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A vibrotactile belt to display precise directional information for visually impaired

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Abstract: This paper presents a vibrotactile belt to display precise directional information for visually impaired. Considering the characteristics of tactile perception, the torso-related transfer function was used to arrange actuators on the belt, and a coding algorithm using vibrotactile funneling illusion was proposed to display precise directional information. A psychophysical experiment was performed to evaluate the validity of the belt in displaying precise directional information. The experimental results indicated that the vibrotactile belt using our proposed coding algorithm achieves a resolution of 7.5 degrees with a high recognition accuracy of up to 91%. The current work provides valuable guidance for the design of vibrotactile navigation aids.

Keywords: haptic device, vibrotactile display, torso-related transfer function, vibrotactile funneling illusion

Classification: Circuits and modules for electronics display

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1 Introduction

The favorable effects of vibrotactile (vibratory tactile) displays on navigation performance, situational awareness, and workload reduction have been shown for blind people, pilots and drivers [1, 2, 3]. Vibrotactile displays have been widely used to provide directional navigation cues such as guiding commands: backward, stop and forward [4]; turn-left, turn-right, and go-forward [5]; or cardinal directions: frontal, back, left, right [6]. However, most of vibrotactile displays were used to provide simple directional information. Vibrotactile displaying of precise directional information is rarely studied.

The skin covering the torso is capable of precisely encoding information since it contains hundreds of mechanoreceptors [7]. A belt-type display can be worn under a coat without attracting public attention [8]. Therefore, we designed a vibrotactile belt to display precise directional information. The first belt-type vibrotactile display ever reported in the literature is the "ActiveBelt", designed to convey directional information using 8 vibrators [9]. Recently, a vibrotactile belt with 8 vibration motors arranged evenly around the torso was developed to provide directional guidance for blind walkers [10]. Although these vibrotactile belts could provide guiding information for visually impaired, they can not be used to cue precise directional information.

The precise directional information is required to guide blind people to their destination accurately, since a small error in cueing direction may cause a large deviation of the traveler's orientation relative to the desired path [11, 10]. Besides in a vibrotactile navigation system, the geomagnetic sensor with high precision (e.g., TMC3000NF by NEC Tokin) is generally used to detect direction, which then is converted into vibration patterns. Therefore the vibrotactile displays without fine resolution cannot take full advantage of the precision of the geomagnetic sensor. In applicable belt-type vibrotactile displays which have been reported, the minimum recognizable directional deviation in the horizontal plane of the waist is approximately 15 degrees [11]. However a resolution of 15 degrees may not precise enough to cue slighter deviations from the intended path for visually impaired. From the standpoint of vibrotactile perception, a resolution of approximately 10 degrees in the horizontal plane of the torso is feasible [12]. According to study of Cholewiak et al., subjects' overall accuracy of localization performance for 6 or 8 vibrotactile stimuli presented to sites around the torso was higher than 92% [13]. The goal of current work is to achieve a resolution of less than 10 degrees with recognition accuracy of more than 90%.

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The factors that influence the precision of vibrotactile cueing direction include the arrangement and number of tactors set around the torso [13], and coding algorithm of displaying directional information [14]. In most vibrotactile displays, tactors were located around the torso with same degrees between each adjacent pair [7, 10]. However previous psychophysical experiments of vibrotactile perception on torso indicated that the equally spaced tactors will not be perceived as equally distributed [12]. The bias between the tactor angle and perceived angle changes as a function of tactor angle. This function was called torso-related transfer function (TRTF). The implementation of TRTF in applications that require high precision of cueing directions is suggested [12]. The vibrotactile funneling illusion has also been reported as effective in improving the resolution of the cueing direction [15, 5]. By activating two adjacent vibration tactors simultaneously, it is possible to elicit a vibrotactile funneling sensation just like a virtual tactor vibrating at midpoint of them [16]. The perceived tactile sensation of the virtual tactor is almost equivalent to that of a real tactor [17]. In this work, we implemented the torso-related transfer function to determine the arrangement of tactors around the torso, proposed a coding algorithm using vibrotactile funneling illusion to cue precise directional information. A psychophysical experiment was performed to evaluate the validity of the belt in displaying precise directional information.

2 Design of vibrotactile belt

Displaying rich directional information intuitively with as few tactors as possible is a general principle of designing vibrotactile displays. In this section we will describe the number and arrangement of tactors set on the torso, and how the precise directional information was intuitively encoded with vibration patterns. As shown in Fig. 1, the hardware system of vibrotactile belt is consisted of controller, geomagnetic sensor and actuator. The controller receive directional signal detected by the geomagnetic sensor and activate actuators to vibrate. The actuators used in current work are coin motors in regular cell phones (Fig. 1 right). Compared to other types of vibrotactile actuators (e.g., linear resonant actuator and piezoelectric actuator), the coin motors are size-small, low-price and energy efficient [18], which make them an ideal choice for vibrotactile belt. The KOTL C1234B016F flat coin motor was selected as tactor to evoke vibrotactile sensation (http://www.kotl.cn/cn/default.aspx). The vibration intensity produced by the motor can be controlled by PWM duty.

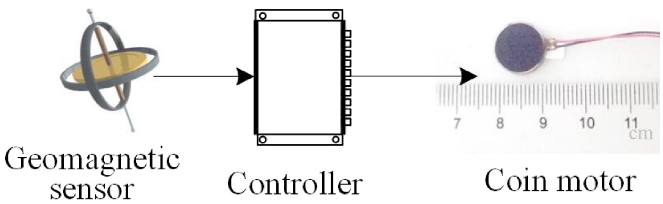

Fig. 1. System block diagram of vibrotactile belt

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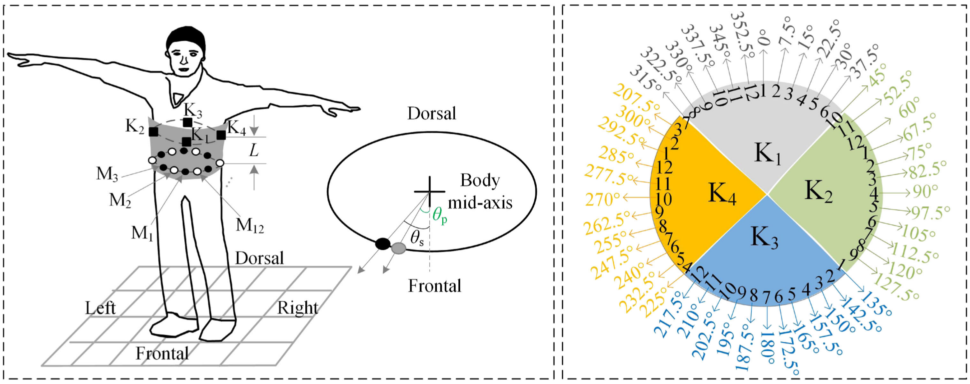
2.1 Arrangement of tactors

The arrangement and number of tactors set around the torso are key to designing vibrotactile belt with fine resolution. According to work of Cholewiak et al., the number of tactors set on one row around the torso must be less than about 8 tactors for achieving a high recognition accuracy [13]. Thus 6 tactors were arranged around the torso (Fig. 2(a) lower tactor row). Since 6 tactors are not enough to spatially indicate directional information with resolution of less 10 degrees, other 4 tactor (Fig. 2(a) upper tactor row) were set around the torso on cardinal sites (frontal, dorsal, left and right), which are easy to be localized and discriminated [12, 19, 10]. The L (14 cm) in Fig. 2(a) is the distance between the upper and lower row, which should be set to higher than the vibrotactile two-point threshold (TPT). The TPT was defined as the minimal distance necessary for a subject to recognize a stimulus pair as two separate stimuli [20].

In Fig. 2(a), black solid filled circles and no filled circles stand for real tactors and victual tactors on lower row respectively. In Fig. 2(b), the number $1, 2, \ldots, 12$ represents $M_1, M_2 \ldots M_{12}$ respectively. As illustrated in Fig. 2(b), the tactor of K_1, K_2, K_3, and K_4 indicates the frontal orientation (gray area), right orientation (light green area), dorsal orientation (light blue area), and left orientation (orange area) respectively. The tactor pairs K_1–M_1, K_2–M_4, K_3–M_7 and K_4–M_8 just corresponds the direction of 0, 90, 180, and 270 degrees respectively. Thus the combination vibration patterns from the two row are easy and intuitive to be recognized into corresponding directions by users, and will not obviously delay the user's response.

To display directions with high precision, we arranged tactors on each row with different angular distance between each adjacent pair. The experimental results obtained by Van Erp show that the bias between the tactor angle (θ_s) and perceived angle (θ_p) changes as a function of tactor angle [12]. The definition of θ_s and θ_p is shown in Fig. 2(a) right. The curve depicting how the bias changes with θ_p is shown in Fig. 3. Thus the θ_s changing with θ_p can be obtained as illustrated in equation (1).



(a) (b)

Fig. 2. Overview of vibrotactile belt and directional coding algorithm. (a) Distribution of tactors around the torso, and schematic diagram of tactor angle and perceived tactor (shown in gray filled circle) angle relative to the center of frontal. (b) Schematic diagram of coding algorithm for displaying directions.

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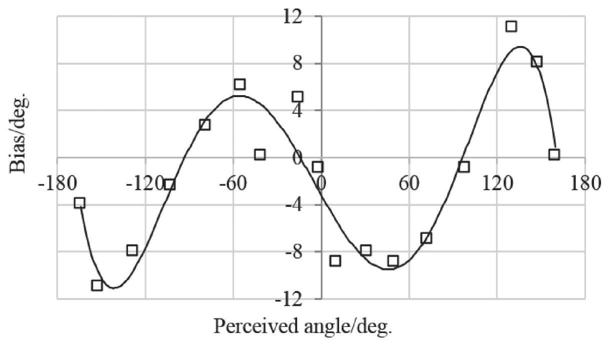

Fig. 3. Bias (θ_p-θ_s) as function of perceived angle, inferred from Van Erp's work [12].

$$\theta_s = \theta_p - f_{tr}(\theta_p) \tag{1}$$

The fitting function ($f_{tr}(\theta_p)$) given by Fig. 3 was called Torso-related transfer function (TRTF). The tactors on lower and upper row are arranged according to equation (1) to make all the tactors to be perceived as equally spaced with 60 and 90 degrees respectively.

To make the belt suitable for people of different waist size and maintain the angular distances calculated according to the TRTF, we selected a highly elastic material (Polyurethane) as the cloth to attach tactors. The natural length (L_{es}, see Fig. 4) of the elastic belt for arranging tactors was set to 55 cm, which is the minimum size of standard Chinese adults' wrist circumferences. [21] The elastic belt should be spread naturally on a hard plane without any stretching before the tactors are bonded to the belt using strong adhesive. For the convenience of arranging tactors on the belt, the angular difference ($\alpha_{s(i)} = \theta_{s(i+1)} - \theta_{s(i)}$) between each adjacent pair of tactors was converted to corresponding distance ($D_{s(i)}$) as shown in equation (2).

$$D_{s(i)} = \frac{\alpha_{s(i)}}{\sum_{i=1}^{n} \alpha_{s(i)}} \cdot L_{es} \tag{2}$$

Where i $\in [1, 2, 3, 4, 5]$, n $= 5$ for lower row; i $\in [1, 2, 3]$, n $= 3$ for upper row. By substituting the $\theta_p = [0, 60, 120, 180, 240, 300]$ and $\theta_p = [0, 90, 180, 270]$ degrees to the equation (1), the arrangement distances for lower and upper row can be obtained respectively ($D_{su(i)}$s, $D_{sl(i)}$; see Fig. 4).

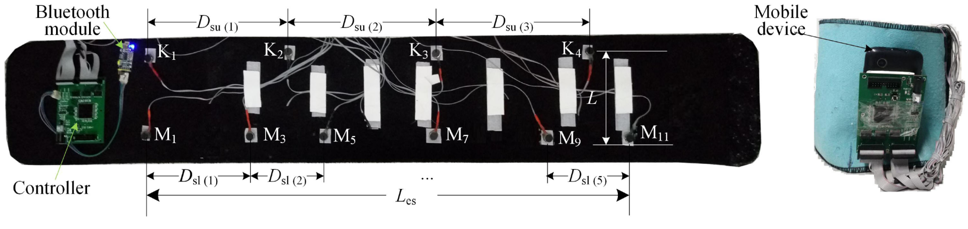

Fig. 4. The arrangement of tactors (left) and the prototype of vibrotactile belt (right). Geomagnetic sensor was integrated in a mobile device. Directional signal detected by geomagnetic sensor was transmitted to the controller through Bluetooth. All the tactors and the controller were powered by the battery in the mobile device.

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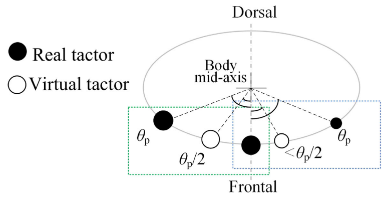

Fig. 5. Schematic diagram of vibrotactile funneling illusion on torso. The size of the tactor indicates the perceived intensity of vibration.

2.2 Vibrotactile coding algorithm

The coding algorithm is key for a effective vibrotactile display. An intuitive and well-perceivable coding algorithm can reduce training time and increase user acceptance of the vibrotactile display. In current work, the vibrotactile funneling illusion was used to increase the resolution of displaying direction.

As indicated in previous psychophysical experiments [22], when two adjacent vibrotactile stimuli are applied on skin, subjects tend to perceive a vibration locating between them. Thus two adjacent tactors could be activated simultaneously to produce an intermediate sensation to increase resolution of displaying direction [11]. This sensation phenomena called vibrotactile funneling illusion can be used to generate a virtual tactor shown in no filled circles in Fig. 2(a) between each adjacent pair. When two adjacent tactors vibrate with same intensity on torso (green dotted box in Fig. 5), the vibration will be felt as a virtual tactor locating at middle of them [23]. When two adjacent tactors vibrate with different intensity (blue dotted box of Fig. 5), the location of the virtual tactor will approach the real tactor which has the stronger perceived intensity [24]. In current work, we used mid-point vibrotactile funneling illusion to double the number of tactors on lower row as illustrated in Fig. 2(a) (labeled with $M_1, M_2, \ldots, M_{12}$).

As illustrated in Fig. 2(b), The direction is intuitively cued by the tactor pair on upper and lower rows. The four tactors: K_1, K_2, K_3 and K_4 on upper row determine the four orientations: $[-45, 45), [45, 135), [135, 225), [225, 315)$ degrees respectively. The tactors on lower row determine the accurate direction in each orientation. Specifically, the direction of 0 degrees was cued by activating the K_1 and M_1, direction of 7.5 degrees was cued by activating the K_1 and M_2, and so forth. For convenience of controlling motors on two rows, the coding algorithm as shown in Fig. 2(b) was converted into the equation (3).

$$\begin{cases} i_u = \left\lfloor (D_p \geq 315) \cdot \dfrac{360 - D_p}{360/N_u} + (D_p < 315) \cdot \dfrac{D_p + 45}{360/N_u} + 1 \right\rfloor \\ tmp = \left\lfloor \dfrac{D_p - \left\lfloor \dfrac{D_p}{360/N_u} \right\rfloor \cdot (360/N_u)}{360/(N_u \cdot N_l)} + (N_u - 1) \cdot (i_u - 1) + 1 \right\rfloor \\ i_l = (tmp \leq 12) \cdot tmp + (tmp > 12) \cdot (tmp - 12) \end{cases} \tag{3}$$

Where "$\lfloor\ \rfloor$" is the bracket function. $D_p \in [0, 360)$ is the direction detected by geomagnetic sensor. $i_u \in [1, 2, 3, 4]$, $i_l \in [1, 2, \ldots 12]$ is the activating location on upper and lower row respectively. $N_u(4)$ and $N_l(12)$ is the total number of tactor set

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on lower row and upper row respectively. The above equation is the algorithm of activating the tactor, which can be easy written in the controller of vibrotactile belt. For instance, by substituting $D_p = 330$ into above equation, the activating locations ($i_u = 1$, $i_l = 9$, i.e., K_1, M_9) on two rows can be calculated, which corresponds to the coding diagram in Fig. 2(b). As seen from the middle trace of equation (3), the vibrotactile belt enable users to receive vibrotactile directional instructions with a high resolution up to 7.5 ($360/(12 \times 4)$) degrees.

In order to enhance the effectiveness of coding precise directional information, the temporal and intensity parameters of activating tactors on the two rows should also be considered. Previous vibrotactile studies indicated that localization of vibrotactile stimulus improves with the duration of stimulus (DoS) ranging from 80 ms to 320 ms [25]. The vibrotactile information will be fragmentary if the DoS falls below that range [26], hence the DoS was set to 300 ms in current study. The funneling illusive effect between the tactors in the upper and lower rows should be wakened by increasing the distance between upper and lower row, it may affect subjects' discrimination of vibration locations on upper and lower row. The distance between upper and lower rows was set to 14 (cm) which is higher than two-point threshold. In this condition, the funneling sensation is faint. Considering the easiness of discriminating vibration patterns, the intensity was set to be strongest (100% dc duty) in the current study.

3 Psychophysical experiment

The psychophysical experiment was conducted in a static environment in which subjects wearing our belt perceive the vibration patterns encoding directional commands presented by a computer software. The objective of the experiment is to verify the feasibility of the vibrotactile belt in displaying precise directional information.

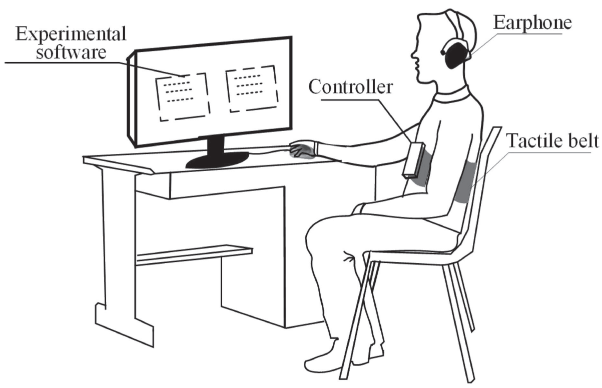

Fig. 6. Experimental setup

3.1 Experimental setup

20 subjects (15 males, 5 females) participated in the two experiments. Their ages ranged from 20 to 30 years, all of whom were right-handed and reported having no known cutaneous or kinesthetic problems. During the experiment, subjects were prompted to sit comfortably on a chair. They were asked to wear headphones playing white noise (Fig. 6).

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The metrics of recognition accuracy, and reaction time were implemented to evaluate the effectiveness of the vibrotactile belt for cueing direction information. Recognition accuracy (%) is defined as percentage of the number that subjects report a direction correctly to the total number of presenting the direction. In the experiment, each of direction is presented repeatedly for all the subjects. This definition can be found in previous studies of vibrotactile localization on torso [10, 27]. Their experimental results also indicated that the higher accuracy the closer user's perceived direction approach to the corresponding presented direction. Thus recognition accuracy defined by the correct percentage is statistically equivalent to the average deviation error. Reaction time (second) is defined as the elapsed time between starting the presentation of a vibrotactile command and the moment that subject has reported an angle in response. The reaction time here includes cueing time taken for presenting a complete vibrotactile command and the time for the subject's brain to process the input signal and take action. It should be noted that the time taken for a subject to report his perceived direction is not included in the reaction time. Subject report perceived direction by clicking radio button, and the time taken for clicking button can be recorded in a experimental software.

3.2 Experimental procedure

Before starting the formal experiment, All the subjects were required to train for 2 hours to memorize vibration patterns encoding directions. Vibration patterns encoding 48 directions were presented randomly to subjects. Each vibration pattern was repeated 3 times. Hence a total number of 144 trials (repeated times × tactor number on lower row × tactor number on upper row) were performed for each subject. At the end of each trial, the subject is required to report the direction by clicking radio button within 6 s. To reduce the practice and habituation error easily occurring in psychological experiments [28], a random vibration pattern different from before was given to the subject if the subject can not report within 6 s. No feedback on recognition accuracy was provided during each trial. In each trial, the subject's reported direction and reaction time were automatically recorded by a experimental software.

3.3 Experimental results

The results of average recognition accuracy and reaction time for each presented direction are depicted with a radar graph as shown in Fig. 7. The average recognition accuracy across all presented directions was approximately 91.84 percent (sd: 7.12%). The average reaction time across all presented directions was 1.17 seconds (sd: 0.12 seconds).

In accordance with previous studies of vibrotactile belts [11, 9, 12], the cardinal directions (0, 90, 180 and 270 degrees) were easier to be discriminated than other directions. The closer that a direction approaches one of the cardinal directions, the higher recognition accuracy and shorter reaction time. There was no significant difference between the real and virtual tactors with regards to both recognition accuracy and reaction time. Overall, the vibrotactile belt using funnel tactile illusion can achieve a recognition accuracy of 91.8% (see Fig. 7(a)) with reaction time less than 1.2 seconds.

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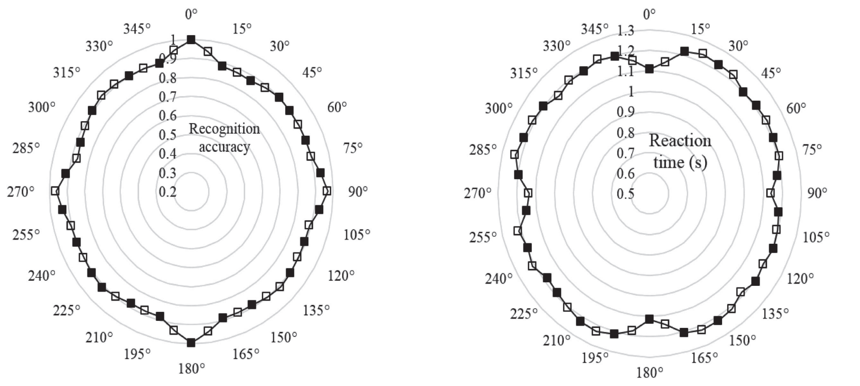

Fig. 7. Experimental results of average recognition accuracy (a) and reaction time (b) over presented directions. Solid filled markers indicate directions cued by real tactors, no filled markers indicate directions cued by victual tactors.

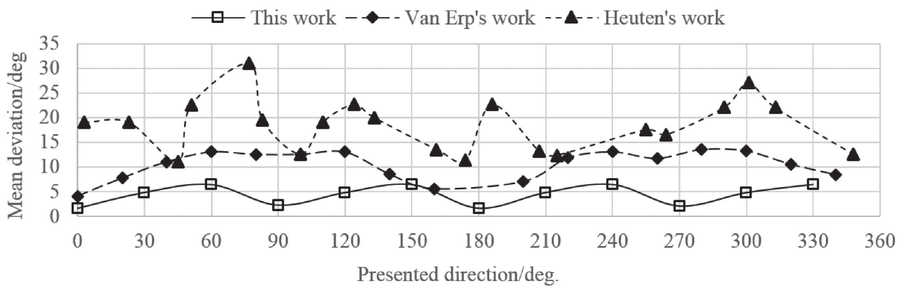

Fig. 8. Mean deviation for each presented direction compared to Heuten's work [11] and Van Erp's work [12]

As a review of previous torso-worn vibrotactile displays, the vibrotactile belt designed by Heuten et al. displayed directions with a median deviation of 15 degrees, which may be the lowest deviation in reported vibrotactile belts. The TRTF used to arrange the tactors around the lower row of our belt was originally proposed by Van Erp et al., but they did not carry further research to verify its effectiveness. To evaluate the effectiveness of implementing TRTF and the proposed coding algorithm, a figure depicting the average deviation (the absolute difference between presented and perceived angle) across cued directions by different belts was given. As seen in Fig. 8, our vibrotactile belt showed a much lower mean deviation than the Heuten's work. Although the mean deviation at the cardinal directions (e.g. abdomen and dorsal) is still significantly lower than other directions, the mean deviation curve over all directions is more evenly distributed than that in Van Erp's work. What is more important is the proposed coding algorithm has achieved great improvement on resolution and recognition accuracy compared with previous work, suggesting that the TRTF can indeed improve the effectiveness of tactile devices used on the torso.

4 Discussion and conclusion

In this study, we have designed a vibrotactile belt by implementing TRTF, and experimentally investigated the effectiveness of the proposed coding algorithm in

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displaying precise directional information. The vibrotactile belt is low price, easy to implement and enable users to receive vibrotactile directional commands with a resolution of 7.5 degrees.

In current study, sighted subjects wearing blindfold were asked to train the system for two hours, which may be too long in practice. However the vibrotactile belt is feasible in practice, since subject need not to be trained when the they are already proficient in the our proposed vibration patterns encoding directions. Besides the vibrotactile belt is mainly used for visually impaired. Blind people are generally more skilled to use vibrotactile cues than sighted people [29].

In future, we will further improve the resolution of the belt by implementing continue coding algorithm based on funnel tactile illusion with one tactor row. Specifically, the direction of 0 degrees can be coded by activating the tactor M_1 (Fig. 2(a)) with maximum intensity and switching off tactor M_3. If the direction turns continuously from 0 to 60 degrees, the intensity is reduced for M_1 tactor and increased for M_3 tactor accordingly. At direction of 30 degrees, both of two was activated with same intensity. Using this continue coding algorithm, directional resolution will be greatly improved. And this coding algorithm can be easily implemented though rewriting a program without changing the hardware of the system.

Finally, it should be noted that there are many other applications that may benefit from this vibrotactile belt such as backing up large vehicles, firefighting or landing aircrafts. Helicopter pilots and truck drivers frequently maneuver large vehicles in crowded environments with a variety of confusing stimuli that can lead to accidental control reversals or directional errors. The vibrotactile belt with fine resolution may help to improve situational awareness, thus preventing accidents.

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