Int. J. Human-Computer Studies 97 (2017) 34–44

Contents lists available at ScienceDirect

Int. J. Human-Computer Studies

journal homepage: www.elsevier.com/locate/ijhcs

Investigation of suitable body parts for wearable vibration feedback in walking navigation

Nem Khan Dim, Xiangshi Ren*

The Center for Human-Engaged Computing, Kochi University of Technology, 185 Miyanokuchi, Tosayamada-Cho, Kami-Shi, Kochi, Japan 782–8502

ARTICLE INFO

Article history:
Received 19 June 2015
Received in revised form
28 May 2016
Accepted 6 August 2016
Available online 8 August 2016

Keywords:
Navigation
Wearable vibration

ABSTRACT

Many studies have demonstrated the benefits of wearable vibration devices for walking navigation (Tsukada and Yasumura, 2004). Despite the potential benefits, suitable body parts for wearable vibration devices have not been defined or evaluated until now. We conducted three experiments to identify suitable body parts in terms of perceivability, wearability and user body location preferences for vibration devices. We tested vibration feedback on nine body parts (the ear, neck, chest, waist, wrist, hand, finger, ankle and foot). Experiment 1 and Experiment 2 were conducted in the lab and in real-world walking settings in order to find suitable body parts. Our results indicate that the finger, wrist, ear, neck and feet had the highest perceivability and user preferences. Experiment 3 was conducted to understand the practical usability of those vibration positions in walking navigation. Our study results suggested that the feet are not suitable locations for vibration feedback in walking navigation. Based on the study results, we present design implications and guidelines for wearable vibration devices.

1. Introduction

Recently, walking navigation systems have become more efficient and user reliance on such systems is on the rise. Researchers (Brewster and Brown, 2004 and Brewster et al., 2007 have shown that vibration feedback is especially beneficial in mobile situations where other human senses are distracted by complex environmental factors. Nowadays, many wearable vibration devices are available on the market (Fig. 1) and despite the recognized potential benefit of wearable vibration devices for navigation, a detailed understanding of the suitable bodily positions for vibration devices is lacking. Furthermore, important design factors such as context of use, user comfort, wearability and mobility for navigation have not been adequately explored. Thus, it is important to find the most suitable vibration positions to convey directional information when walking; these positions should be practical and comfortable to wear in real mobile contexts.

In Experiment 1, we tested vibration perception in eight vibration positions: the ear, neck, chest, waist, wrist, hand, ankle and foot (Fig. 2a). However, according to suggestions offered by the participants, the finger was added in Experiment 2. Furthermore, vibration positions on the ear, wrist, hand, finger, ankle and foot were mirrored. Thus the vibration positions in Experiment 2 were increased from 8 to 15 positions (Fig. 2b).

In addition to vibration perceptions, knowledge about interference from movement on each body part was also required to determine the most suitable vibration positions. Previous studies (van Erp, 2005; Jones et al., 2009; Karuei et al., 2011) have demonstrated diminished vibration perception on some body parts. However, these studies were conducted in lab settings. We considered that interference from motion in the lab setting would likely be significantly different from that in real walking settings because real mobile environments impose a load on the visual and auditory senses which may distract the user from paying attention to less sensitive body parts. Thus, to understand suitable vibration positions, we also conducted experiments in a real mobile setting (Experiment 2). Results from Experiments 1 and 2 indicated that the ear, wrist, finger, neck and foot were the most sensitive to vibrations. In Experiment 3, to assess the practical usability of the vibration positions for walking navigation, the participants performed map navigation using the vibration positions suggested from Experiments 1 and 2. Results from Experiment 3 indicated that the feet were less effective for vibration feedback in walking navigation situations.

We addressed three specific research questions.

Q1. Among the body parts of interest, which positions offer the best vibration perception in static and walking conditions respectively? (Experiment 1)
Q2. Which vibration positions are the most preferable for users to use in real mobile settings? (Experiment 2)

* Corresponding author.
E-mail address: xsren@acm.org (X. Ren).

http://dx.doi.org/10.1016/j.ijhcs.2016.08.002
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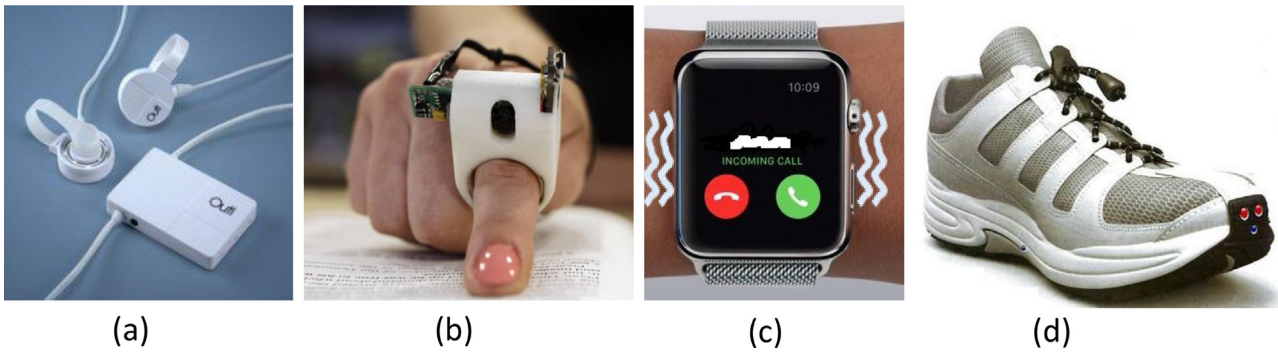

Fig. 1. Wearable vibration devices. (a) ThinkGeek™ vibration earphone, (b) FingerReader™ text reading device for visually impaired, (c) Apple Watch Smartwatch™, and (d) Le Chal™ haptic shoe for blind people.

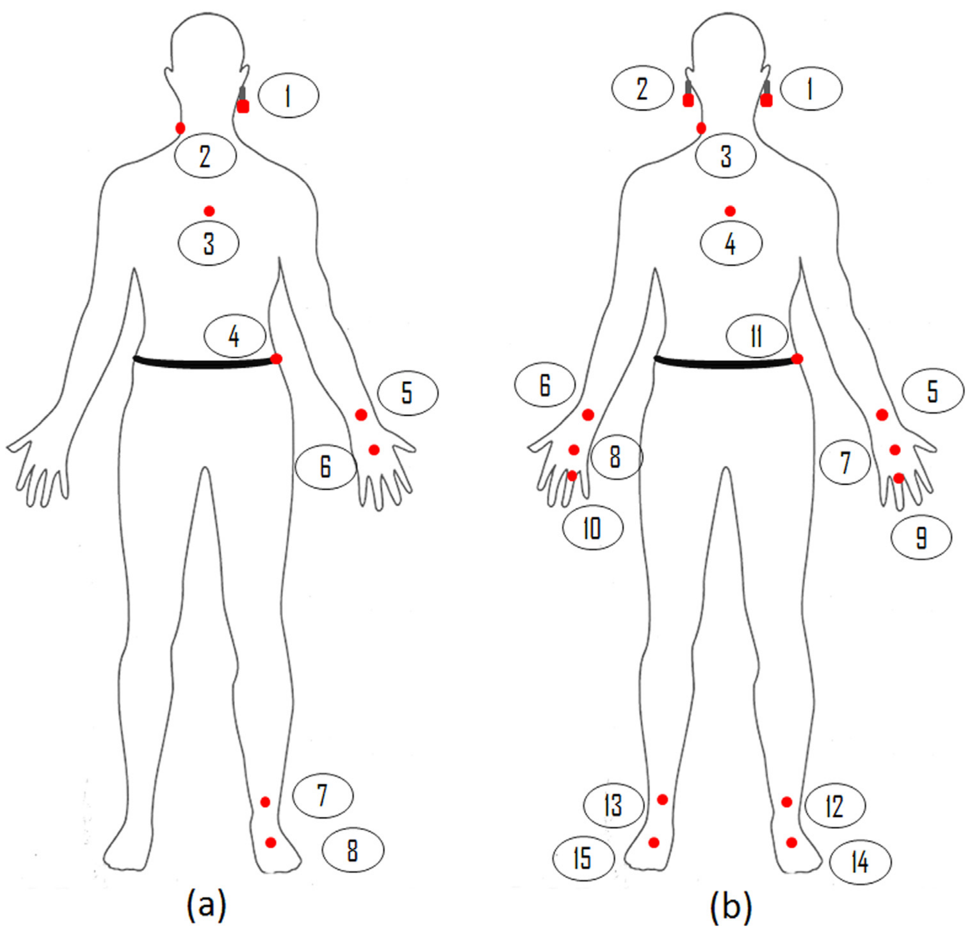

Fig. 2. Proposed vibration positions (shown with "•"). (a) Eight vibration positions in Experiment 1. (b) Fifteen vibration positions in Experiment 2.

Q3. Which vibration positions are practical and usable for walking navigation? (Experiment 3)

The study results were compiled and presented as design guidelines for wearable vibration feedback in walking navigation. The contributions of our study are:

- Evaluation of vibration perception on different body parts when users are walking in real mobile environments
- Identification of the most suitable body parts for walking navigation
- Design guidelines for wearable vibration devices for walking navigation

2. Related work

For our study, which is focused on vibration feedback for walking navigation, we highlight the most relevant literature in human haptic perception, wearable vibration and walking navigation.

2.1. Human haptic perception

Haptic perception across different body parts varies depending on the size and adaptation of the receptors in each body location (Johnson and Hsiao, 1994; Johnson, 2001). Many researchers examined vibration sensitivity of particular body parts including the back, waist, chest, wrist and thigh (van Erp, 2005; Jones et al., 2009; Karuei et al., 2011). Among the body parts of interest, the wrist was proved to be the most sensitive to vibration; thighs and feet were the least sensitive, followed by the waist, arms and chest. Lederman and Klatzky (2009) who reported the sensitivity of different body parts to haptic stimuli based on two-point and point-localization threshold methods, noted that the fingertips had the highest haptic acuity. Notably, the more distal parts of the body have higher haptic spatial acuity (Lederman, 1991).

Animal and human experiments have also shown that the cortical responses to cutaneous stimuli are profoundly diminished during movement (Rushton et al., 1981; Chapman et al., 1987; Jiang et al., 1991; Karuei et al., 2011). The studies showed that both passive and active movement of the limbs decrease haptic perceptions in humans. Angel and Malenka (1982) demonstrated correlations between sensory suppression and movement speed in detection rates of the index finger tip. They reported that human haptic perception rates were higher while stationary or moving slowly than when moving quickly. Other researchers studied the same effect using vibrotactile simulation (Post et al., 1994; Pakkanen et al., 2008; Morrison et al., 2012). It was found that perception to vibrotactile stimuli was also affected by movement. Karuei et al. (2011) suggested that vibration perceptions in the lower body parts (e.g., thigh and feet) are more affected by movement in walking than upper body parts are.

The studies consistently showed that movement during physical exertion had a significant effect on the perception of tactile stimulation. However, there is no clear understanding about the relative sensitivity of these body parts when exposed to motion in walking "in the real mobile" settings. Our study presents vibration perception on several body parts for designing wearable vibration devices.

2.2. Wearable vibration

Van Erp and Van Veen (2003) presented a multi-purpose tactile vest for astronauts that supported the astronaut's orientation awareness. Vibration on the torso indicated the direction of the standard International Space Station (ISS) orientation. Rukzio et al. (2009) developed a guidance system that used vibration on a mobile phone to represent directions on a public display. The user's phone vibrated when the direction on the public display matched the direction of the user's route. Wearable haptic devices were also evaluated for driving support systems. Ho et al. (2005) examined directional vibration feedback in a driving simulation. The study reported that encoding directional information of an oncoming car on the torso (i.e., front vs. back stimuli) was promising. Straughn et al. (2009) compared tactile and audio feedback for pedestrian collision warning applications for drivers. For tactile feedback, tactors were attached to the drivers' left and right biceps. The study indicated that tactile feedback on the drivers' biceps was more effective than audio signals for collision warnings. Other researchers (Van Erp et al., 2006) demonstrated applications of tactile displays on the body for sports and showed that tactile feedback improves rowing efficiency compared to traditional feedback systems.

All these studies consistently indicate the potential utility of vibration feedback for wearable computing. However, suitable body parts for vibrators for walking navigation were not adequately evaluated or understood.

2.3. Walking navigation systems

Ross and Blasch (2000) presented a wearable orientation system that used a stereophonic sonic guide, speech output and shoulder tapping interfaces. Holland et al. (2001) and Strachan et al. (2005) presented spatial audio interfaces for feedback in global positioning systems (GPS). Visual and audio information are not necessarily the optimal feedback modes in mobile situations. This is especially the case where the users' eyes and attention are engaged with several tasks and where there is a lot of traffic or crowd noise.

Some researchers (Tsukada and Yasumura, 2004; Van Erp et al., 2005; Heuten et al., 2008) evaluated directional vibration feedback on the waist belt. Other researchers (Traylor and Tan, 2002; Ertan et al., 1998) also applied directional vibration feedback for navigation on the users' back. The studies showed that tactile feedback can be used to provide non-visual information to help users find their way around. However, differentiating directional vibration patterns on a single body site is confusing and probably increases the users' cognitive load in overloaded mobile environments. This assumption was confirmed by Alvina et al. (2015) who found that it was difficult for participants to perceive spatial vibration patterns on particular body parts. Bosman et al. (2003) introduced GentleGuide, a wrist-mounted vibration feedback system for indoor navigation. The study showed that two vibration devices on two locations, one on each wrist, is more effective than using a single output device on one body location. Consistent with this finding, we proposed that optimal tactile interfaces for walking navigation can be achieved by an effective combination of several body sites. However, there remained a lack of understanding about suitable body parts for vibration feedback in walking navigation.

In summary, human perception of haptic sensation varies across human body parts, and it was confirmed that movement diminishes haptic perception. The literature has also shown several applications for wearable haptic sensors on different body parts. However, factors remaining unanswered are (a) relative interference with vibration detection via body parts caused by movement in real mobile contexts, and (b) identifying the most suitable body parts for vibration feedback in walking navigation. Therefore, our study focuses on suitable body parts and design guidelines for vibration feedback in walking navigation.

3. Experiment 1: vibration perceivability in static and walking conditions[1]

Experiment 1 compares participants' vibration perception on different body parts in varied conditions. The experiment was conducted to address Q1: Among the body parts of interest, which positions offer the best vibration perception in static and walking conditions respectively?

3.1. Vibration positions

To investigate vibration perception in different body parts, we proposed eight body parts (see Fig. 2a). Our design was based on careful consideration as to whether vibrations are easier to perceive in particular positions (Lederman and Klatzky, 2009), whether vibrators can be easily integrated into clothing or accessories (Gemperle et al., 2001), and whether vibrations in those positions are wearable in the long-term in real-world settings. The vibration system was made so that the vibrations could be wearable and felt through the users' clothing and accessories.

Table 1 and Fig. 3 show how the vibrators were attached to the body parts.

[1] An early part of the study, Experiment 1, has been published in ChineseCHI 2015 conference.

Table 1
Setup of vibrators for each vibration position.

Vibration position	Setup of the vibrators
Ears	Attached to ear-ring
Neck	Attached to necklace
Wrist	Embedded in watch
Hand	Attached to glove
Chest	Attached to shirt
Waist	Attached to belt
Ankle	Attached to sock
Front foot	Attached to shoe at the front-foot position

3.2. Design

We investigated the participants' vibration perception in three conditions: standing, normal walking and fast walking. The average speed for normal walking was 1.25 m/s. For the walking speed, we referred to the average walking speed that is recommended for design (Knoblauch et al., 1996). For the fast walking speed, we conducted a pilot study to decide the most comfortable (average) speed for the participants. Informed by the pilot study, we used 4.5 m/s as the average speed for each participant. The pilot studies also investigated the most suitable vibration duration for all motion conditions. We tested using stimulus durations of 700 ms, 1000 ms, 1500 ms and 2000 ms for static and motion conditions. For our study, we chose 1000 ms for the static condition and 1500 ms for the motion conditions because these durations were the minimum durations that allowed reasonable perception and comfort for the participants. The vibration duration for walking conditions was longer because perception was degraded in motion conditions and our participants needed more time to effectively perceive the vibration.

The independent variables were vibration positions (eight body parts) and motion conditions (standing, walking and fast walking). Perceivability and subjective preferences were measured. The vibration positions and motion conditions were within subject. Thus, each participant took part in 72 trials (8 vibration positions $\times$ 3 motion conditions $\times$ 3 repetitions).

3.3. Participants and apparatus

Ten university students (7 males and 3 females) participated in the study. The age range was 20–26 (mean=22.1, SD=1.79).

Eight LilyPad vibrators (rated speed—12,000 rpm, frequency—200 Htz, vibration amplitude—0.8 G, dimension—20 mm outer diameter and thin 0.8 mm PCB, weight—1.2 g, Volt—3 V) were used (SparkFun, 2016). To control the vibrators, we used Rastar Remote Motor Controllers at 27.145 MHz. Three AAA batteries (1.5 V) were used for the power system (vibration frequency at applied voltage was 300Hz in an ideal state). The vibration system was made to be wearable by the participants (see Fig. 3). For the walking and fast walking conditions, we used an Alinco walking machine (a regular treadmill).

3.4. Procedure

Before starting experimental trials, the purpose of the study and the experiment procedure were explained to the participants. Then, the participants were asked to take off their coats or jackets and to wear the vibration system. The participants were wearing all of the vibrators, and we did not change the position of a single vibrator for any of the trials. A vibration for each position was released three times with a time gap of around 2.5 s between each vibration. The order of the vibration positions was randomized. The trials in each vibration position were performed in three conditions, i.e. standing, walking and fast walking. After each motion condition, the participants rated the ease of

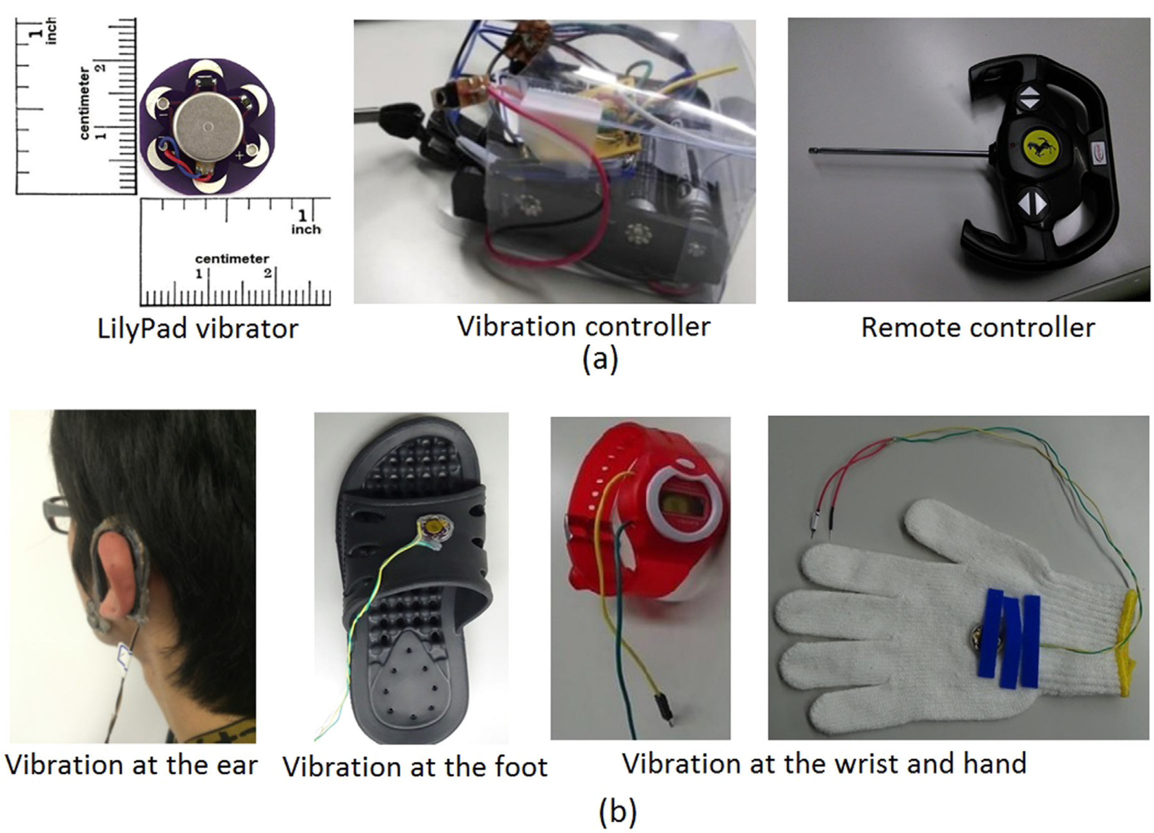

Fig. 3. Vibrations used in Experiment 1. (a) Vibration system.(b) Examples of vibrators attached to accessories.

perception of the vibration for each position, on a 7-point Likert scale, with 1 as the most difficult to perceive and 7 as the easiest to perceive.

After all experimental trials had been completed, the participants were asked to rate the statement, “I would like to wear the vibrator in this position in real-world usage” for each vibration position (1=strongly disagree and 7=strongly agree).

3.5. Results

The data of primary interest were the participants' ratings of vibration perception and subjective ratings regarding the preferred vibration positions for wearable vibrator devices.

3.5.1. Vibration perception

A two-way repeated measures ANOVA (analysis of variance) was used with the two factors, vibration position and motion speed. Motion conditions significantly affected the participants' vibration perception ($F(2,18)=47.62$, $p=0.00$). The vibration positions also had a significant effect on perception ($F(7,63)=17.98$, $p=0.00$). Motion and vibration position also had significant interaction effect on vibration perception ($F(14,126)=5.06$, $p=0.00$). Overall, vibration on the ear had the highest perceivability and vibration at the chest offered the lowest perceivability in all conditions.

Post hoc pairwise comparisons with Bonferroni correction showed that the ear, hand and foot had significantly higher perceivability than the chest, wrist, waist and ankle ($p \le 0.032$). Perception was significantly lower in walking and fast walking conditions than in the static condition. A significant difference was also found between walking and fast walking conditions ($p \le 0.033$). Perception scores of the vibration positions in each condition are shown in Fig. 4.

3.5.2. User preference

A one-way repeated measures ANOVA (analysis of variance) was used with the factor of the vibration position. User preferences for vibration positions significantly differ across body parts ($F(7,63)=7.63$, $p=0.00$). Post hoc pairwise comparisons showed that the ear, hand and wrist had significantly higher preference scores compared to the neck, chest, waist and ankle ($p \le 0.039$).

One of the participants commented that vibration on the ear is so discernable that the vibration intensity should be lower than that for the other body parts. Another participant stated, “If I could change the vibration strength myself, I would make the vibration in the waist stronger.” Most of the participants stated that vibration in the neck is not comfortable. One participant suggested that wearing vibrators as a ring on a finger may also be effective. The participants' subjective ratings on each body part as a suitable vibration position are shown in Fig. 4.

3.6. Discussion

Recalling our research question Q1, results from Experiment 1 suggested the following.

Among the body parts of interest, which positions offer the best vibration perception in static and walking conditions respectively?

The ear, hand, foot and neck offered the best perceivability in all conditions. In terms of preferences, the ear, wrist, foot and hand had the highest scores. Despite high vibration perceivability, the neck was not preferred by users due to a strong sense of discomfort. By contrast, the wrist was identified as the preferred position by most of the participants even though perception at the wrist is not as strong as at the ear or the hand. Most of our participants also nominated the ear as a preferred vibration position because vibration at the ear was easy to perceive. The chest and waist had the lowest scores both in terms of perception and preference.

Regarding the effects of motion, the ear was the least affected by motion, followed by the hand. The chest and waist were the most affected by motion. In mobile conditions, increasing the level of vibration intensity and using more powerful vibrators may be useful to optimize perception. However, using a system in mobile contexts raises several considerations (e.g., system weight, power consumption). Thus, vibrations at the waist may not be preferable for mobile contexts because stronger vibration intensity and power consumption would be required.

Experiment 1 suggested appropriate body parts for wearable vibration. However, we also found some experimental limitations in the study. First, for the purpose of directional information in navigation, vibration at the neck was tested at the side of the neck (left/right) rather than that at the back. We speculated that the low comfort level at the neck could be because of the neck to which vibration was applied. It might be more comfortable if the vibrations were applied at the back of the neck (near the spine). Second, perceivability in the wrist was found to be quite low when the vibrator was embedded in a watch. The wrist offered high vibration perceivability when vibration was directly applied to the users' skin (Karuei et al., 2011). This implies that changing the vibration setup (e.g., attaching the vibrator to a glove) may increase perceivability at the wrist. Third, the vibration positions were not mirrored on both sides of the body. It would be beneficial to assess vibration perception on the left and right sides of the body respectively (e.g. left hand and right hand). These issues were addressed in Experiment 2.

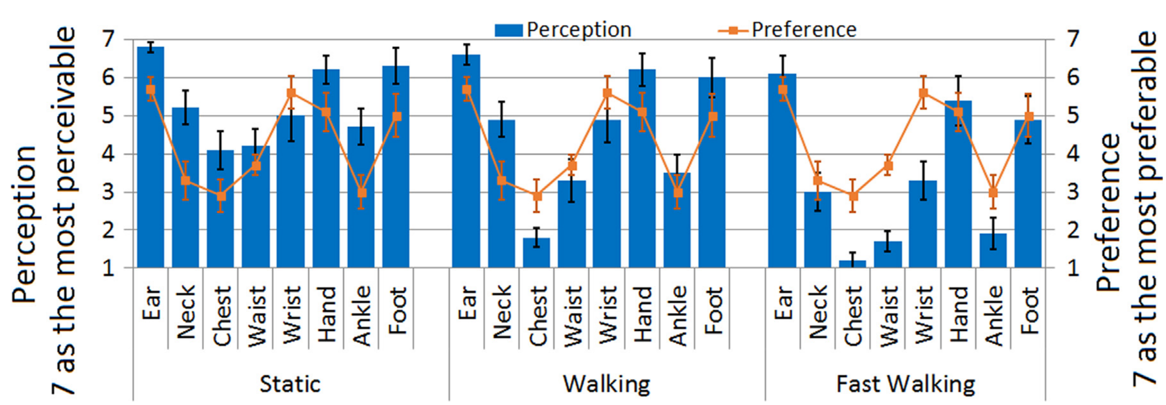

Fig. 4. Perceivability ratings (with standard error bars) for each of eight vibration positions, user preference ratings for each vibration position.

4. Experiment 2: vibration perceivability in real mobile environments

Experiment 1 investigated vibration perception and the effect of motion on different body parts. We aimed to investigate differences between vibration perception and user preferences in the lab setting and in the real mobile settings in order to determine suitable vibration positions for real-world settings. Thus, Experiment 2 was conducted to address Q2: Which vibration positions are the most preferable for use in real mobile environments?

4.1. Design

The study was conducted in a public park. The same experimental design, experimental procedure and stimulus duration for vibration as in Experiment 1 were applied. However, in Experiment 1, the walking speeds on the walking machine were constant across the participants. In Experiment 2, in the natural walking setting, the participants were instructed to walk at the usual speeds, those that typified their normal and fast walking conditions. Walking speeds for each condition for all participants were recorded. The average walking speeds were 1.50 m/s for normal walking and 2.27 m/s for fast walking.

For vibration positions, as suggested by the participants in Experiment 1, we added another vibration position i.e., on a finger. Vibration positions on the ear, wrist, hand, finger, ankle and foot were mirrored. Thus the vibration positions in Experiment 2 were increased from 8 to 15 positions. The study was conducted in 3 conditions, static, normal walking and fast walking.

4.2. Participants and apparatus

Eighteen volunteers (9 males and 9 females) from the university participated in the study. The age range was 25–38 (mean=29.3, SD=4.1). None of them had participated in Experiment 1. All of the participants were right handed.

Fifteen vibration motors were used. The vibration motors were the same as in Experiment 1. However, the controller in Experiment 1 was able to accommodate only four vibrators. Thus in order to drive 15 motors in Experiment 2, the controller had to be improved. The motor controller in Experiment 2 consisted of a vibrator controller and a remote controller. For the motor controller, an Arduino Uno Adafruit 16-channel motor driver shield and a PWM driver circuit was used to drive the 15 vibrators. The motor driver shield was powered by an SG 9 V battery which drives the vibration motors at 6 V. For the remote console, an Arduino Mega and 15 push buttons were used. Four AA (1.5 V) batteries were used to power the remote controller. The vibration controller and the remote console were connected using two Xbee wireless modules. Each Xbee module was connected to the Arduino Uno and Arduino Mega using an Xbee shield (see Fig. 5).

4.3. Procedure

Before the experiment, participants changed into the experimental clothing (see Fig. 6). The vibrators were attached in the same way as in Experiment 1, except for the wrist position; in Experiment 2, the vibrator was attached to the glove at the wrist. Furthermore, the vibrator at the neck was applied at the back of the neck. The vibrator on the finger was attached to the glove at the ring position. Vibrations were randomized across the body parts. The interval between vibrations was randomized to be between 3 and 5 s.

The participants performed the experimental tasks in three conditions: static, normal walking and fast walking. After completing the experimental tasks for one condition, the participants were asked to rate the perceivability of each vibration position on a 7-point Likert scale (1=very difficult, 7=very easy to perceive). Using the same scale, the participants were asked to rate the statement, “I would like to wear the vibrator in this position in real-world usage” for each vibration position (1=strongly disagree and 7=strongly agree).

4.4. Results

Data of interest were participants' rating for vibration perception and preferred vibration positions for real-world applications.

4.4.1. Vibration perception

A two-way repeated measures ANOVA (analysis of variance) was used with the two factors of the vibration position and motion speed. Motion condition significantly affected vibration perception ($F(2,34)=7.23$, $p=0.002$). The vibration position also had a significant effect on perception ($F(14,238)=19.45$, $p=0.00$). Motion and vibration position had significant interaction affect on perceptions ($F(28, 476)=3.59$, $p=0.022$).

Post hoc pairwise comparisons with Bonferroni correction showed that the ears, neck, fingers and feet had significantly higher perceivability than the chest, wrist, waist and ankle ($p \leq 0.01$). Perception was significantly lower in walking and fast walking conditions than in the static condition ($p <= 0.019$). No significant effect was found between walking and fast walking conditions ($p=0.881$). Also, there was no significant differences for all mirrored sites ($p=0.594$). Perceivability scores for the vibration positions in each condition are shown in Fig. 7.

4.4.2. User preference

A one-way repeated measures ANOVA (analysis of variance) was used with the factor of vibration position. User preferences

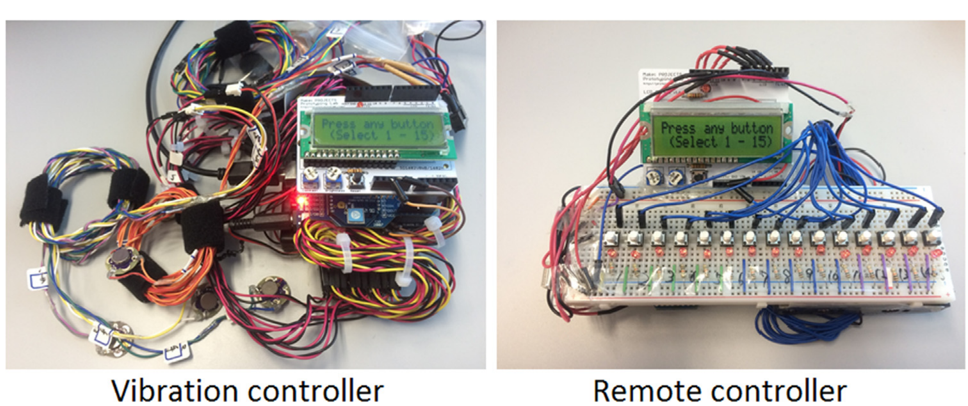

Fig. 5. The vibration system in Experiment 2.

Fig. 6. Participant in normal walking condition.

for vibrator positions significantly differ across body parts ($F(8,136)=6.62$, $p=0.001$). Post hoc tests indicated that the finger, wrist, ear and foot had significantly higher preference scores than the waist, hand, ankle and chest ($p \le 0.041$). Most of the participants stated that vibration on the chest was the least comfortable. The choice of vibrator positions for our study was based on careful consideration as to whether vibrators can be easily integrated into clothing or accessories in those positions in real-world settings. Thus, the best perceivable vibrator positions and the most preferable positions were not much different. The participants' subjective ratings for each body part as a suitable vibrator position are shown in Fig. 7.

4.5. Discussion

Informed by the study results, Q2 was addressed as follows.

Which vibration positions are the most preferred by users in real mobile settings?

In real-world settings, the ears, fingers, wrists, feet and neck were found to be the most perceivable and the most preferable vibration positions. Perceivability ratings for all vibration positions in Experiment 2 were lower than that in Experiment 1. The ears were the only positions that offered the same vibration perceivability in both Experiment 1 and Experiment 2. In terms of preferences, the ears had the highest preference in Experiment 1, however, subjective preference for the ears decreased in Experiment 2. In Experiment 2, while the same vibration motors as in Experiment 1 were used, the vibration motors were driven at 6 V strength (4.5 V in Experiment 1), which made vibration intensity slightly stronger. Thus, in Experiment 2, vibrations in the ears were so discernable that participants felt less comfortable when the same vibration intensity was applied as in the other vibration positions. One of the participants (female) stated that the waist is more preferable because the waist was more intrusive than the other vibration positions. However, most of our participants (both males and females) stated that the waist tickled when vibration was applied.

Subjective preferences for the hand also decreased in Experiment 2. We speculated that the decreased preference for the hand was because the participants did not want to wear a glove all the time in real-world usage. Wearing a vibrator on the hand probably requires users to wear a glove and it is less natural and less comfortable when compared to wearing vibrators directly on the wrist or the finger. As in Experiment 1, the chest, waist and ankle had the lowest preference ratings. In summary, while the ear, wrist, hand and foot were most preferred by users in Experiment 1, the neck and fingers were preferred above the hands in Experiment 2.

As we hypothesized, changing the vibrator position at the neck in Experiment 2 increased user preferences for the neck for wearable vibration without diminishing vibration perceivability. Also, vibration perceivability at the wrist increased when the vibrator was attached to the glove. There was no significant difference between the left side and the right side (of the body) for vibrator positions in terms of perceivability with only a few exceptions. One of the participants said that it was easier to perceive the vibration on the right foot than on the left foot. Another participant stated that vibration on the left ear was easier to perceive than that on the right ear.

From close observation, we also noted that participants sometimes missed the vibration while walking in the real-world mobile environment. The participants stated, “I'm not sure whether you have given the vibration or not. Did you? ” “I think I did not receive

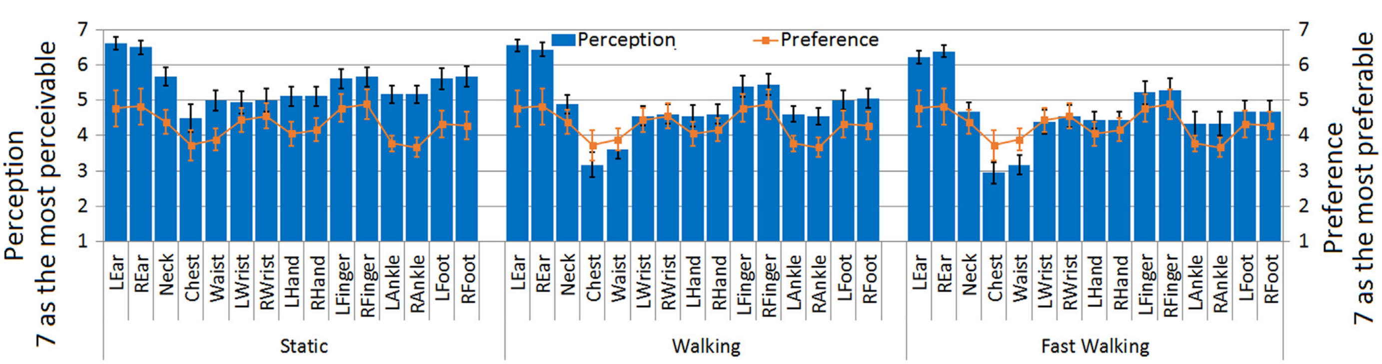

Fig. 7. Perceivability ratings (with standard error bars) on each of 15 vibration positions, user preference ratings for each vibration position.

any vibration for quite some time." Many participants mentioned distraction while walking during the study.

Experiment 1 and Experiment 2 suggested the most suitable body parts for wearable vibration both in terms of perception and preferences. However, it is still questionable how well these vibration positions convey navigational instructions when applied to walking navigation. Experiment 3 was thus conducted to address this question and assess the potential of wearable vibration feedback for walking navigation.

5. Experiment 3: practical usability for walking navigation

Experiment 3 sought to assess the potential of each vibrator position (i.e. the wrists, fingers, feet, ears and the neck) as suggested by Experiment 1 and Experiment 2 for application in real navigation situations. Using these vibration positions, the participants performed map navigation (see Fig. 8). Thus, Experiment 3 aims to address Q3: Which vibration positions are practically usable for walking navigation?

5.1. Design

For the ears, wrists, fingers and feet, both left and right sides were used to encode left/right turning information. Vibration at the neck was used for start/stop commands. Three maps were presented for each vibration position. Thus, each participant performed 12 (4 positions $\times$ 3 maps) navigation tasks.

5.2. Participants and apparatus

Fifteen volunteers (8 males and 7 females) from the university participated in the study. The age range was 22–37 (mean=28.1, SD=4.4). Ten of them had participated in Experiment 2. One of the participants was ambidextrous and the rest were right-handed. The same vibration system as in Experiment 2 was used in Experiment 3.

5.3. Procedure

The study was conducted in the public grounds of the university campus. The participants wore the vibration system and navigated the maps. The navigation tasks included following the directional information encoded in the vibrations.

The participants started walking when they received vibration at the back of the neck. They were instructed to walk at their normal walking speed. The experimenter walked about 5 m away from the participants delivering directional vibrations for turning left or right from the remote control. If the participants made a wrong turn, this was recorded as an error, and a vibration for the 'stop' command was delivered. If the participants ignored the vibration for more than 5 s (Bosman et al., 2003), it was recorded as a missed command. The participants followed the instructions until they received the vibration at the neck as a signal that they had arrived at the destination. Errors, number of missed commands and subjective ratings were collected.

After the experimental trials, we asked the participants to rate perceivability, comfortability to wear, intuitiveness and their preferences for each vibration position. We also asked the participants about their overall impression of wearable vibration systems for walking navigation. The participants were asked to rate the statement, "I would like to use it if a wearable vibration system became available," using a 7-point Likert scale (1=strongly disagree and 7=strongly agree).

5.4. Results

Data of interest were errors and missed commands, subjective ratings on intuitiveness, comfort and preference for the real application.

A one-way repeated measures ANOVA (analysis of variance) was used with the factor of the vibration positions (ear, wrist, finger, foot and neck). Friedman tests were used to analyze subjective assessments.

5.4.1. Errors and missed commands

Vibration positions had a significant effect on errors ($F(4, 56)=4.53$, $p=0.003$). Post hoc pairwise comparisons with Bonferroni correction indicated that the feet had significantly higher errors than other vibration positions $(p \leq 0.009)$. The percentages of errors and missed commands are shown in Fig. 9. Vibration positions also had a significant effect on missed commands ($F(4, 56)=9.06$, $p=0.009$). Post hoc pairwise comparisons indicated that most of

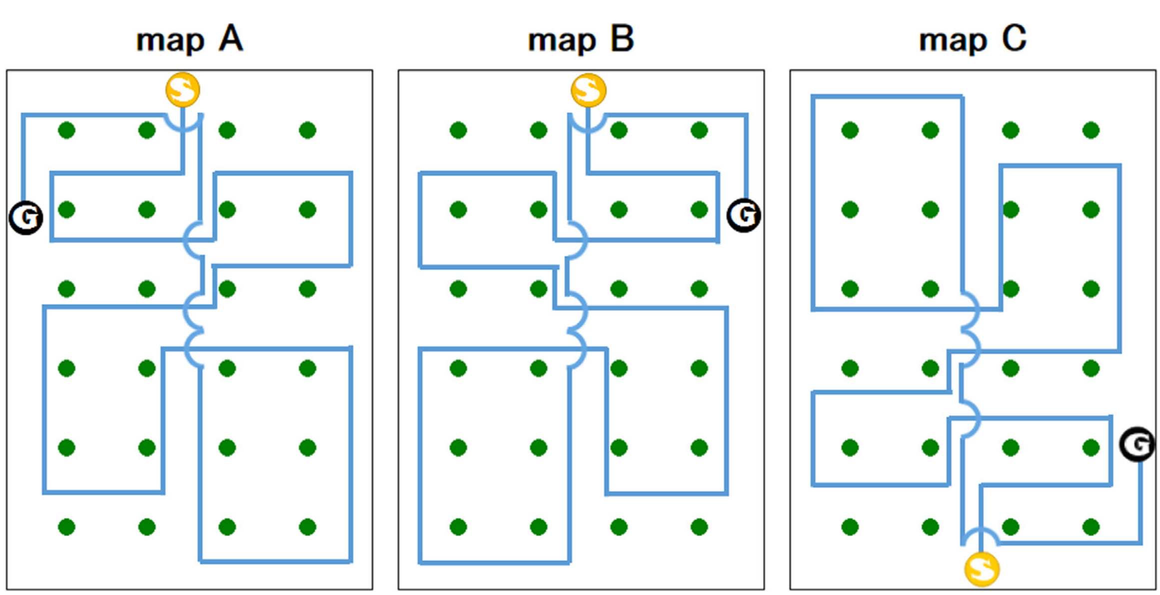

Fig. 8. Navigational maps used in the study.

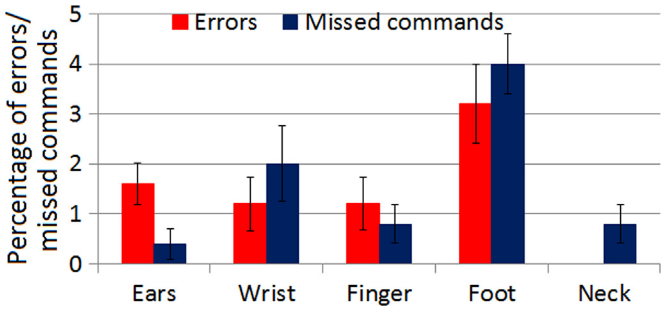

Fig. 9. Percentage of errors and missed commands.

the missed commands and errors occurred when the vibration was delivered to the feet ($p \le 0.033$).

5.4.2. Subjective ratings

Friedman tests indicated that vibration position had no statistically significant effect on users' subjective ratings for perception and comfortability. Vibration position had no significant effect on intuitiveness ($X^2(4)=9.379$, $p=0.052$). In general, the feet offered lower intuitiveness compared to other vibration positions. Vibration position had a significant effect on preferences ($X^2(4)=17.181$, $p=0.002$). The fingers, wrist and neck were the most preferred by our participants. User subjective ratings for each vibration position are shown in Fig. 10.

Despite delivering the highest perceivability, the ears were less preferred compared to the wrist, finger and neck. We speculated that this is because vibration in the ear was uncomfortably discernable when the same vibration intensity as in the other positions was applied. Nevertheless, one of the participants commented, " It's a good idea to use vibration at the ear, it is very easy to understand". Thus, it would be desirable to use lower intensity vibration at the ear in mobile contexts, where power consumption is one of major considerations. When asked to rate the desirability to use wearable vibration for navigation, the participants agreed or strongly agreed with the statement.

5.5. Discussion

Informed by the study results, we address Q3 as follows.

Which vibration positions are practically usable for walking navigation? The study results revealed that using vibration feedback across body parts is effective feedback for walking navigation. In terms of vibration perceivability and wearability, all positions are comparable to one another.

However, the participants made more turning errors when depending on vibrations on the feet. The feet appeared to be less intuitive when compared to other vibration positions. When asked about the intuitiveness of vibrations, one of the participants stated, " Vibration on the ears makes me turn my face, vibration at the finger or the wrist makes me turn my body, but the vibration at the foot is sometimes confusing." Another participant stated, "When I get vibration at the feet, I feel like I have to use my feet too much at the same time because I have to make my step, feel the vibration and figure out the direction all at the same time."

We paid close attention when the participants made turning errors. We found that turning errors when applying vibration to the feet were mostly because the directional vibrations at the feet were confusing when the participants were walking. However, most turning errors when applying vibrations at the other positions were found to be errors caused by "mental slips" (Norman, 1981). When making turning errors, the participants often stated, "Oh, I was supposed to turn the other way". Most of the participants commented that vibration at the neck matched its intended commands (start and stop).

In summary, all suggested vibration positions except the feet are suitable positions for feedback in walking navigation.

6. Design implications and guidelines

From the study results and close observations throughout the experiments, we propose the following design guidelines.

6.1. Recommended body parts

Consistent with haptic spatial acuity theory (Lederman, 1991), we could suggest that the more distal parts of the body (i.e. ears, wrists, fingers, neck and feet) had the highest vibration perceivability. However, our study results also suggest that lower body parts (i.e. the feet) were not appropriate body parts for navigation during activities like walking. To summarize, for conveying directional information for navigation, the ears (ear-rings or earpieces) appeared to be the most suitable when considering perceivability, wearability and power consumption in mobile settings. The finger and wrist are the second most preferred positions for directional information. These vibration positions can be used interchangeably for directional information. The neck is the preferred candidate for conveying non-directional instructions (e.g., road information, proximation to target). With respect to two-point discrimination in the human body (Sherrick and Cholewiak, 1986), designers should avoid using the vibration positions that are too close to each other (e.g., the hand and wrist) for frequently used commands in a single system.

6.2. More vibration patterns

The vibrations in our studies had fixed frequencies and vibration intensities. More complex navigation information (e.g., road information, approximation to targets) can be presented by using different vibration patterns i.e., by varying frequencies and vibration intensities. Some researchers have proposed different vibration patterns on different body parts. For example, Alvina et al. (2015) demonstrated spatial vibration patterns across different body parts. Azadi and Jones (2014) and Summers et al. (1997) also showed the design of different vibration patterns based on the properties of vibrotactile stimuli including frequency, amplitude and temporal variations. Thus, in addition to using directional

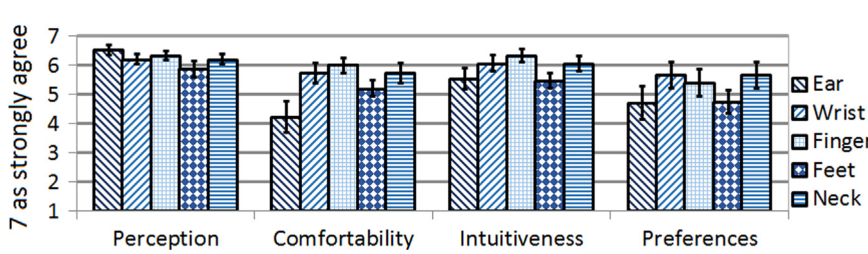

Fig. 10. Subjective ratings for vibration positions.

vibration feedback from different body parts, it is a good idea to apply different vibration patterns on a particular vibration for more complex and varied information.

6.3. Redundant vibrations

Throughout the experiments in the real mobile experimental settings, we found that vibrations were often missed by the participants. When designing wearable vibration devices for navigation, it is always good to expect that users could miss the vibrations or could make turning errors. To prevent user errors, vibration instructions should be given more than one time. It will be beneficial to use different vibration intensities to convey the proximation of users to turning points and targets.

6.4. Adaptive vibration intensity

Apparently, different body parts have different vibration perceivability, thus location-specific vibration intensity should be applied. The users' walking speed would also affect vibration perceivability. Although increasing the vibration intensity would increase salience, strong vibration intensity is not always preferable. Thus, in real world usage, vibration intensity should vary depending on the body site and users' walking speed. Also, it is beneficial to design vibration systems to be user adjustable according to the circumstances (e.g., stronger when outdoors, not so strong in quieter settings).

6.5. Applicability

Potential applications for vibration based navigation systems are numerous for different users in different domains. For example, these systems will be useful not only for ordinary pedestrian users but also for people with visual impairments, hearing impairments and also for military operators. Designers should pay attention to the particular needs of the target users for design priorities and choice of vibration positions. For example, applying vibrations to the ears may not be the best design option when designing these systems for blind users who rely on hearing for safety in mobile situations.

6.6. Accessories and clothing

To optimize vibration perceivability, vibrators should be attached firmly against the body. In our study, perceivability was high when the vibrators were attached to the users' clothing. However, simply integrating vibrators into accessories (e.g., watch) could diminish vibration perceivability. Thus, careful set up should be made when the vibrators need to be integrated into accessories. From comments of the participants during the experiments, we also noted that the vibration setup should be flexible and physically discreet in real-world applications.

7. Conclusion and future work

This study presents appropriate body parts for vibration feedback in order to facilitate the design of effective vibration feedback for walking navigation. The study investigated static and fast walking in the lab setting (Experiment 1), walking in real mobile settings (Experiment 2), and walking navigation (Experiment 3). The main findings are:

- The distal body parts (i.e., ears, wrist, fingers, feet, neck) deliver better vibration perceivability. These body parts can be used interchangeably for wearable vibration feedback in walking navigation.
- Lower body parts (feet) are not preferable candidates for vibration feedback in navigation.
- Walking in real mobile settings produced diminished vibration detection compared to findings in the lab setting.

Based on the study results, we suggested implications for designing wearable vibration devices. This study will be useful for designing and expanding the potential of wearable vibration systems.

Our future work will extend the study to include more participants with more diversity in demographic backgrounds. Future work will also include finding suitable vibration intensities for each vibration position that can offer acceptable perceivability and response times in mobile contexts.

Acknowledgements

The authors would like to thank Handityo Aulia Putra, Machida Taiga, John Cahill and other members of The Center for Human-Engaged Computing at Kochi University of Technology, for their wide-ranging support. We are also grateful to our participants for their effort and anonymous reviewers for their thoughtful suggestions.

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