Running Guidance for Visually Impaired People Using Sensory Augmentation Technology Based Robotic System

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***Abstract*—Participating in sports is of great significance to people's physical and mental well-being. While physical activity is commonplace for healthy individuals, it presents challenges for those with visual impairments, as they can not rely on visual cues to perceive essential information related to sports participation, such as their surroundings. Many related studies including our previous work for assisting users in doing sports using sensory augmentation technology, which couples haptic feedback with people's desired movements, are proposed for this challenge. On the basis of these studies, we propose a system for guiding visually impaired users running outdoors using a drone-based robotic system to locate a user and a track, calculate desired moving directions, and provide haptic feedback to the user. We conduct an experiment to explore how accurately people can recognize the directions conveyed by the proposed guidance method. Subjects were asked to select their felt directions on a tablet while running on a treadmill at 6.5 km/h and 7.5 km/h. The results show subjects could recognize the cued directions with an average resolution of 19.8° and 19.6° at different speeds, respectively, and there is no significant difference exist between the two speeds. In addition, we guide users in realistic running scenarios on sports tracks. Subjects in this experiment wore an eye mask to simulate the visually impaired. They were instructed to run by following the perceived directions conveyed by haptic feedback. According to the results, they could run within a specific track 81% of the time with the proposed system.**

***Index Terms*—Human-centered robotics, physically assistive devices, wearable robotics.**

I. Introduction

According to the data of 2020, the number of blind individuals has continuously grown, which has nearly reached 43.3 million people. In addition to blind individuals, there are additional 285 million people with moderate or severe visual impairment [1]. Because it is difficult for them to use the visual channel to acquire information about their surroundings, visually impaired individuals face challenges when engaging in sports, which are essential for maintaining people's health.

Traditional guide tools like a guide dog, blind walkways, or a white cane could aid visually impaired individuals with daily locomotion tasks involving low-dynamic movement, such as walking down the street. However, these devices are generally difficult to use to assist visually impaired individuals in sports such as running since they will impede the motion of the user when they are participating in sports. Currently, visually impaired individuals require the assistance of a human guide to help them to do sports, like the human guide either holds the runner's elbow or uses a connected elastic rope to assist them to run. Given the staggering number of people living with visual impairment worldwide [1], the demand for human guides is immense. This need becomes even more critical in countries grappling with an aging society. However, there is a stark reality to confront: there may simply not be enough human guides to fulfill this escalating demand, creating a concerning gap in service provision.

Lately, a number of researchers have proposed diverse methods based on sensory augmentation technologies for guiding visually impaired people to move around without a human guide. Sensory augmentation describes technologies that deliver new information to users' existing sensory channels (visual, auditory, tactile, and olfactory channels), such as augmenting the visually impaired users' spatial awareness with haptic feedback [2]. It is important to note that sensory substitution and sensory augmentation are related but not the same notion. Both attempt to improve function for people who have sensory impairments. They are classified according to their level of sensory impairment. For total impairment, haptics act as a sensory substitute; for partial impairment, haptics act as sensory augmentation [3]. Our goal is to assist visually impaired persons who may be blind or not but cannot identify their surroundings most of the time; thus, we use the term sensory augmentation in this letter. Kemeth et al. [4] presented a radio frequency-based system to aid visually impaired field runners by conveying spatial information with their waist-mounted haptic actuators. Rector et al. [5] investigated how to make users aware of "left" and "right" information by

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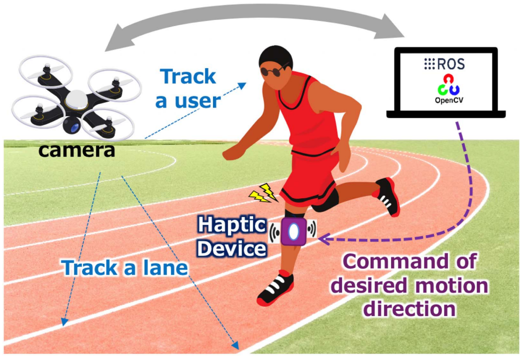


Fig. 1. Concept: using a drone and a haptic device to guide visually impaired people.

applying haptic feedback to their wrists to guide them in moving on a desired sports track. Barontini et al. [6] proposed a haptic device with an obstacle avoidance function that uses an RGB-D camera to guide visually impaired people to a goal indoors. Scheggi et al. [7] proposed a two-person cooperative navigation system in which a blind user wears a camera to capture images. These images are then transmitted to a remote operator who generates vibrations to convey directional information based on the visual input. This finding suggests that if we can provide an appropriate visual feed to the system, effective guidance can be achieved. In this letter, we utilize a robotics system to act as the "remote controller" in the navigation process.

From the aforementioned research, it is clear that sensory augmentation could assist users in comprehending spatial information and could be implemented in the sports guidance field. Based on these findings, we developed a wearable sensory augmentation device that is attached to the user's lower leg and transmits directional information via six vibrators [8]. With this device, we proposed a concept to guide users' outdoor jogging with a drone-based robotic system [9]. In this concept (Fig. 1), we used a drone to collect images of a user and their soundings, which were then analyzed by a computer vision-based program to locate the user and detect the desired moving path. We ran tests to see if the idea worked on a road with a length of 20 meters and the drone hovered at a specific point without tracking the users. From the results, we discovered that the concept could assist users in jogging along a desired path under the experimental area.

In this letter, firstly, we determine the accuracy with which persons who are running can comprehend spatial information cued by haptic feedback through direction recognition experiments. The results indicate that users could determine the reference direction with a resolution of around 19.7° on average. Then, on the basis of the previously proposed concept, we propose the guidance system, which included suggesting the motion guide policy for users and the sports lane recognition mechanism. This system is working to guide users on a real sports track with the drone following the user. To assess the feasibility of the guidance system, a series of running guidance experiments are conducted. During the tests, we observed that users could alter their moving direction to run within the intended track, and that the system helped users stay on the track 81% of the time, almost double the value of the control condition in which users ran without assistance. Besides, we found the proposed system has a comparable overall performance with the human guide which is the most traditional running guidance method for visually impaired people. The experiments in this letter have got permission from all subjects and approved by Tohoku University.

This letter's primary contribution consists of three points. First, we suggest a drone and haptic-based outdoor running assistance system for the visually impaired. Compared to our previous work [9], this work contains significant algorithmic and methodological improvements, signifying our system's leap from theoretical plausibility to practical utility. In this work, we were able to accomplish actual sports guidance with a drone following a user on a real sports field, as opposed to hovering a drone in a single place and guiding users only on a short custom-built experimental track. Second, we evaluate the direction resolution of users utilizing the system; the results indicate that the resolution is adequate for usage in the guidance task. Finally, we apply the suggested system in a real guidance situation, and the findings demonstrate that the performance of the proposed system is comparable to that of a human guide.

The remainder of this letter is structured as follows: in Section II, we provide an overview of the proposed guidance system; in Section III, we describe the running direction recognition experiment; in Section IV, we present the in-field running guidance experiment which is held on a sports field; in the final two sections, we discuss the findings from the experiments and provide a conclusion and future works of this research.

II. Outdoor Guidance System

A. System Overview

The main structure of the proposed guidance system is depicted in Fig. 2. This system comprises mostly three functions: collecting information about users' motions and their environment by a drone, detecting the desired moving direction to keep users running inside a track, and transmitting spatial information to the kinesthetic channels of the user via a wearable haptic device. In our previous work, we employed this particular haptic device to assist users in locating a specific point [8]. This device utilized six vibrators to provide cues for various directions. The cues were generated based on a phenomenon where, when two vibrators vibrated simultaneously, individuals perceived a single vibration instead of two, with the sensation of vibration being located between the two motors. Also, we explored the feasibility of using a drone to guide people in outdoor movement [9]. In this earlier work, we focused on keeping the drone hovering at a specific location without actively tracking the users. However, in the present work, we have made modifications to the guidance system to enable it to effectively guide users by actively following them in an actual sports scenario.

We utilize a DJI MAVIC 2 PRO drone to autonomously track the user. The drone is equipped with a controller that allows us to send commands and receive real-time images from its camera. The drone's controller received images will be sent to the system's master controller using a USB interface and video

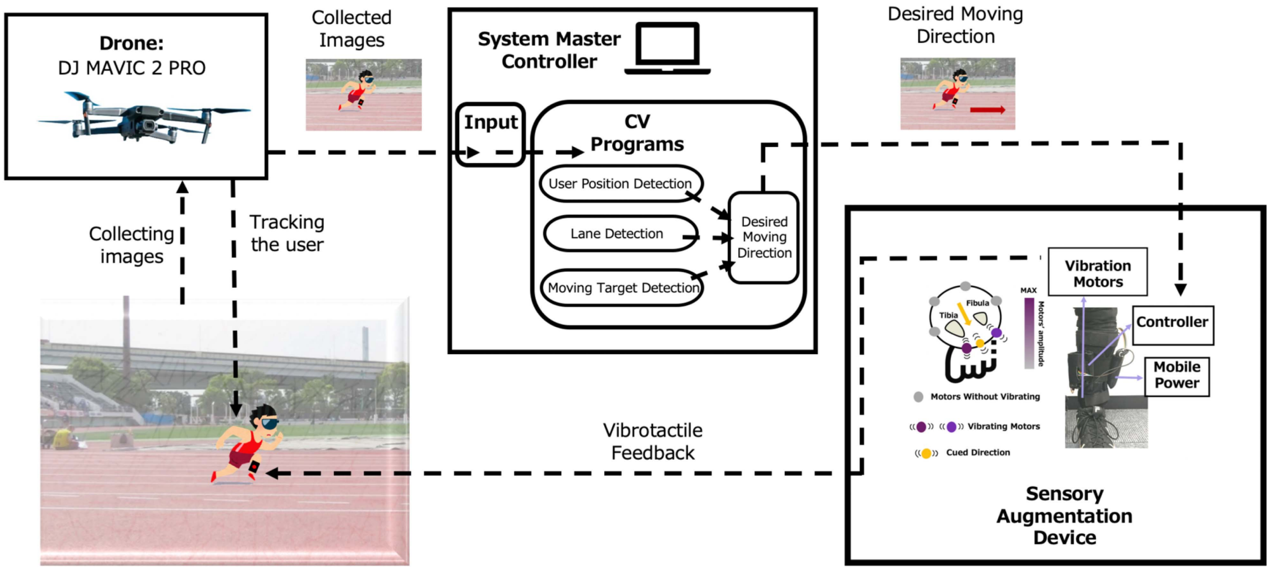


Fig. 2. Guidance system overview.

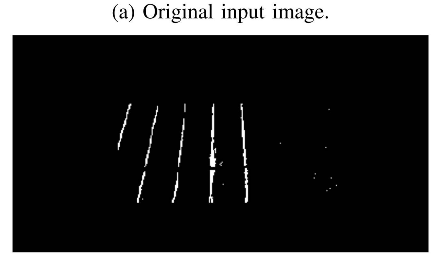
capture software in real-time. Once the drone is in flight, we can select the user on the controller, and the drone will automatically track the designated user. Throughout the tracking process, the drone strives to maintain a consistent distance from the user, adjusting its flying speed according to the user's running pace. The master controller uses OpenCV-based algorithms to process the received videos. These algorithms are able to extract sports lanes from the original input video and users while they are running. Moreover, the algorithms can pinpoint the desired track in which users should remain and find the desired moving target at this time. By assessing the relative position among the user, the target lane, and the moving target point, the master controller judges whether the user is inside of the lane or not, calculates the required users' moving directions and encodes the directions into the vibration commands, which are then published to nodes running on the wearable haptic device. Finally, the haptic device triggers vibrations to provide spatial awareness to users.

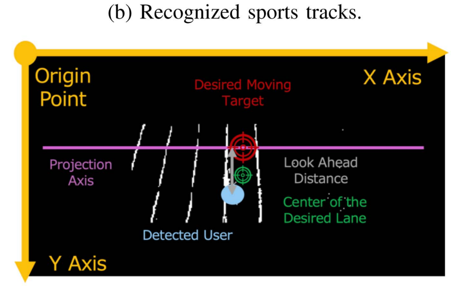
B. Calculation of Desired Runner Moving Direction

Before determining a user's desired moving direction for each input image, the system should detect the user, identify sports tracks, and detect the user's moving target. We use the wildly used Kernelized Correlation Filter (KCF) [10] tracker to locate the user. This kind of tracker is able to track the user from the received video streaming.

On the majority of athletics tracks, the color of the track's surface differs from the color of the track lines; for instance, the sports field where we conducted our experiment has a green grass surface with red track lines (Fig. 3(a)). We use this characteristic to differentiate between running lanes. First, the region of interest (ROI) of the gathered photos will be filtered by an RGB-based filter that can identify pixels with a similar color to the track's lines. After this processing, we can determine the contours of the lines. The obtained lines' contours are with some noise pixels which are caused by the sunlight.


(a) Original input image.


(b) Recognized sports tracks.



(c) Detecting the user's desired target based on the recognized tracks and the user's position.

Fig. 3. Example of extracting sports tracks and finding a desired target.

In order to decrease these noises, we also process the original input images with an HSV-based filter. Then, we perform a conjunction operation on the output contours of two distinct filters and do morphology operations to obtain contours of lines with less noise, the processed image is shown in Fig. 3(b).

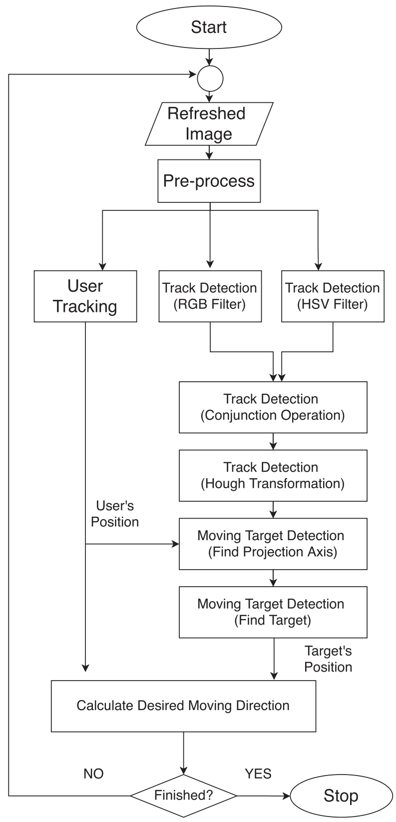


Fig. 4. Flowchart for calculation of desired moving direction.

Now, we gather the pixels of the lines, which are not separated into individual lines. We apply the Hough transformation to identify straight contours from observed pixels in order to differentiate pixels into distinct straight lines.

Then we can obtain an axis called "Projection Axis" to help us find the desired moving target of users. To determine the "Projection Axis," we first calculate its slope by determining the slopes of the desired track's two boundary lines, denoted as k_1 and k_2. Then, we find a slope k that is approximately perpendicular to both k_1 and k_2, representing the slope of the "Projection Axis". Next, we identify a point P through which the Projection Axis passes. This point P is determined by moving the current user's position in the negative y-axis direction of the pixel coordinate system by the look-ahead distance. By using the slope k and the point P we can obtain the "Projection Axis." Next, the X coordinate of the intended running lane's center is projected onto the Projection Axis, and the Projection point is designated as the desired moving target (Fig. 3(c)).

The desired direction which will be published to the haptic device is defined as the angle between the user's current moving direction (obtained from user's previous position and current position) and the direction from the user to the desired moving target. The main process of calculating the desired moving direction is summarized in Fig. 4.

C. Sensory Augmentation Device

Directional cue-communicating devices can be categorized into three types, the wearable device, the handheld device, and the ground-fixed device. For example, Moriyama et al. [11] proposed a wearable device that is attached to the user's forearms to convey directional information. Spiers et al. [12] present a handheld cube to indicate directions by rotating the cube. Carignan et al. [13] suggested a ground-fixed exoskeleton to guide the user to move the arms in the desired way. Considering the fact that providing directional feedback for running humans needs high portability, we use a wearable haptic device to cue users.

The haptic device (Fig. 2) consists of six coin-type vibrators mounted inside of a sports legging to provide users with vibrotactile feedback which could elicit a fast response from humans. To indicate desired directions, we employ a phenomenon known as phantom tactile sensation (or funneling illusion), which means users feel just one vibration if two vibrators with the appropriate spacing are pulsating simultaneously [14]. Moreover, by adjusting the strengths of the two vibrators, both the amplitude and position of the produced vibration may be controlled [15]. Using this type of feedback, we can increase the number of cued directions with a limited number of vibrators rather than add vibrators. For example, as shown in Fig. 2, suppose we want to generate vibrations in the direction represented by the yellow arrow. We can activate two adjacent vibrators (in purple) at the same time and adjust their specific amplitudes of them according to the formula described in the letter [15] to generate vibrations in the desired direction. In our prior research, this type of input was used to guide individuals walking to an arbitrary spot [8] and jogging along a short, straight path [9].

III. Running Direction Recognition

Although we previously investigated the vibration perception accuracy of the proposed device while individuals were in stationary and walking states [8], it is important to acknowledge that there are many differences in the muscular state and other factors when individuals are running compared to walking and standing. Therefore, we cannot equate the perception resolution obtained from the previous experiments to the resolution experienced during running. As a result, in this section, we assess the accuracy with which running users perceive directions conveyed via proposed haptic feedback, as well as the effect of running speed on recognition resolution.

A. Experimental Setup

In this experiment, there is one factor (running speed) with two levels (6.5 km/h and 7.5 km/h). These two speeds have been determined because they are faster than the dividing line between running and walking speeds and are not so fast that users would be unable to run for enough time to complete the experiments.

We recruited 10 subjects, who are adults without any mental or physical disorders, for this experiment. Each subject was administered two sets of tests at each of the two running speeds, with the order of the sets determined randomly. For each running speed, we generated vibrotactile feedback in 12 distinct directions ranging from 0° to 330° (0°, 30°, 60°... 300°, 330°), and in a single direction, the test was performed two times, for a total of 24 trials at one speed were completed. As we did in the experiments to detect the direction resolution when users are in static and in the walking situation [8], we arrange the six vibrators evenly around the lower leg and we set one motor in front of the lower leg as 0°. As a result, the other motors are set as the place at 60°, 120°, 180°, 240°, and 300°, respectively. Also, we use the phantom tactile sensation phenomenon which refers to having a feeling of one vibration when the two vibrations are generated at the same time to generate vibration at 30°, 90°, 150°, 210°, 270° and 330°, respectively. The order of each trial is determined randomly. In every trial, a vibration duration of two seconds was consistently used. In each trial, subjects were required to wear the proposed haptic interface and run on a treadmill at a predetermined speed. Following the vibration, participants were asked to select perceived directions on a dial displayed on a tablet. This dial is accurate to 1°.

B. Experimental Result

The perceptual resolutions at the two running speeds in each direction are summarized in two interquartile range (IQR) graphs respectively, shown in Fig. 5(a) and (b). From the IQR graphs, we could see that the subjects' selected felt direction was in close proximity to the produced direction, with only slight deviations.

In addition, we discovered that the average resolutions at the two running speeds are 19.8° and 19.6° respectively (Fig. 5(c)). To detect whether this difference is significant or not, a t-test is conducted. The result shows $p > 0.05$, which indicates as the running speeds increase subjects have the same perceptual resolution. These facts suggest that the proposed phantom tactile sensation-based haptic interface could be used for running guidance.

IV. In-Situ Outdoor Running Guidance

In the previous articles, we conducted a conceptual validation experiment to assess the feasibility of our proposed concept [9]. During that experiment, the drone remained stationary at a specific location, resulting in a relatively static experimental process. Additionally, the previous experiments were conducted on a custom-built experimental track.

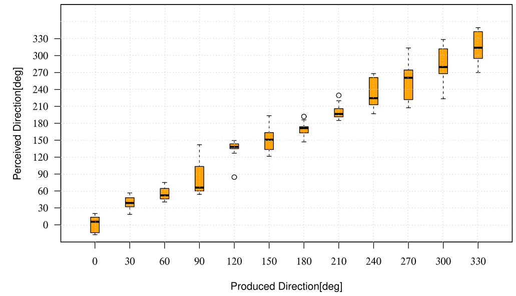
In contrast, the purpose of this experiment is not conceptual validation but rather demonstrate system's operational feasibility within real-life sports scenarios. We implemented continuous drone tracking of the users, enabling dynamic guidance for sports navigation. Moreover, we validated the system's performance on a real sports track. Besides, we compare the system to the conventional running guidance method for the visually impaired, which is guided by a human guide.

A. Experimental Setup

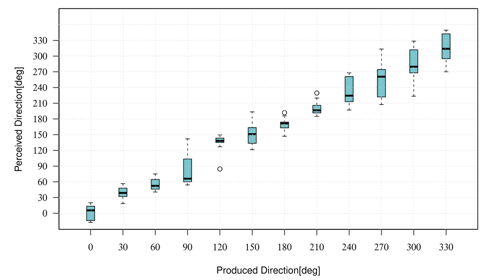
There are three experimental conditions: guiding users with our suggested approach (Pro), guiding users with a human guide (Human), and not providing any guidance feedback (None).

The experiments were carried out on seven healthy adults. Subjects were told to run in a straight path as quickly and as straight as possible while blindfolded under the aforementioned experimental conditions (Pro, Human, and None). Each participant ran five times trails in a row under each experimental condition, for a total of fifteen trials. The order in which the conditions were applied to each volunteer was random. Subjects were required to wear an eye mask as well as a set of protective tools such as a helmet, vest, knee pads, and elbow pads during the experiment. The drone automatically follows runners at an altitude of around 8 m, which may change due to natural factors such as wind strength. This experiment was conducted on a 48-meter-long, 1.2-meter-wide straight track in a sports field.

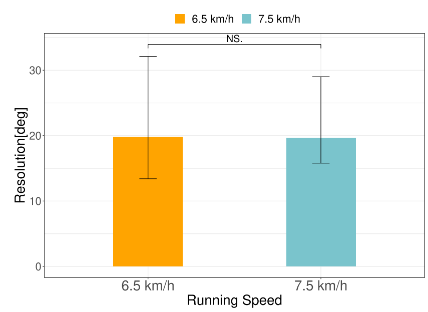
Subjects were instructed to stand at the track's starting line before each trial (Fig. 6(a)). For the Pro condition, if subjects stray from the targeted path, the system provides directional information to the volunteers via continuous haptic feedback (Fig. 6(b)), and volunteers should run in accordance with these instructions (Fig. 6(c)). If participants are within the required track, however, no haptic feedback is produced (Fig. 6(d)). This



(a) Resolution at speed at 6.5 km/h.



(b) Resolution at speed at 7.5 km/h.



(c) Comparison of average resolutions.

Fig. 5. Perceptual resolution at different running speeds. For Fig. 5(a) and (b), the orange or blue boxes represent the interquartile range and contain data between the first and third quartiles. The x-axis and y-axis of the graph represent, respectively, the directions that are produced and those that are perceived. The black dash in each box represents the sample mean. The circles depict abnormal samples outside of the ± 1.5 IQR range. For Fig. 5(c), the average resolutions at different speeds with error bars are depicted, and the $NS.$ means no significant difference exists between the two speeds ($p > .05$).

(a) The user stands by.

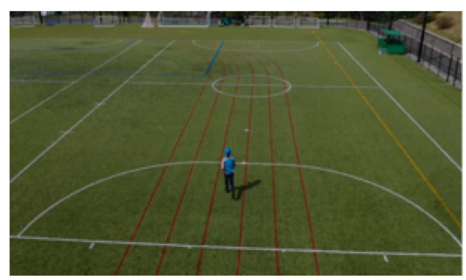
(b) The user deviates from the desired track. In this situation, the haptic feedback is produced continuously until the user goes back the track.

(c) The user follows directions cued by vibrations.

(d) The user goes back to the desired track. In this case, no vibration is produced.

Fig. 6. Guidance scenario using the proposed system.

(a) The user is guided by a human guide who uses an elastic tether and verbal commands to convey information, and the user could stay on track most of the time.



(b) The user runs without any guidance. The user tends to deviate from the track and hard to go back to the desired track.

Fig. 7. Guidance scenarios using the human guide method and without using any guidance.

method is ignited by a shared control policy. The shared control policy refers to a control strategy that combines humans' control commands with the robotic system's control decision to deal with different scenarios [16]. In this letter, the control of the user's moving direction is shared. When the user is on the track, the user's moving direction is decided by the user self; while the user moves out of the track, the haptic feedback is used to control the user's moving direction. We use this strategy to prevent users from experiencing long-term, continuous vibration, which may result in vibration fatigue (which could annoy users and reduce their sensitivity to the vibration) [17], [18].

For the Human condition, users should follow the instructions of a human guide, who guides users through an elastic tether and voice commands, like saying "little left", "more left" and so on (Fig. 7(a)). In this case, users can run within the track for the vast majority of the time. For the None condition, the users are just informed to run as straightly and as quickly as possible without any feedback. In this situation, users tend to stray from the path and never return (Fig. 7(b)).

B. Experimental Metrics

We employ two quantitative evaluation measures, the Time In Lane (TIL) (shown in (1)) and the Valid Moving Speed (VMS) (shown in (2)). The TIL is for assessing how much time blindfolded people could run within the track under different conditions. The VMS metric directly reflects the speed at which a user can move and indirectly reflects the practical applicability of different conditions. For example, if a method achieves high TIL but has an extremely low VMS, we cannot conclude that this method is suitable for real-world applications.

$$TIL(\%) = \frac{T_l}{T_t} \tag{1}$$

$$VMS(m/s) = \frac{E_u}{T_t} \tag{2}$$

where T_l means the time the user was moving within the track, T_t represents the total time of the user moving for one trial, and E_u indicates the Euclidean distance between the user's positions

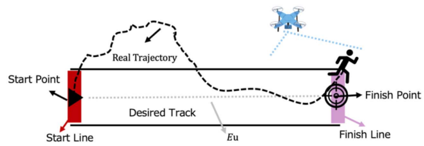


Fig. 8. Definition of the Eu to calculate the valid moving speed.

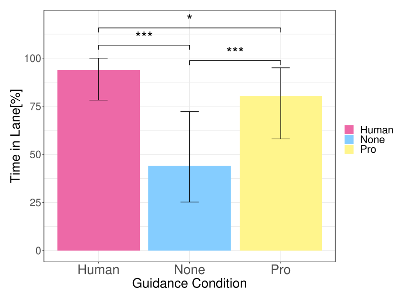


Fig. 9. Average TIL values of in-field running guidance experiment. The higher TIL value represents users traveling more time in the lane. The $*$ indicates $p < .05$, and the $***$ indicates $p < .001$.

along the line which is from the center of the starting line to the center of the finishing line (Fig. 8).

To assess the proposed method from a broader perspective, we also investigate the subjects' sense of agency. In this context, the term sense of agency (short for SoA or SA) refers to one category of people's awareness regarding the extent to which they believe their actions contribute to the desired outcomes; this feeling is also known as the sense of control. In numerous fields, including rehabilitation and the human-computer interface, the SoA is an important evaluation metric [19], [20], [21].

We measure SoA using a 7-point scale Likert question, which is one of the common tools for measuring users' SoA. We asked the subjects if they believed they had control over their movement. They can assign one to seven points to their responses, which correspond from strong disagreement to strong agreement.

C. Experimental Result

From the results of the TIL (Fig. 9), we can see that subjects in the Human condition and the Pro condition performed nearly double TIL values to run within the desired track compared to the None condition. We use a set of t-tests to determine whether this value differs and has statistical significance; the result indicates that there are statistically significant differences between each condition.

Fig. 10 displays the outcome of the VMS values. Using the proposed system, the subjects achieved higher average moving values than the None condition; however, the t-test analysis reveals that there are no significant differences between the conditions.

The average SoA values for the Pro and None conditions (Fig. 11) are significantly higher than the value for the Human condition, which gives the highest TIL value. This observation coincides with the t-test based analysis, which suggests that

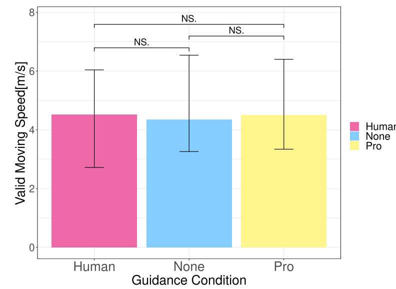


Fig. 10. Average VMS values of in-field running guidance experiment. The higher VMS value represents subjects moving at a faster speed. The $NS.$ means no significant difference exists ($p > .05$).

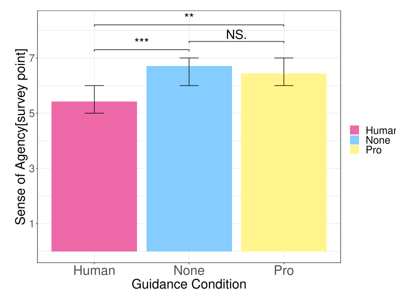


Fig. 11. Average SoA points for in-field running guidance experiment. The higher point represents subjects felt stronger their motion was controlled by themself. The $**$ represents $p < .01$, the $***$ indicates $p < .001$, and the $NS.$ means no significant difference exists ($p > .05$).

human guidance will reduce users' SoA, whereas our proposed method does not affect users' SoA in statistics.

V. Discussion

Based on the direction recognition experiments, we discovered that increasing the running speed did not significantly reduce the resolution that subjects received by the proposed haptic interface. This result is not the same as the outcome of the walking recognition resolution experiment, which revealed faster walking speeds resulted in lower resolutions in our previous letter [8]. These inconsistent results might be because of some differences between the walking states and running states, such as the amount of force that is applied to the lower limb's muscle. In other words, the factors that influence resolution during people walking may not influence resolution while people running.

In the field running guiding experiment, the suggested method is compared to the condition without any guidance and the human guide method, which is the conventional approach for visually impaired individuals. Although the human guidance method could keep users running inside the track for longer periods of time (better TIL values), the proposed system significantly increases the time of subjects moving inside the track compared to the case where no guidance is provided, and contributes to a greater sense of agency than the human guide method. As a result, we can argue that the proposed method is an efficient way to be used to guide visually impaired users running outdoors without impeding users' sense of agency.

In addition, we observe that the subjects' moving speeds increase from 1.2 m/s when they were running on a road between two buildings (present in the letter [9]) to 4.5 m/s when they were running at a sports field. This phenomenon may indicate that if people knew that the experimental area was not a wide open area, they would worry about whether they had left the experimental area, and thus instinctively slow down to avoid potentially dangerous like hitting obstacles and walls.

In this work, we conducted an outdoor navigation test with healthy people who wore an eye-mask to mimic the visually impaired people, and the results showed the system could help the blindfolded people. As a result, we can see the potential of our proposed system to be used for real visually impaired users in the future.

VI. Conclusion

In the letter, we proposed a guidance system for actual outdoor running scenarios using a sensory augmentation device to convey directional cues. We investigated how accurately users could perceive directions conveyed via the sensory augmentation device, the results show that users can discern conveyed directions with a perceptual resolution of approximately 20° when running at 6.5 km/h and 7.5 km/h, and that the resolution does not change significantly between the two speeds. To evaluate the feasibility of the system, we guided blindfolded subjects along a specific sports track. There are two assumptions in this experiment. Taking into account the feature that color contrast between the surface of the track and the track lines exists in the majority of sports tracks, we consider this feature as one of the assumptions of the experiment. The second assumption is that our experiment currently only focuses on guiding in straight tracks, because straight guidance serves as the foundation for many other sports disciplines, such as the high jump and so on. In this experiment, we also compared the performance of the proposed system with the situations in that subjects were guided by a human guide and without any assistance. The results indicate that the proposed system could contribute to the subjects running within a track 81% of the time and did not reduce their running speed with an increased sense of agency compared to the human guide method.

In the future, we intend to apply this method for more difficult tasks, such as guiding visually impaired people through long jumps, javelin throw, etc. Also, in the future, we will modify the current system to a curve guidance system, which involves several differences in technical methods like object detection methods and haptic feedback modalities, compared to the current system. There is a work indicating that haptic feedback can be used to guide a group of individuals to walk toward different goals [22], and this research has inspired future work in which we will explore the feasibility of employing a single drone to guide a group of individuals.

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