants' postures during the first and second practice phase with the feedback via the proposed device are shown in **Fig. 8**. During the feedback phase with the proposed device, the participants' posture improved for separating elbow, sway, and head lift.

Reinforcing awareness of multiple notes

Results from the user study suggest that our proposed device can make users aware of all points and encourage them to improve their posture. The results of the user study show that the proposed device can help users improve their posture of the elbow, head lift, and sway, especially when auditory or haptic feedback was used. As shown in Fig. 6, the error rates of the head lift and sway are significantly reduced in the group using visual feedback in the second practice phase, but there is no significant change in the error rate of the separating elbow. In contrast, for the groups using auditory and haptic feedback of the proposed method, the error rates for all three notes are significantly reduced in practice with the proposed device.

Furthermore, in the questionnaire, the mean value of Q6 ("I was able to practice while being aware of all three points to note") was 2 in the group that used visual feedback, while it was 4.5 in the group using auditory feedback, 4.25 in the group that used haptic feedback, and 4.75 in the group using both audio-haptic feedback. These results suggest that the group that received feedback from the proposed device was more aware of all three notes.

These results suggest that the proposed device can make users aware of multiple precautions and encourage them to improve their posture.

Gaze during the golf swing

Another advantage of practicing while using feedback via the proposed device compared to the visual feedback is that the user's gaze is not fixed. Although using a mirror to check their initial posture and posture at the top of the swing allows people to check their posture, the participants found it difficult to complete the hitting motion while confirming their posture. Some participants, on the other hand, commented that the proposed device allowed them to concentrate on the ball during their swings. In the experiment, most participants swung with their eyes on the golf ball.

6.2 Feedback Method

For haptic feedback, the questionnaire comments showed multiple advantages of the proposed device. The questionnaire on haptic feedback showed that the participants found the vibration itself to be unpleasant, but the awareness of the need to avoid it served as a motivator for practice. We also discovered that a participant could discriminate between feedback sites based on haptic feedback alone when using audio-haptic feedback. These findings suggest that providing haptic feedback motivates people to learn while also making the feedback understandable.

The results of the questionnaire revealed some interesting findings about audio-haptic feedback. All of the participants who re-

© 2022 Information Processing Society of Japan

Fig. 8 Comparison of the participants' posture when using visual feedback (mirror) and the proposed device.

ceived the haptic and auditory feedback rated Q4 ("I would imagine that most people would learn to use this system very quickly.") with a score of 5, meaning they strongly agreed. Furthermore, in Q2 ("I found the system unnecessarily complex."), the mean rating of this item is the lowest among the three feedback methods, even though the feedback is provided via two senses: auditory and haptic. These findings indicate that the audio-haptic feedback was easy to comprehend and improved the user experience.

However, there was no significant difference in the error rate between the phases' audio-haptic feedback methods for head displacement. Since the head is physically close to the ears and the bones are located just below the skin, the sound output from an attached transducer stimulates participants more strongly than the sound output from a transducer attached to the shoulder or waist. As a result, when providing both sound and haptic feedback to the head, the feedback may have acted as a distraction for the user, since no significant improvement in the error rate occurred. In addition, Garcia-Valle et al. suggested that the minimum frequency, at which a user can perceive vibration depends on the part of the body [34]. Based on this idea, this problem could be solved by allowing the user to adjust the intensity of the vibration to a less unpleasant level when using the device.

In this experiment, the number of participants per group was four, making it difficult to make adequate comparisons among them. By recruiting a larger number of participants so that the differences in skills within the groups can be adequately averaged, it will be possible to examine the differences in learning effects between the feedback methods in more detail.

One of the more interesting findings from the user study was that practicing only auditory feedback reduced error rates for all three notes in the same manner that practicing with haptic feedback did. In a previous study on learning golf swing movements, auditory feedback was found to be inferior to visual and haptic feedback in terms of user experiences and learning effects [21]. Therefore, in the design phase of our system, we assumed that it would be difficult for the user to understand complex information if only auditory feedback was used. As a result, we implemented and evaluated a device that can present both auditory and haptic information simultaneously. However, the user study results revealed that users were able to recognize the presented information correctly even when only auditory feedback was used.

Two features of the presented auditory feedback can be considered as reasons why users were able to recognize auditory information correctly in the proposed system. The first feature is that the auditory feedback is provided by placing sound sources at the location of the feedback target. One of the participants who received the auditory feedback said, "It was difficult to distinguish where the feedback was presented by listening to the tone, but I could distinguish from which speaker the sound was being played". The other feature is that the information presented by a single speaker is limited to a small amount of information: whether a sound is played or not. In several previous studies on auditory feedback, a continuously changing sound is presented as a feedback sound. A large amount of information due to the complexity of the sound might cause confusion and low usability. In contrast, the proposed device defines the information presented by sound as 3 bits, a small amount of information that is within the range of human cognition. As a result of these factors, users were able to correctly perceive the auditory feedback and reduce the error rate in all notes.

For the haptic feedback, the error rate was also reduced in all three notes. The participants were able to identify the vibrations presented at the three locations accurately. This demonstrates the usefulness of presenting haptic feedback to parts of the body that are not visible during movement. Haptic feedback is also more applicable than visual feedback because it does not require the device to be in the field of view. Another factor that contributed to the improvement of the user's posture was that the amount of information presented was defined based on the limitations of human perception.

© 2022 Information Processing Society of Japan

6.3 Evaluation of the number of places to present feedback

The participants did not report that they were confused by the feedback in multiple locations in the experiment. The mean value of Q6 (I was able to practice while being aware of all three points to note) in the questionnaire of 12 subjects who used the proposed system regardless of the feedback method was 4. The participants were therefore able to correctly identify the information provided in the three locations.

If we add one more item for which the proposed system provides feedback, the presented information will be 4 bits. Therefore, increasing the number of places where feedback is presented is likely to confuse users. This is because the average number of bits of information that humans can recognize and discriminate is 2.6 bits, and its standard deviation is about 0.6 bit [33].

6.4 Potential System Improvements

Versatility by improving the sensing method

The system used in the user study used optical motion capture for sensing. On the other hand, since motion capture is required at only three locations (head, right arm, and waist), the Inertial Measurement Unit (IMU) can replace this sensing method. This enables a smaller system with wider applicability.

Notes on the feedback target

In this study, we focused on the three points that are widely considered to be particularly important in learning the golf swing: separating elbow, head lift, and sway. However, there are numerous notes on the learner's posture during the swing, such as knee extension and left arm flexion [21], and each learner has different swing form issues. The proposed feedback method can also be applied to these additional notes as well. Thus, we expect that the proposed system will be useful for many golfers to practice.

Consideration of further information presentation methods

Several participants commented on the feedback phase using the proposed device, saying that they knew they were making mistakes but did not know how to correct their problem, adding that they would like feedback on how the previous swing went after each swing. This view may be due to the fact that in this user study, all of the swings in the experiment were performed as quick movements, allowing the participants to perceive errors in their form, but they could not recognize their posture at the moment the errors occurred.

To solve this problem, users must be aware of their posture. A possible solution would be to use the proposed device in a situation where the user practices with a slow and sequential posture check. Another effective way to make users aware of their posture is to combine the device with a widely used practice method such as recording a video of their swings. A synergistic effect is expected when real-time and post feedback are combined.

7. Conclusion

This study proposes a device that provides real-time auditory and haptic feedback to beginners during golf swings. In most nonvisual feedback systems, only one item is presented at a time. In this study, however, a device that presents sound and vibration was placed at the location corresponding to the feedback, and the feedback was presented simultaneously for all three points. The user study suggests that the proposed method significantly improves all three points for the users when compared to the conventional mirror-based visual feedback. We also discovered that the most appropriate feedback method (example: auditory feedback, haptic feedback, or a combination of the two) differs depending on the body part providing feedback.

Acknowledgments This work was supported by JST CREST Grant Number JPMJCR17A3, Japan.

References

[1] Hasegawa, S., Ishijima, S., Kato, F., Mitake, H. and Sato, M.: Realtime sonification of the center of gravity for skiing, *Proc. 3rd Augmented Human International Conference*, pp.1–4 (2012).

[2] Wiggins, G.: Seven keys to effective feedback, *Feedback*, Vol.70, No.1, pp.10–16 (2012).

[3] Ikeda, A., Hwang, D.-H., Koike, H., Bruder, G., Yoshimoto, S. and Cobb, S.: AR based Self-sports Learning System using Decayed Dynamic TimeWarping Algorithm, *ICAT-EGVE*, pp.171–174 (2018).

[4] Tanaka, Y., Kon, H. and Koike, H.: A Real-Time Golf-Swing Training System Using Sonification and Sound Image Localization, *VRST '18*, Association for Computing Machinery (online), DOI: 10.1145/3281505.3281604 (2018).

[5] Jakus, G., Stojmenova, K., Tomažič, S. and Sodnik, J.: A system for efficient motor learning using multimodal augmented feedback, *Multimedia Tools and Applications*, Vol.76, No.20, pp.20409–20421 (2017).

[6] Han, P.-H., Chen, Y.-S., Zhong, Y., Wang, H.-L. and Hung, Y.-P.: My Tai-Chi coaches: an augmented-learning tool for practicing Tai-Chi Chuan, *Proc. 8th Augmented Human International Conference*, pp.1–4 (2017).

[7] Hoang, T.N., Reinoso, M., Vetere, F. and Tanin, E.: Onebody: Remote posture guidance system using first person view in virtual environment, *Proc. 9th Nordic Conference on Human-Computer Interaction*, pp.1–10 (2016).

[8] Van Erp, J.B., Saturday, I. and Jansen, C.: Application of tactile displays in sports: Where to, how and when to move, *Proc. Eurohaptics*, pp.105–109, Citeseer (2006).

[9] Hwang, J.-H., Choi, H.-S. and Shin, W.-S.: Effects of real-time feedback training on weight shifting during golf swinging on golf performance in amateur golfers, *Physical Therapy Rehabilitation Science*, Vol.6, No.4, pp.189–195 (2017).

[10] Tajadura-Jiménez, A., Väljamäe, A., Bevilacqua, F. and Bianchi-Berthouze, N.: Principles for designing body-centered auditory feedback (2018).

[11] Ghai, S., Schmitz, G., Hwang, T.-H. and Effenberg, A.O.: Training proprioception with sound: Effects of real-time auditory feedback on intermodal learning, *Annals of the New York Academy of Sciences*, Vol.1438, No.1 (2018).

[12] Onishi, T., Yasuda, K., Kawata, S. and Iwata, H.: Development of a rhythmic auditory biofeedback system to assist improving the kinetic chain for bat swing performance, *ROBOMECH Journal*, Vol.5, No.1, p.12 (2018).

[13] Koyama, Y. and Watanabe, K.: Auditory golf coaching system using perceptive sportswear based on hetero-core optics, *2014 IEEE 3rd Global Conference on Consumer Electronics* (*GCCE*), pp.643–646, IEEE (2014).

[14] Umek, A., Tomaic, S. and Kos, A.: Autonomous wearable personal training system with real-time biofeedback and gesture user interface, *2014 International Conference on Identification, Information and Knowledge in the Internet of Things*, pp.122–125, IEEE (2014).

[15] Nylander, S., Kent, A. and Tholander, J.: Swing sound: experiencing the golf swing through sound, *CHI'14 Extended Abstracts on Human Factors in Computing Systems*, pp.443–446 (2014).

[16] Smith, T., Bowen, S.J., Nissen, B., Hook, J., Verhoeven, A., Bowers, J., Wright, P. and Olivier, P.: Exploring gesture sonification to support reflective craft practice, *Proc. 33rd Annual ACM Conference on Human Factors in Computing Systems*, pp.67–76 (2015).

[17] Yunus, R., Ali, S., Ayaz, Y., Khan, M., Kanwal, S., Akhlaque, U. and Nawaz, R.: Development and Testing of a Wearable Vibrotactile Haptic Feedback System for Proprioceptive Rehabilitation, *IEEE Access*, Vol.8, pp.35172–35184 (2020).

[18] Prewett, M.S., Yang, L., Stilson, F.R., Gray, A.A., Coovert, M.D., Burke, J., Redden, E. and Elliot, L.R.: The benefits of multimodal information: a meta-analysis comparing visual and visual-tactile feedback, *Proc. 8th International Conference on Multimodal Interfaces*, pp.333–338 (2006).

© 2022 Information Processing Society of Japan

[19] Black, D., Hettig, J., Luz, M., Hansen, C., Kikinis, R. and Hahn, H.: Auditory feedback to support image-guided medical needle placement, *International Journal of Computer Assisted Radiology and Surgery*, Vol.12, No.9, pp.1655–1663 (2017).

[20] Sigrist, R., Rauter, G., Marchal-Crespo, L., Riener, R. and Wolf, P.: Sonification and haptic feedback in addition to visual feedback enhances complex motor task learning, *Experimental Brain Research*, Vol.233, No.3, pp.909–925 (2015).

[21] Woźniak, M.P., Dominiak, J., Pieprzowski, M., Ładoński, P., Grudzień, K., Lischke, L., Romanowski, A. and Woźniak, P.W.: Subtletee: Augmenting Posture Awareness for Beginner Golfers, *Proc. ACM on Human-Computer Interaction*, Vol.4, No.ISS, pp.1–24 (2020).

[22] Liao, C.-C., Koike, H. and Nakamura, T.: Realtime Center of Mass Adjustment via Weight Switching Device inside a Golf Putter, *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems*, pp.1–8 (2020).

[23] Huang, P.Y., Kunkel, J.A., Brindza, J. and Kuchenbecker, K.J.: Haptically assisted golf putting through a planar four-cable system, *2011 IEEE World Haptics Conference*, pp.191–196, IEEE (2011).

[24] Nakamura, T., Saito, D., Wu, E. and Koike, H.: Actuated Club: Modification of Golf-Club Posture with force feedback and motion prediction in VR environment, *ACM SIGGRAPH 2020 Emerging Technologies*, pp.1–2 (2020).

[25] Günther, S., Makhija, M., Müller, F., Schön, D., Mühlhäuser, M. and Funk, M.: PneumAct: Pneumatic Kinesthetic Actuation of Body Joints in Virtual Reality Environments, *Proc. 2019 on Designing Interactive Systems Conference*, pp.227–240 (2019).

[26] Wang, B., Takahashi, N. and Koike, H.: Sensor Glove Implemented with Artificial Muscle Set for Hand Rehabilitation, *Proc. Augmented Humans International Conference*, pp.1–4 (2020).

[27] McDaniel, T., Goldberg, M., Villanueva, D., Viswanathan, L.N. and Panchanathan, S.: Motor learning using a kinematic-vibrotactile mapping targeting fundamental movements, *Proc. 19th ACM International Conference on Multimedia*, pp.543–552 (2011).

[28] Spelmezan, D.: An investigation into the use of tactile instructions in snowboarding, *Proc. 14th International Conference on Human-computer Interaction with Mobile Devices and Services*, pp.417–426 (2012).

[29] Scalera, L., Seriani, S., Gallina, P., Di Luca, M. and Gasparetto, A.: An experimental setup to test dual-joystick directional responses to vibrotactile stimuli, *IEEE Trans. Haptics*, Vol.11, No.3, pp.378–387 (2018).

[30] Elvitigala, D.S., Matthies, D.J., David, L., Weerasinghe, C. and Nanayakkara, S.: GymSoles: Improving Squats and Dead-Lifts by Visualizing the User's Center of Pressure, *Proc. 2019 CHI Conference on Human Factors in Computing Systems*, pp.1–12 (2019).

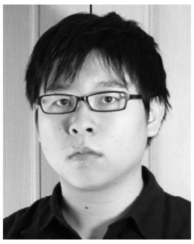
[31] Feeken, C., Wasmann, M., Heuten, W., Ennenga, D., Müller, H. and Boll, S.: ClimbingAssist: direct vibro-tactile feedback on climbing technique, *Proc. 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing: Adjunct*, pp.57–60 (2016).

[32] Van Der Linden, J., Johnson, R., Bird, J., Rogers, Y. and Schoonderwaldt, E.: Buzzing to play: lessons learned from an in the wild study of real-time vibrotactile feedback, *Proc. SIGCHI Conference on Human factors in Computing Systems*, pp.533–542 (2011).

[33] Miller, G.A.: The magical number seven, plus or minus two: Some limits on our capacity for processing information, *Psychological Review*, Vol.63, No.2, p.81 (1956).

[34] Garcia-Valle, G., Arranz-Paraiso, S., Serrano-Pedraza, I. and Ferre, M.: Estimation of Torso Vibrotactile Thresholds using Eccentric Rotating Mass Motors, *IEEE Trans. Haptics* (2020).

Yuka Tanaka received her B.E. degree from Tokyo Institute of Technology, in 2019. She is a master-course studint at Tokyo Institute of Technology. Her research interests include human-computer interaction, and wearable device for sports training.



Takuto Nakamura received his Ph.D. degree in engineering from the University of Electro-Communications, in 2019. He is a researcher at Tokyo Institute of Technology. His research interests include haptics, human-computer interaction, and wearable device for sports training.

Hideki Koike is a professor at School of Computing, Tokyo Institute of Technology. He received his B.E., M.E., and Dr. Eng. from the University of Tokyo in 1986, 1988, and 1991, respectively. After working at University of Electro-Communications, Tokyo, he joined Tokyo Institute of Technology in 2014. He was a visiting researcher at UC Berkeley and University of Sydney in 1994 and 2003, respectively. His research interests include vision-based HCI, projector-camera systems, human augmentation, digital sports, and cyber security.

© 2022 Information Processing Society of Japan