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Human Navigation Using Phantom Tactile Sensation Based Vibrotactile Feedback

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Abstract— **In recent years, multiple navigation systems using vibrotactile feedback have been studied, due to their ability to convey information while keeping free the visual and auditory channels, besides eliciting rapid responses from users. In the current stage, most navigation systems with vibrotactile feedback in the literature focus on guiding users around space using a fixed number of vibrotactile cues, which are limited by the number of vibrators. Achieving more precise guidance with a limited number of conveyable directions is difficult, as users cannot be directly guided to the desired position. In this paper, we present an approach to guide people around space using multidirectional vibrotactile feedback (MVF). The MVF can produce vibratory cues on the user's left lower leg with an average directional resolution of $15.35°$ for cases when the user is not moving, using only six vibration motors, by exploiting a vibrotactile illusion called Phantom Tactile Sensation (PTS). In a preliminary test of dynamic direction recognition experiment, users reported they tend to become less sensitive to vibration under long-time continuous vibration. As a result, besides offering users a continuous vibration to indicate directions, we also considered producing the cues during either the swing or stance phase to users in this experiment. The result of a direction recognition experiment while walking shows that the average recognition error for the cues when produced in the swing or stance phases are lower than the recognition error when the cues are continuously produced. We carried out a navigation experiment to test the feasibility of using the proposed direction display to guide people around an open area in real-time. In this experiment, users were able to reach the goal within the time limit guided only by the proposed feedback around 90% of the times for both gait phases.**

I. INTRODUCTION

People need directional information to locate desired places and positions when they are trying to reach an unknown location. There are traditional ways to receive directional instruction, such as using GPS via people's mobile phones or reading a map of their surroundings. However, under these methods, besides occupying the hands holding the guidance aid, their visual and auditory channels are also busy, which may reduce their ability to notice their environment. According to a survey [1] related to cell phone distractions, more than 15% of interviewees admitted they have hit a pedestrian or an object because they were distracted by focusing on their phone. Besides the safety issues, drawbacks of traditional navigation methods also include situation induced impairments such as strong sunlight reflections on the screen of a cell phone, which may difficult for navigation using such a device [2].

In order to overcome the drawbacks of traditional navigation methods, some researchers have proposed multiple methods to convey directional information using haptic feedback. Using this kind of feedback, the auditory and visual channels remain free. In other words, users can notice their surroundings with fewer eyes' and ears' distractions. Vibrotactile feedback is a popular type of haptic feedback, mainly because it can be provided in all of the skin and elicit fast responses from the users. These two features encourage many researchers to study how to achieve real-time navigation tasks using vibrotactile feedback [3]–[10]. For examples, Xu et al. [3] proposed a prototype of shoes that utilize vibration as the main feedback to provide users with four patterns of guidance, representing front, back, left and right, for visually impaired people; Van Erp et al. [10] outlined a vibrotactile waist belt using eight tactors to display four cardinal directions and four oblique directions; Nagel et al. conducted navigation in both outdoors and virtual reality environments with 13 tactors around user' waist [9].

Besides the vibrotactile feedback, some researches focus on other types of haptic feedback with non-vibratory interfaces, like shape-changing, skin stretch, and inertial interfaces. Shape-changing haptic devices are designed to convey navigation information by changing devices' shape and volume. Spiers et al. developed both 1DOF and 2DOF handheld devices, named The Haptic Taco [11] and The Animotus [12] respectively to achieve navigation tasks. The Haptic Taco can expand or contract its body to convey the proximity based navigation information. The Animotus rotates itself to note heading information and extends its body to code distance information. Skin-stretch haptic devices give users multidirectional cues by changing tangential stretches on the skin. Quek et al. [13] augmented the stiffness perception using a 1DOF skin stretch device. Chinello et al. [14] proposed a wearable skin stretch device around an arm to guide the arm's rotation and translation by four cylindrical end effectors. Inertial tactile devices produce inertial force to indicate a target's position, such as the Force Blinker 2 [15], which conveyed the desired direction by controlling the rotation speed and angle of a weight.

Both vibratory or non-vibratory interfaces have their own merits and challenges. In the case of vibratory interfaces, most vibrators are lightweight, which makes them suitable for being worn without impeding the motion, and have a relatively low cost. However, there are some drawbacks too. Physically, most vibratory interfaces can only produce vibration where vibrators are placed on the skin. It is hard to directly display directions where no actuators exist. Another

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frequent argument against constant vibrotactile stimulation is that it disturbs users' concentration and annoys users [9]. Some shape-changing and inertial interfaces can point to any specific directions with a reduced number of actuators in the 2D space, and most existing devices for the two navigation interfaces are handheld. However, producing guidance cues on hands may limit users' capacity to interact with the environment [14].

In this paper, we propose a method to guide people around space by producing vibrotactile directional cues with a resolution of around 15° using multidirectional vibrotactile feedback (MVF). We use a vibrotactile illusion called Phantom Tactile Sensation (PTS) to produce vibrotactile feedback around the left leg of the trainee in order to indicate the direction where we want them to move. We should note that the PTS in this paper refers to the funneling illusion [16] rather than the phantom limb illusion [17]. Furthermore, we tried to improve the perceived resolution and reduce annoyance by producing vibration based on gait phases. Through a set of experiments, we confirmed that users understood the conveyed directions, and were able to reach arbitrary points in space by following these cues. Our method provides a new option to navigate walking people using vibrotactile feedback. This method can provide directional cues on the skin of the lower limb where no vibrator is placed, and produce the cues based on gait phases in order to reduce vibration fatigue. Using our method, users can reach a particular place in an open area while keeping auditory and visual channels free; also allowing them to interact with surroundings freely using their hands. This paper is organized as follows: in section II we introduce how to display directions using the MVF and present our haptic device; we conduct direction recognition experiments in static and dynamic state in section III and section IV respectively; in section V, we demonstrate a real-time navigation task; finally, we discuss and conclude our paper in section VI and section VII respectively.

II. DIRECTION DISPLAY METHOD

A. *Phantom Tactile Sensation Based Direction Display*

There are some approaches in the literature that aim to increase the number of directions that can be conveyed with a limited number of vibrotactile actuators. Woldecke et al. [18] proposed a belt with four vibration motors to convey any direction by producing sequences of vibrations with different durations. Each motor represents a cardinal point, and the direction is presented using the two motors that form the quadrant where the direction vector lies in. The duration for each vibration is decided from the direction vector's projection length in the cardinal direction represented by the motor, and they are presented in sequence. Each cue takes around 1 s to be produced.

To make users understand directions without translating two sequences of vibrations produced at different times, we use a direction display method proposed by the authors to control the motion of the wrist while moving in space [19] and follow a trajectory [20]. This method uses an array of six vibrotactile actuators around limbs and produces "virtual" vibrations between these actuators using the PTS. The schematic of the PTS is shown in Fig. 1. If two vibrators on the user's skin are in close proximity and they are vibrating simultaneously, the user's brain perceives one average vibration instead of two. There are many models of the PTS. In this paper, we used one model proposed by Israr et al. [21]. Based on the literature about the PTS [16], [22]–[25], Israr et al. proposed a model based on the energy summation model in the Pacinian channels to control both the location and intensity of the perceived PTS, and they stated this method can be applied to any body location. In this paper, by controlling the PTS between the six motors surrounding the limb accordingly, we can produce cues on the limb with a perceptual resolution of 15.35° when the limb is static. Furthermore, we extended the concept of using the PTS based cues to guide walking users.

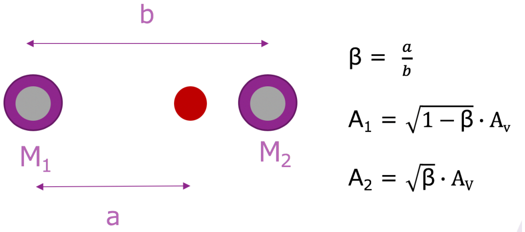


Fig. 1. Schematic of the Phantom Tactile Sensation. Two concentric circles mean motor A and motor B, respectively; the red circle presents the position of felt vibration; the distance between the two motors is b, and distance between the motor A and the position of felt vibration is a. A_1 and A_2 are the amplitude of two vibration motors respectively, and A_V indicates the amplitude of the virtual cue produced using the PTS. For example, when the two motors have the same amplitude ($A_1 = A_2$), users will feel the vibration occurred in the middle between the two motors ($a = \frac{b}{2}$). By controlling the PTS, we can produce cues at any point between two actuators [21].

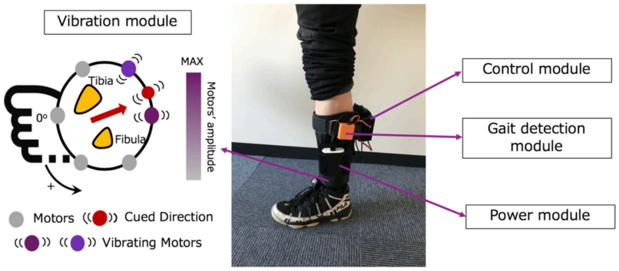


Fig. 2. Overview of the haptic device and direction display.

B. *Haptic System*

We decided to provide this kind of vibrotactile feedback on the users' left lower leg, mainly because the lower legs are generally aligned with the direction of motion of users in the global reference frame during locomotion. Another consideration for this decision is related to the necessary number of vibrators. In order to produce the PTS, vibrators need to be close to each other. Producing the PTS around the lower legs could require fewer vibrators compared to other body parts that are also aligned with the direction of motion, such as the waist.

Our haptic device consists of four functional modules integrated on a legging as shown in Fig. 2. We arranged six coin type vibration motors (FM34F) distributed evenly around the leg as the vibration module. All vibrators are linked together with an elastic strap placed inside of the legging. We used a Raspberry Pi 3B+ with a custom extend board as the control module of our haptic device. We control six independent PWM signals from a PWM driver (PCA0685) to control the vibration intensity of each motor. In this study, the maximum frequency of vibration motors is 217 Hz which is suitable for people to perceive vibration [26]. A Darlington array (TD62083AFG) is used to amplify signals from the PCA9685. The gait detection module employs an Inertial Measurement Unit (IMU) to detect gait phases for dynamic direction recognition and navigation experiments. The power module supplies 5 V to all the other modules. For our software, we employ the Robot Operating System (ROS) running on Linux for easy communication among various modules.

III. STATIC DIRECTION RECOGNITION

A. *Experimental Setup*

In this section, we carried out an experiment to measure users' recognition of directions indicated by the PTS based MVF produced on the lower limb when the users' legs are not moving (i.e., while standing). We recruited 15 volunteers without any nervous system disease or physical disorder to participate in our experiment. Volunteers were asked to stand on a spot and asked them not to move their legs. We installed the haptic device on the volunteer's left lower limb near the ankle as we presented in the last section. We produced vibrotactile feedback in 12 different directions $(0^\circ, 30^\circ, 60^\circ \ldots 330^\circ)$, two times each, in random order. In each test, the duration of vibration was fixed as 2 s. Volunteers selected the perceived directions in a dial with a precision of 1°. In other words, users can choose an answer from 360 directions $(0^\circ, 1^\circ, 2^\circ \ldots 359^\circ)$.

B. *Experimental Result*

According to the interquartile range (IQR) graph (Fig. 3), in most directions, the median of the perceived directions (black dash) is close to the produced direction. We measured the average error of perceived direction, which was 15.35°. The recognition error in this experiment is larger than the recognition error when the device is worn on the wrist [19]. This difference of error might be caused by a difference in sensitivity between the leg and the wrist. However, we deemed this accuracy enough for guiding users in space. We also measured the sizes of the users' legs to study whether leg size influences the result. The measured data of the ankle sizes and average errors is depicted in Fig. 4. A Pearson product-moment correlation coefficient (r) was calculated to assess the relationship between the leg sizes and average perceived errors. However, there was no obvious correlation between the two variables ($r = -0.15$, $df = 13$, $p = 0.5853$); which indicate that the ankle size does not affect directional recognition in this experiment.

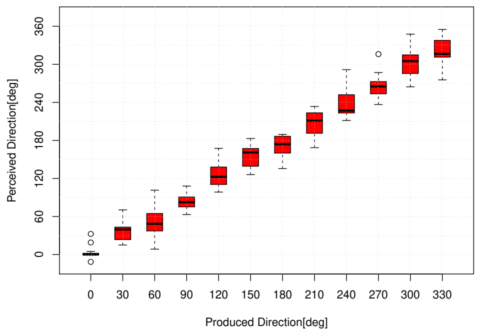


Fig. 3. Direction recognition for each displayed direction in static state. Red boxes represent the IQR, which contain the data from the first quartile to the third quartile. The x-axis and y-axis of the graph represent the produced directions and the perceived directions, respectively. The black dash inside each box represents the mean of samples. Circles indicate abnormal samples outside ± 1.5IQR.

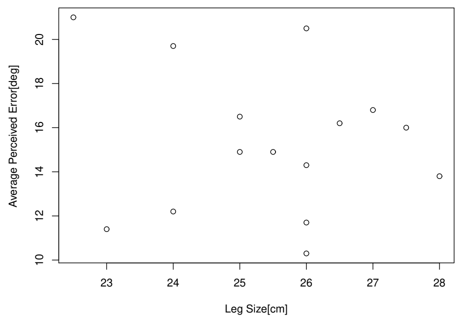


Fig. 4. Average perception errors according to leg sizes in static state.

TABLE I

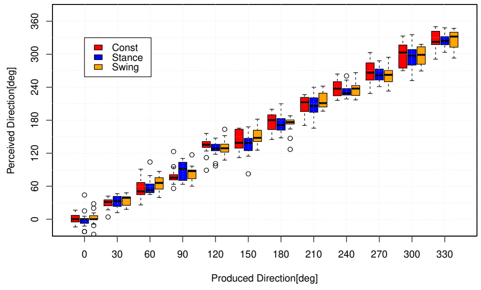
CONDITIONS OF DYNAMIC DIRECTION RECOGNITION

Number	Condition
One	Swing Phase at 4 km/h
Two	Stance Phase at 4 km/h
Three	All Phases at 4 km/h
Four	Swing Phase at 5 km/h
Five	Stance Phase at 5 km/h
Six	All Phases at 5 km/h

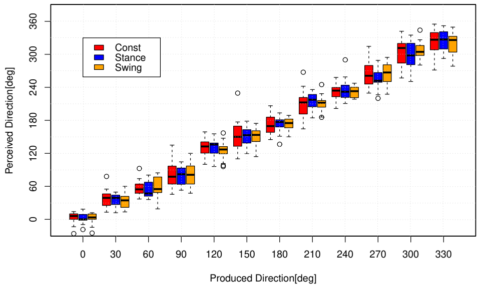
IV. DYNAMIC DIRECTION RECOGNITION

A. *Experimental Setup*

We conducted a similar direction recognition experiment to evaluate whether users can recognize directions indicated by the proposed feedback while walking. In preliminary tests, we produced the desired direction continuously, and five among a total of six users reported they became less sensitive to vibration under long-time continuous vibration. Consequently, besides constantly indicating the desired direction, we decided to indicate the desired direction only during either the swing or stance phase to users in this experiment. Normally, the stance and swing phases represent around 60% and 40% of a gait cycle, respectively [27]. As



(a) Walking on a treadmill at 4 km/h.



(b) Walking on a treadmill at 5 km/h.

Fig. 5. Direction recognition for each displayed direction in dynamic state. Blue boxes indicate only producing vibrotactile feedback in the stance phase; orange boxes indicate only generating vibrotactile feedback during the swing phase; red boxes indicate producing vibration during all phases. The x-axis and y-axis of the graph represent the produced directions and the perceived directions, respectively. The dash inside each box represents the median of the corresponding perceived directions. Circles represent abnormal samples outside ±1.5IQR.

we apply vibrotactile feedback only to the left lower limb, the time interval between two consecutive vibrotactile stimuli would be about 0.6 s or 0.4 s for a gait cycle of 1 s, when the stimuli are produced during the stance or swing phase, respectively. We also compared the direction recognition at different speed to study the effect of walking speed on recognition resolution. We determine the two walking velocities as 4 km/h and 5 km/h, for the velocities are close to the average walking speed of people (4.5 km/h) suggested by Dim et al. [28]. Consequently, this experiment includes two independent variables (gait phase and walking speed) with six conditions listed in Tab. I.

To produce vibration only during one kind of phase, we used an IMU (LSM9DS0) placed on the leg to detect gait events, for the IMU has advantages of convenient installation [29] and long term durability compared to pressure sensors attached to the shoes [30]. We measured the local minima and maxima in angular velocity and linear acceleration of the legs to detect gait events [31].

Fifteen volunteers joined our dynamic direction recognition experiment. Each volunteer had six sets of tests in accordance with the experimental conditions. Our program randomly decided the order of the six sets of tests. In each test, we produced vibration for two gait cycles. For the stance (or swing) level, the vibration was generated two times during the stance (or swing) phase. For the constant level, users could perceive vibration continuously during two whole gait cycles of the left leg. Within each set, we used the same experimental setup from the static direction recognition experiment (12 directions, two times each, random order), only this time users were walking on a treadmill at specific speed instead.

TABLE II
SUMMARY OF DYNAMIC PERCEPTUAL RESOLUTION

Subject	Condition					
	One	Two	Three	Four	Five	Six
A	9.8°	9.0°	12.3°	15.9°	10.8°	17.3°
B	10.6°	8.7°	13.6°	12.0°	12.3°	19.8°
C	15.3°	15.4°	15.0°	13.3°	19.4°	14.7°
D	10.1°	17.2°	13.5°	12.0°	16.5°	25.1°
E	16.8°	16.4°	16.6°	17.6°	21.3°	20.0°
F	16.1°	17.3°	19.5°	15.5°	20.7°	17.6°
G	7.5°	9.2°	14.1°	11.1°	8.2°	11.5°
H	10.5°	16.0°	15.5°	11.6°	13.7°	18.1°
I	9.3°	12.6°	12.5°	9.2°	9.7°	12.3°
J	11.2°	12.5°	13.2°	10.0°	12.3°	14.2°
K	12.8°	17.9°	16.4°	15.2°	17.8°	18.0°
L	13.8°	14.4°	16.4°	15.7°	16.2°	20.9°
M	12.4°	10.4°	18.9°	12.4°	11.0°	17.2°
N	13.1°	13.0°	11.3°	11.8°	14.4°	12.9°
O	13.1°	14.3°	16.3°	14.2°	14.3°	19.3°
Mean	**12.2°**	**13.6°**	**15.0°**	**13.2°**	**14.6°**	**17.3°**

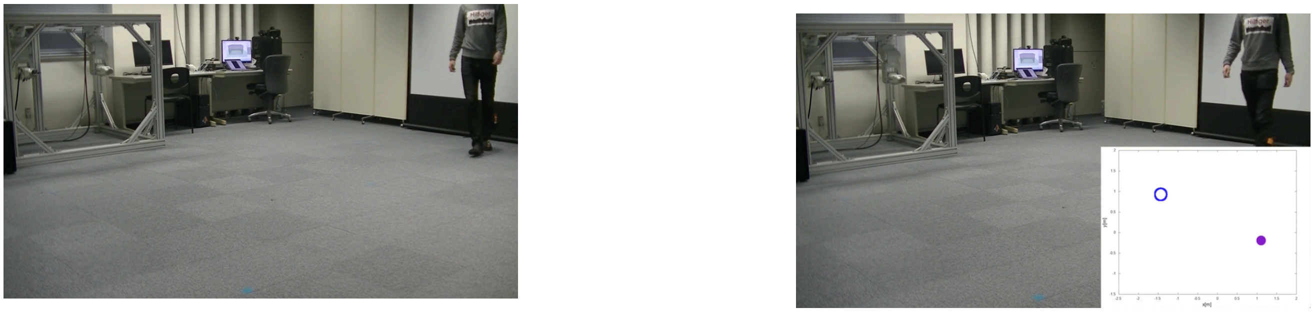
B. *Experimental Result*

The IQR graphs (Fig. 5) reflect the users could perceive directions near the related produced directions for all controlled conditions. Furthermore, Tab. II illustrated average perceptual errors for the conditions. Because this experiment has two independent variables (gait phase and walking speed), a two-factor repeated measures ANOVA analysis was performed using Rstudio (Version 1.1.463). The input used for the ANOVA test was the mean perceptual errors per subject, listed in Tab. I, in each condition. This ANOVA illustrates significant differences for both walking speed ($F = 9.5189$, $p = 0.0081$) and gait phase ($F = 14.5658$, $p = 0.0000$). This seems to indicate that a faster walking speed reduces the accuracy of the direction perception. To compare the interactions between the feedback timing, we performed a post hoc analysis using Shaffer's Modified Sequentially Rejective Bonferroni Procedure. The results indicate that the error was smaller than the continuous vibration when the cues were displayed during the swing phase or swing phase (all-swing: $t = 6.0515$, $adj.p = 0.0001$; all-stance: $t = 2.7218$, $adj.p = 0.0165$). Also, there is significant difference between the stance phase and swing phase ($t = 2.3765$, $adj.p = 0.0323$).

V. REAL-TIME NAVIGATION IN OPEN AREA

A. *Navigation Approach*

In order to evaluate the feasibility of the proposed approach to guide people in space, we decided to compare it with traditional visual feedback (VF) method, which displays



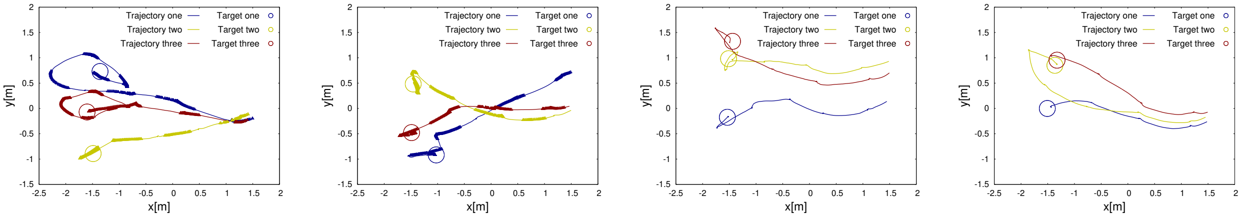
(a) User walks into experimental area.

(b) System randomly produces a desired zone.

(c) User walks following the directional cues.

(d) User reaches the desired zone.

Fig. 6. Setup of human navigation experiment.



(a) Trajectories for the Swing.

(b) Trajectories for the Stance.

(c) Trajectories for the Const.

(d) Trajectories for the VF.

Fig. 7. Trajectories of a volunteer. The colored circles represent the desired points, and the colored lines show the route followed by the user. If the end of the line reaches the circle of its color, the person successfully reached the desired point within 20 s. For the Swing and Stance, △ means a point where vibration produced, and the more dense of the △ the slower speed is.

desired directions on an electronic device and has been largely applied to the navigation field. We utilized a motion capture system from Motion Analysis to measure the user's position and orientation, and then shared it in real-time using ROS. Based on this information, the control program calculates the desired direction based on the person's pose and the desired position. After that, for the MVF, the corresponding motors were activated to produce a vibration in the corresponding direction in order to guide the user towards the desired position. For the VF, the desired direction was displayed by rotating an arrow on a tablet's screen with the rotational resolution of 1°. When users reach a zone, the arrow will disappear to convey stop information.

B. Experimental Setup

We carried out this experiment on 15 volunteers. We mounted the haptic device on the volunteer's left lower limb and placed the IMU above the haptic device for detecting gait phases. Each volunteer performed the guidance task, and there were four controlled conditions: using the MVF in swing phase (Swing), using the MVF in stance phase (Stance), using the MVF in all phases (Const), and using the VF. Three trials were performed for each condition, for a total of 12 tests per volunteer.

In each test, we asked volunteers to walk into the experimental area from any point of the start line (Fig. 6(a)). We define the position where the volunteer entered the experimental area as the start point, and our system randomly placed the desired point for that trial 3 m away from the start point (Fig. 6(b)). We did not tell volunteers this distance and it is fixed. The cues are produced while the user hasn't reached the desired point, and a time limit of 20 s was set based on a preliminary test that has 20 trails (conducted by two users, each user took ten trails) evenly distributed among the four experimental conditions (aforementioned in this sub-section) and one control condition where users walked randomly and feedback was only provided if they reached the target. For the experimental conditions, 14 trails were finished within 10 s; and 2 trails were finished using 14.3 s and 19.7s, after overshooting multiple times. As a

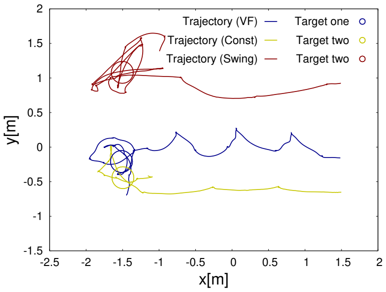


Fig. 8. Trajectories of failures caused by overshoots.

TABLE III
MULTIPLE COMPARISON OF THE ME

Comparison	t	$adj.p$
Swing-Stance	2.7410	0.0478
Swing-Const	7.0993	0.0000
Swing-VF	4.1622	0.0029
Stance-Const	1.5954	0.3988
Stance-VF	0.4229	0.6788
Const-VF	1.0159	0.6539

TABLE IV
RANKING POINTS FOR NAVIGATION EXPERIMENT

Condition	Most Clarity	Least Distraction
Swing	27	49
Stance	34	39
Const	32	32
VF	57	30

result, we set the time limit of the 20s to avoid users find targets just based on random attempts rather than the directional feedback, and to ensure users have enough time to deal with the overshoots. Volunteers were requested to walk following the conveyed directions without stopping to keep their legs always moving, so the cues were consistently produced (Fig. 6(c)). When volunteers reached the desired zone, our navigation system triggered a custom vibrotactile pattern, where all the motors vibrate in 0.5 s intervals twice, to indicate the user that they had reached the desired position ((Fig. 6(d)).

C. Experimental Results

In Fig. 7 we present the trajectories traveled by a subject in this experiment. Volunteers could locate the desired position with the time limit in most situations. Actually, the Values of the Success Rate (SR), which represents the percentage of times were the user successfully reached the goal, are 89% (Swing), 96%(Stance), 91% (Const), and 96% (VF).

For all conditions, users failed 13 times to reach targets. These failures were caused by the signal drift of the motion capture system (5 times) and the users overshooting the target (8 times). Although the motion capture system can offer a reliable measurement of the user's position most of the time, signal drift occurred five times among the total 180 trails of the experiment. When this happened, the produced cues were inconsistent with the user's position, so the user seemed to be walking randomly. On the other hand, sometimes volunteers overshot the dead zones while moving because the diameter of one dead zone around the desired position is only 0.30 m, however, usually, the average step length an adult is longer than this diameter. Occasionally, overshoots made a user just get in and out of a dead zone without properly standing inside the zone (Fig. 8). Particularly, 50% of failures due to the overshoots happened in the experimental condition of the swing phase.

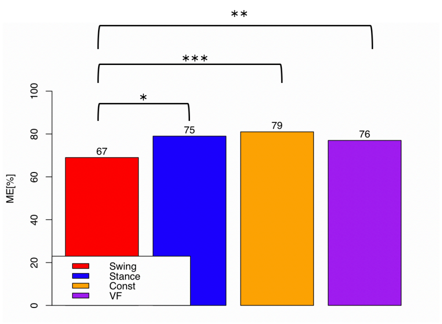


Fig. 9. The average ME values.

Besides the SR, we also used the Motion Efficiency (ME) and the Walking Speed (WS) as two metrics in order to evaluate human navigation experiments. The ME represents the ratio of the ideal shortest distance to the distance of the actual routes that volunteers traveled during the experiments [32]. The higher the ME, the more efficient the routes that volunteers traveled to reach the desired zones. The WS reflects how fast volunteers could walk during the navigation experiments. The equations to calculate these metrics are shown below:

$$SR(\%) = \frac{n}{N} \tag{1}$$

$$ME(\%) = \frac{E_p}{U_p} \tag{2}$$

$$WS(m/s) = \frac{U_p}{T} \tag{3}$$

where n represents the number of times the user successfully reached the desired zone, N represents the total number of trials, E_p is the euclidean distance from the start point to the desired point and U_p is the distance traveled by the user, sampled at 200 Hz. T means the time between the start point to the dead zone. We should note that in this experiment, most tests completed less than 20 s ($T < 20s$).

Most of the average ME values per condition, shown in Fig. 9, are greater than %70. We conducted a one-way repeated measures ANOVA for the ME whose input is the mean ME values per subject. This ANOVA shows significant differences in ME ($F = 7.7921$, $p = 0.0003$). Then, a post-hoc analysis using Shaffer's Modified Sequentially Rejective Bonferroni Procedure was performed, and its result is listed on Tab. III. The mean values of WS are 0.55 m/s (Swing), 0.58 m/s (Stance), 0.52 m/s (Const), and 0.60 m/s (VF), and

TABLE V
SUMMARY OF THE CONDUCTED EXPERIMENTS

	Static Direction Recognition	Dynamic Direction Recognition	Navigation
Setup	Static	Walking on a treadmill	Walking on an open area to a target 3 m away (under 20 s)
Goal	Direction identification	Direction identification	Reach a random destination
Speed	0 km/h	4 km/h and 5 km/h	Around 0.55 m/s or 2.0 k/h for all conditions
Results	15.35° accuracy	Under 18° accuracy for all conditions; The swing phase performed the best resolution; Resolution is more accurate at speed of 4 km/h	Location reached 90% of the times; The Swing performed the worst for the ME; No significant difference for the WS

there was no significant difference for the WS ($F = 2.1795$, $p = 0.1046$) after a one-way repeated measures ANOVA.

Besides the aforementioned quantitative analysis, we took a survey job for each volunteer. We required them to rank the four conditions from Most Clear to Least Clear, and from Least Distracting to Most Distracting. We scored the point from four to one coincided with the ranking; for example, if one condition placed as the Most Clear (Least Distracting) by a user, this condition will earn four points. The total point for each quantitative metrics is 150. The collected data is shown in Tab. IV. We discovered that most volunteers found VF as the modality that conveys the direction in the most clear way. However, most volunteers stated that the VF also distracted them from their surroundings while walking. We also observed that users reported less distraction in the Swing and Stance conditions compared to the continuous vibration.

VI. DISCUSSION

From the experiments, we observed that users were able to recognize the direction presented by the cues, and use them to navigate to arbitrary points in space. We summarize all the experiments in Tab. V. From the dynamic direction experiment, we noticed that the resolution decreases when the walking speed increases. This should indicate that the best resolution would be achieved when the user was standing still, but this was not the case. This seems to indicate that the factors affect the dynamic resolution may not influence the static resolution, because the static and dynamic states have several differences besides the speed, such as the stress applied on the leg's muscle.

During the navigation experiments, we observed that cues produced on the swing phase caused users to have the worst ME among all conditions. These results are interesting, as we previously observed that producing the vibrotactile cues during the swing phase allowed users to recognize the direction more accurately. We think that this inconsistency might be caused due to people tending to overshoot near the desired zone. If we produce haptic feedback during the swing phase, people who overshot (by the right leg) the desired position may have to take the new step for the left leg to receive the information that instructs them to go back and how directions are required, such as the third trail of Fig. 7(a). For other conditions, users do not need another step to be guided go back after an overshoot. Therefore, sometimes the overshoots could reduce the ME for the Swing. This indicates that although users can perceive directions with higher resolution when cues are produced during swing phase, producing them during the stance phase provides better guidance in the current navigation experimental setup. In the future, we will modify the stop pattern to reduce the influence of the overshoots by immediately providing directional cues after an overshoot, disregarding the current gait phase.

In the navigation task, we achieved guiding users to walk to arbitrary points. However, users walked to the points with speeds around 2.0 km/h using the vibrotactile feedback, which is slower than the normal walking speed (4.5 km/h) and the experimental speed for the dynamic direction recognition. Besides, we noticed the WS for the VF (2.2 km/h) is also slower compared to the normal walking speed. This situation might be caused by different factors, such as the limited size of the walking area (4 m × 3.5 m), which would be quickly exited if walking at fast speeds, or users being over-conscious about the fact of being in a scientific experiment, performing under limited time. We will consider these factors in future experiments, such as trying to take tests in the larger space equipped with a precise system to locate users and asking them to relax as much as possible.

Also, it is interesting to note that the MVF cues enabled users to perform similarly to the traditional visual navigation methods, as there were no significant differences for either WS nor ME when compared to vibrotactile cues (except comparison between swing phase and the VF in the ME). However, the qualitative results seem to indicate that there's a tradeoff between distraction and clarity of the perceived cue. This might be due to the difference in the amount of information perceived through the sense of sight and the sense of touch, respectively. Users can get a better idea of the direction of motion from visual feedback, but they become less aware of their surroundings, which is something that vibrotactile cues help avoid. Thus, from these experimental results, we conclude that the proposed method can be an unobtrusive way to guide people to walk around space, particularly for tasks that require their sight to be focused somewhere else, like looking for a specific artwork in a museum.

VII. CONCLUSIONS

In this paper, we proposed a method to guide people around space using the MVF around the leg. This vibrotactile feedback can indicate direction with the static perceptual resolution of 15.35° to the users using the PTS. Besides, we generate stimuli based on gait phases to reduce vibration fatigue. We carried an experiment to show that people could recognize directions displayed in dynamic states. We observed that the perceived direction resolution is decreased when the walking speed increases from 4 km/h to the 5 km/h, and all direction resolutions are under 18° for all conditions. By telling users to walk towards the perceived direction with the MVF, we were able to guide them to arbitrary points in space with a similar performance to when navigating under the traditional visual guidance method.

In the future, we'd like to adjust the stop pattern for reducing the effect of the overshoots. Also, we plan to run experiments with more volunteers, to measure the direction resolution while running, and to evaluate if our method is applicable for navigating users while running. Based on the results, we will modify the approach accordingly and apply it to sports, such as blind soccer.

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