Motion Control of Cycling Wheelchair With Continuously Variable Transmission and Clutch

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A Phantom-Sensation Based Paradigm for Continuous Vibrotactile Wrist Guidance in 2D Space

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Abstract— **Vibrotactile feedback has long been used to improve the human motor learning process through information transfer. However, in most of the approaches described in the literature, only the joint angles of the limb are guided. To guide motions that involve multiple degrees of freedom (DOFs), the user needs to interpret multiple simultaneous vibrotactile cues (at least one cue per joint), which is difficult. In this paper, we guide the user's wrist position in space producing a vibrotactile cue at any place around the wrist by using a vibrotactile illusion known as "Phantom Sensation" (PS). In a user study, the vibrotactile cues produced by PS were located with reasonable accuracy with an average error of $7.869°$. To maintain consistency between the vibrotactile cue location and the global frame, we measured the user's wrist rotation and adjusted the position of the vibrotactile cue accordingly. The subjects recognized the location of the vibrotactile cue even while rotating their hand with an average error of $9.305°$. By using the proposed feedback paradigm, we guided users' wrists in space. In this experiment, we measured the subjects' motion path efficiency (ME) under two conceptual mappings ("push" and "pull"). The ME measures the directness of the user's wrist moving toward the desired position. The subjects reached the desired positions under the vibrotactile feedback alone. The average MEs of the "push" and "pull" mappings were 44.26% and 52.41%, respectively.**

I. INTRODUCTION

Traditionally, humans learn a motion or motor skill by receiving instructions and feedback from a more experienced person. Vibrotactile technology has been widely explored as a real-time feedback mechanism for enhancing the feedback and the motor learning process during a motion. However, most of the reported approaches guide the motion by coordinating human joints' angles in joint space. When coordinating the motion of an arm (for instance), these approaches require the user to interpret several simultaneous vibration cues applied at different places.

In this research, we propose a feedback paradigm that provides a steady vibrotactile cue at any point around the wrist, thereby guiding the wrist as an end-effector in a two-dimensional space. To produce the cue at any point, we use a vibrotactile illusion known as "Phantom Sensation" (PS). Our approach advances haptic feedback technology in the following ways: (1) Instead of coordinating each joint angle, we apply a single vibrotactile cue to the wrist. By using the directional information provided by the cue, the user can adjust the wrist position or trajectory. (2) Under this guidance, the user needs to only interpret a single localized vibration, rather than multiple simultaneous cues at different places. (3) As the vibrotactile cue is steady and its position can be arbitrarily changed, information about the position/trajectory errors can be conveyed instantaneously. (4) The location of the vibrotactile cue is adjusted by referring to the user's wrist angle; therefore, its direction remains consistent with the world coordinate frame.

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II. RESEARCH BACKGROUND

A. Feedback in Motor Learning

Motor learning is the process by which humans explore the different parameters of the motion (e.g., movement duration, force, joint angle) and vary these parameters to produce different motion outputs [1]. During this process, feedback is very important as it allows the subject to understand the relationship between the parameters and the resulting motion [2]. Improving the motor learning process, in particular by enhancing the feedback provided to the trainee, has attracted much interest in recent years [3].

Feedback in motor learning can be classified as intrinsic (arising from the trainee's proprioception) or extrinsic (related to the external motion information) [4]. Extrinsic feedback is usually perceived through multiple senses, such as vision (visual feedback), hearing (auditory feedback), and touch (haptic feedback).

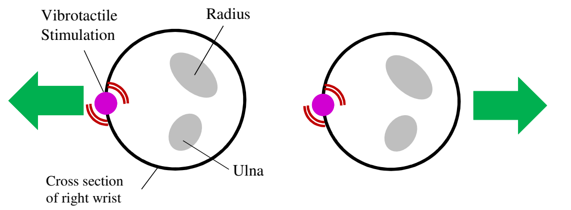
Haptic feedback is the process of "conveying information by applying forces, vibrations, or motions to the user" [5]. Haptic interfaces are of particular interest, as (unlike the other senses) the touch sense is distributed throughout the body. In addition, the touch sense is said to be up to twenty times faster than vision [6].

Aiding the motor learning process by haptic feedback is known as "Haptic Training" [7]. The training can be passive (when a motion or trajectory is driven by forces applied to the user) or active (when the user performs the motion using his own muscles).

B. Vibrotactile Feedback

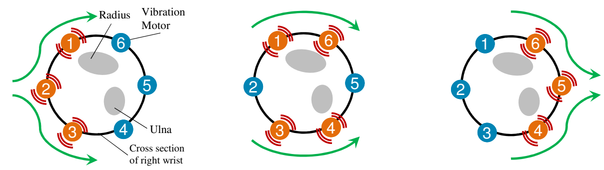
In active haptic training, the haptic feedback is commonly produced by vibrotactile actuators, which are popular for their small size and comparatively low cost. Small size is especially convenient when performing activities, as motion information can be conveyed in real time without impeding the user.

In an extensive study, Stanley et al. [8] applied five haptic cues to the skin (tapping, squeezing, dragging, twisting, and vibrating) and evaluated their performance in guiding the wrist rotation. Overall, the best guidance was provided



(a) "Pull" conceptual mapping (b) "Push" conceptual mapping

Fig. 1: "Push/pull" conceptual mappings



(a) $t = t_0$ (b) $t = t_1$ (c) $t = t_2$

Fig. 2: Activation sequence of generating a direction sensation

by a pulsing tap on both sides of the wrist. However, steady vibration elicited a very fast response and direction recognition (less than 0.5 s).

Vibrotactile feedback has been applied to diverse tasks, such as correcting the bowing motion during violin playing [9], snowboarding [10], boat rowing [11], percutaneous needle insertion [12], and rehabilitation of stroke patients [13]. Each of these motions requires a different conceptual mapping, which defines the way in which subjects map the vibrotactile cues with the target motion. Most commonly, the cues are localized near the joint and individually mapped onto a defined joint motion.

In Van Der Linden et al.'s study, a violin player was trained to move the bow up and down when sensing a vibration at the back of the elbow and at the wrist, respectively [9]. In this mapping, often referred to as the "push" or "repulsion" metaphor, the user should move the stimulated joint in the opposite direction to the vibrotactile cue (Fig. 1b). The other analog (the "pull" or "attractive" metaphor) is also frequently applied (Fig. 1a). In a comparison study of these two mappings for a gait retraining task, subjects preferred the "pull" mapping [14].

C. Conceptual Mappings using Vibrotactile Illusions

More intuitive mappings can be achieved by vibrotactile illusions such as saltation. Lieberman et al. [15] proposed a system that guides the user's arm toward a certain position by vibratory cues. Elbow flexion/extension, wrist abduction/adduction, and wrist flexion/extension are guided by "push" mappings, whereas circular sensations around the wrist and elbow are generated by saltation effects, which provide information about the joint rotation angle. The error magnitude is reflected by changes in the vibration amplitude. The study reported that vibrotactile feedback lowers the real-time error and improves the learning rate by up to 23%.

McDaniel et al. [16] created two new conceptual mappings based on saltatory vibration patterns, which they named "push/pull" and "follow me". In the "push/pull" mapping, a user should "push" or "pull" the limb that runs parallel to the perceived saltatory illusion. Alternatively, the "follow me" mapping directs the user to move the limb that was stimulated along the direction indicated by the saltatory pattern. The effectiveness of each mapping was tested in eight different motions (elbow flexion/extension, forearm pronation/supination, wrist flexion/extension/abduction/adduction). The saltatory "push/pull" metaphor was found to be the most natural for elbow flexion/extension, while the "follow me" metaphor was considered more natural for the other motions (forearm and wrist). Jin et al. [17] compared the performance of the saltatory "push/pull" metaphor with those of visual and acoustic feedbacks.

The present paper extends our previous work [18], in which a conceptual mapping named Direction Sensation produced a moving sensation around the forearm (in any direction) using two vibrotactile illusions. Similar to McDaniel's "follow me" metaphor, this mapping guides the motion of the forearm in the direction conveyed by saltatory patterns around both sides of the forearm (see Fig. 2). The produced direction depends on the start and end points of the saltation effect. When no vibrotactile actuator is placed at the start and end locations of the saltation effect, virtual vibrotactile cues are produced using the PS vibrotactile illusion (for details, see Israr et al. [19]).

However, the users' reaction time to the saltatory effect (usually between 2.5 s and 4.5 s) is considerably longer than that of single vibrotactile cues (200–500 ms) [20]. This time delay is the greatest disadvantage of our previous work. Therefore, although the saltatory approach can convey any direction around the arm, any motion error incurred during the propagation of the saltatory effect cannot be conveyed until the next saltatory effect. Consequently, users' motions are intermittent and the time of reaching the target positions is lengthened. These problems degrade the performance of tasks such as trajectory following and position guidance.

D. Joint Space Guidance

Several models purport to describe the motor learning process. Early models, such as Adam's Closed Loop Theory [2], propose that humans learn specific "motor programs" for each movement. Later, Schmidt [1] proposed that instead of a 1:1 mapping between motions and motor programs, humans study the relationship between motion parameters (such as joint angle, force, and duration) and the resulting motion and create generalized motor programs.

In these models, the parameters are varied to obtain the resulting motion and are assumed to be consciously observed and controlled by the human brain. Localized vibrotactile feedback is consistent with this concept because each vibrotactile cue around the body can be associated to a motion parameter.

However, when guiding a motion involving several degrees of freedom (DOFs), such as the swing of a tennis racket, the subject should recognize and interpret simultaneous vibrotactile cues in different joints (wrist, elbow, and shoulder). Increasing the number of vibrotactile cues to be recognized by the user increases the trajectory-following error of the arm [20].

E. End-effector Space Guidance

In a more recent model known as the leading joint hypothesis (LJH), motor learning is described as the process of discovering the biomechanical properties of the body, which are exploited by the central nervous system to achieve a desired goal [22]. The LJH model proposes that one joint (usually the proximal joint) leads the motion and that the other (subordinate) joints control the movement speed, direction, and accuracy of the desired end-effector motion [21]. According to the LJH, the body automatically selects the appropriate joint torques to suit the characteristics and requirements of the motion of the end-effector.

Some haptic guidance approaches consider guiding the trajectory of the end-effector (human hand or foot) rather than the joint angles [23], [24]. In these approaches, feedback is provided near the end-effector (hand, wrist, or handled tool). Therefore, these systems can guide a high-DOF motion using a single feedback cue. Most of these approaches use force feedback, but Basu et al. proposed a vibrotactile guidance system in the end-effector space for percutaneous needle insertion [12]. They compared vibrotactile guidance in joint space, Cartesian space, and tool space and identified tool space guidance as the most effective vibrotactile approach for the needle-insertion task.

III. WRIST GUIDANCE APPROACH

A. Motion Guidance Paradigm Overview

In this research, we propose a vibrotactile feedback paradigm that produces a single vibration around the wrist. Different from existing approaches, the vibrotactile cues are PS vibrotactile illusions, which can be produced anywhere around the wrist.

Vibrations in a certain direction around the wrist are easily generated if the direction coincides with the location of a vibration motor. When that vibration motor is activated, the subject will feel the vibration at the site of the actuator.

When the above condition is violated, we produce a “virtual” vibration stimulus in the skin using the PS vibrotactile illusion. This illusion occurs when two closely spaced vibration motors in contact with the skin are actuated simultaneously; therefore, the subject feels a single stimulus at the midpoint of the two vibration motors. The “virtual” stimulus position can be controlled by weighting the amplitudes of both actuators, as proposed by Israr et al. [19].

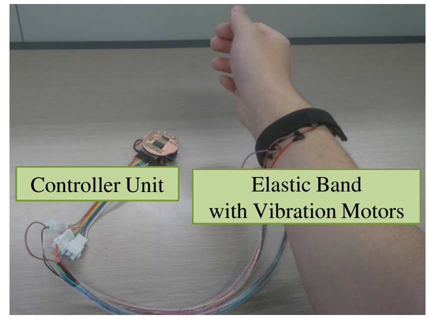


Fig. 3: Vibrotactile feedback device

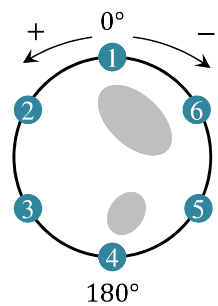


Fig. 4: Arrangement of vibration motors around the wrist (large and small gray ovals denote the radius and ulna, respectively)

B. Haptic Device for Wrist Guidance

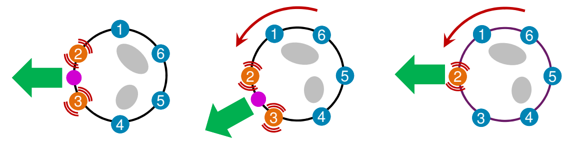
To test the proposed vibrotactile feedback approach, we arranged six vibration motors in an elastic band worn around the wrist. Fig. 3 shows the vibrotactile feedback device. The space between the actuators (approximately 3 cm) is evenly distributed, and within the maximum distance in which a PS can be produced [25]. The vibrotactile actuators are pancake-type eccentric FM34F motors manufactured by T.P.C. The distribution of the motors is shown in Fig. 4.

The amplitude of each actuator is controlled by pulse width modulation (PWM). The actuator’s maximum frequency is 216.6 Hz at its maximum amplitude, close to the peak sensitivity of Pacinian corpuscles (approximately 250 Hz [26]). The driving hardware is an Adafruit Flora Microcontroller connected to a 12-bit PWM driver (PCA9685) through I^2C. The motors are controlled through the PWM output and a Darlington Array to provide sufficient current. The device communicates with a PC through a Bluetooth module (HC-06).

When worn on the wrist, Motors 1 and 4 are aligned with the radius and the ulna, respectively, as shown in Fig. 4. The angles around the wrist range from $-180°$ to $180°$, referenced to the radius. According to this definition, the vibrotactile actuators are situated at $0°$ (the radius), $\pm 60°$, $\pm 120°$, and $180°$.

C. Rotation Angle of the Wrist and Effect on Feedback

Under the proposed approach, the produced direction coincides with the direction in the global coordinate system only if Motors 1 and 4 form a line perpendicular to the



(a) Vibrotactile cue at 90°
(b) Wrist rotates 30° anticlockwise
(c) Vibrotactile cue location changes to keep 90° between the cue and the global coordinate system

Fig. 5: Rotation effect of the wrist and its compensation

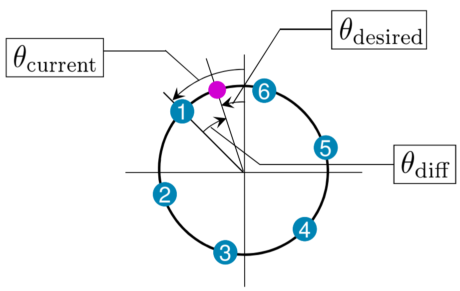


Fig. 6: Schematic of the wrist's rotation

ground (Fig. 5a). When the subject rotates the wrist, the application site of the vibration moves accordingly (Fig. 5b), changing the direction of the perceived vibration. To resolve this problem, i.e., to ensure a constant direction in the global coordinate system, we need to consider the wrist's rotation angle and accordingly control the position of the vibrotactile cue (Fig. 5c).

The wrist's rotation angle was measured by a 3D motion-sensor device known as Leap Motion, which measures the movements of hands and fingers. It is worth noting that the Leap Motion can be replaced by other systems that can estimate the wrist rotation, such as motion capture systems, tracking suits or IMUs, and it's not intended as a final solution to the wrist tracking issue. A diagram of a rotated wrist is shown in Fig. 6. The angle measured by Leap Motion is θ_{current}, and the intended direction of the vibrotactile cue (w.r.t. the global coordinate system) is θ_{desired}. In the local coordinate system of the wrist, the cue direction is the difference between these two angles, namely, $\theta_{\text{diff}} = \theta_{\text{desired}} - \theta_{\text{current}}$. The motors to be activated are then determined under the criteria shown in Table I, and the amplitude of each motor is calculated using the Energy Model proposed by Israr et al. [19].

D. Wrist Guidance in 2D Space

To guide the wrist in space, our approach maps the produced vibrotactile cues around the wrist to either "push" or "pull" conceptual mappings. Users are taught to move along with or opposite to the vibrotactile cue.

In this research, the motion space of the wrist is defined as the x-y plane parallel to the frontal plane. As depicted in Fig. 7, the direction $\theta(t)$ from the wrist position toward the

TABLE I: Correspondence between θ_{diff} and the activated motors

θ_{diff}	Actuated Motors
$-180°$ to $-120°$	Motor 4 & Motor 5
$-120°$ to $60°$	Motor 5 & Motor 6
$-60°$ to $0°$	Motor 6 & Motor 1
$0°$ to $60°$	Motor 1 & Motor 2
$60°$ to $120°$	Motor 2 & Motor 3
$120°$ to $180°$	Motor 3 & Motor 4

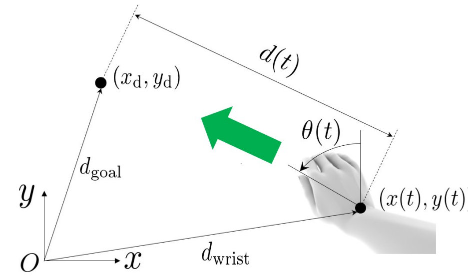


Fig. 7: Wrist Motion in the Frontal Plane

desired position in this plane is given by

$$\theta(t) = \begin{cases} \dfrac{\pi}{2} + \arctan\dfrac{y_{\text{d}} - y(t)}{x_{\text{d}} - x(t)} & \text{if } x_d - x(t) < 0 \quad \text{(1a)} \\ \dfrac{\pi}{2} - \arctan\dfrac{y_{\text{d}} - y(t)}{x_{\text{d}} - x(t)} & \text{if } x_d - x(t) > 0 \quad \text{(1b)} \\ \dfrac{\pi}{2} - \text{sgn}(y_d - y(t)) \cdot \dfrac{\pi}{2} & \text{otherwise,} \quad \text{(1c)} \end{cases}$$

where $(x(t), y(t))$ is the wrist position and $(x_{\text{d}}, y_{\text{d}})$ is the desired position. After calculating the direction to be conveyed using Eq. (1a)-(1c) and considering the wrist angle, we determine which vibrotactile actuators should be activated to produce the vibrotactile cue. However, the subject cannot infer his or her distance to the desired position from the direction alone. Therefore, we also calculate the amplitude of the produced vibration as a function of the distance between the wrist and the desired position. The vibration amplitude A_{v} is calculated as

$$A_{\text{v}} = A_{\text{min}} + K_{\text{d}} d(t), \quad (2)$$

where A_{min} denotes the minimum amplitude, K_{d} is the feedback gain of the proportional control, and $d(t)$ is the distance between the current and desired positions. The feedback gain K_{d} was tuned so that A_{v} took a value between the maximum amplitude A_{max} and the minimum amplitude A_{min}. According to Eq. (2), the vibration amplitude increases and decreases as the wrist position retreats from and approaches the desired position, respectively. At the desired position, the vibration stops.

IV. EXPERIMENTAL STUDY

A. Vibrotactile Cue Direction Recognition

In this experiment, we evaluated whether subjects can accurately understand the direction indicated by the vibrotactile cue, and whether the proposed method properly compensates the wrist's rotation angle. The participants were ten males

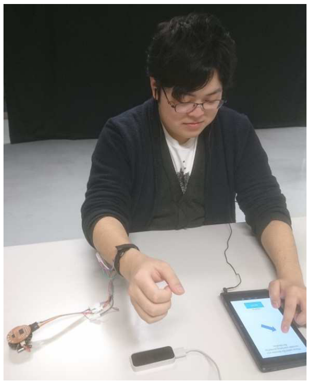


Fig. 8: Experimental setup

(aged 21–30) with no history of physical or neurological disorders. The subjects were requested to wear the haptic device on the right wrist and headphones playing pink noise to mask the sounds generated by the vibrotactile actuators (Fig. 8).

The subjects were presented with eight different directions (0°, ±45°, ±90°, ±135°, 180°) that were produced six times each in a random order, thus totaling 60 samples per direction. Each vibrotactile cue was produced for 5 s. Subjects were requested to select their perceived direction of the vibration using a dial displayed on a tablet device. The dial's precision was 1°.

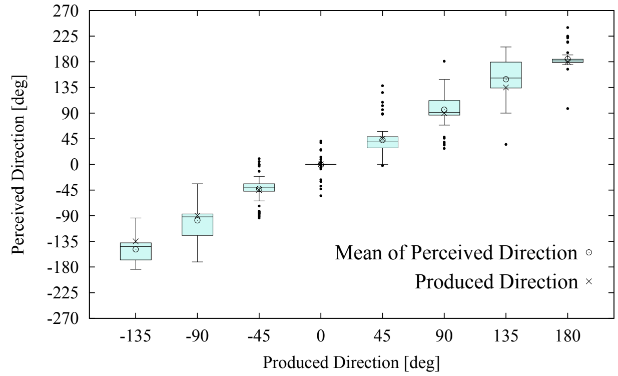
The experiment was divided into two tasks:

- Task A- Recognition with fixed wrist: in this task, the wrists of the subjects were fixed and the rotation angle was not considered. This task revealed whether PS effectively creates virtual cues in arbitrary directions.
- Task B- Recognition while rotating the wrist: in this task, the wrist rotation angle was considered, and the vibrotactile cue position was adjusted to maintain a direction with respect to the global coordinate frame. Users were requested to rotate their wrist, and then answer the perceived direction.

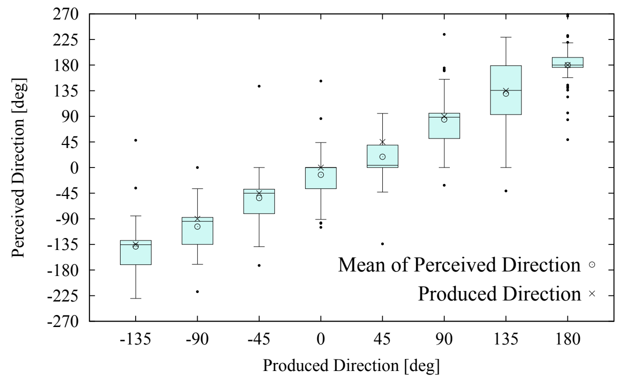
The results of Tasks A and B are shown in Fig. 9a and Fig. 9b, respectively. In Task A, the most well-recognized directions were 0° and 180°. This result is natural, as vibrotactile actuators 1 and 4 align in these directions. However, as confirmed by the differences between the produced directions and the means of the perceived directions, subjects also recognized the vibrotactile cues in the directions generated by PS. The average error of all directions was 6.606°. This average error increases to 7.869° after excluding the directions 0° and 180°, which are not produced using PS.

In Task B, the distributions of the answers became more scattered, probably because of the delay in actuating the vibration motors. After applying the driving voltage, the eccentric mass motors (FM34F) need approximately 100 ms to reach the desired amplitude. Therefore, the motors might lag behind the rotation speed of the wrist, causing subjects to perceive a different direction.

Despite the wider distributions, the mean of the perceived direction remained close to the produced direction. The



(a) Task A - Recognition with fixed wrist



(b) Task B - Recognition with rotating wrist

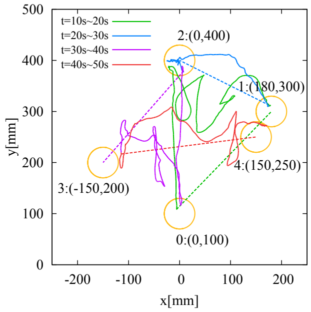
Fig. 9: Distribution of direction recognitions for each presented direction. Blue boxes represent the interquartile range (IQR), which contains 25 to 75% of the data (P_{25} and P_{75}). The line inside the boxes represents the sample median. Points represent samples outside ± 1.5IQR

average error in this task was 9.305°, quite similar to the average error in Task A. Thus, we consider that the wrist's rotation is adequately compensated to maintain the correct direction with respect to the global coordinate system.

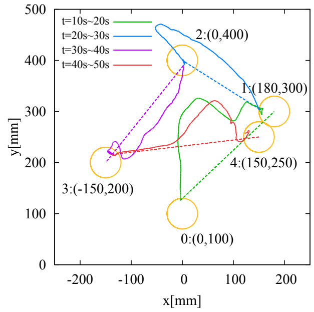
B. Experiments on Wrist Guidance

Next, we tested whether the same ten subjects could guide their wrist in space following the proposed vibrotactile cues. By using the proposed feedback approach under both "push" and "pull" conceptual mappings, the subjects were expected to reach four positions in the x-y plane in an interval of 10 s. Results of the experiment for one user under both mappings are shown in Fig. 10. The position was considered to be reached when $d(t)$ was within 30 mm of the target position (i.e., a radius r =30 mm deadband area). When the wrist reached the desired position and the vibration stopped, the subject was requested to wait until the desired position changed at the end of the interval.

Each task was completed three times for each conceptual mapping. To avoid task-learning bias, the order of the conceptual mappings was balanced among the subjects. The first two repetitions were intended as practice runs to familiarize the subjects with each conceptual mapping, and the desired positions were set randomly.



(a) "Push" conceptual mapping



(b) "Pull" conceptual mapping

Fig. 10: Experimental task results of Subject A. Starting from (0, 100) mm, the subjects were required to reach positions (x_d, y_d)=(180,300), (0,400), (-150, 200) and (150, 250) mm by mapping the vibrotactile cues using the "push" and "pull" metaphors. The dotted lines represent the optimal distance toward the next point. Subjects move to the initial position in the time interval $0 \sim 10$ s

1) Numerical results: The experimental results of six subjects are presented in Fig. 11. In most cases, the subjects reached the desired positions by using the proposed feedback. Moreover, when the subjects overshot the target boundaries, the proposed approach allowed them to correct their wrist position.

The performances of the users guided by each conceptual mapping were evaluated by the motion path efficiency (ME), which measures the directness of the subject's motion while traveling to a desired position [27]. In other words, a 50% ME ratio would mean that the user traveled twice the distance of the optimal trajectory. The ME is calculated as

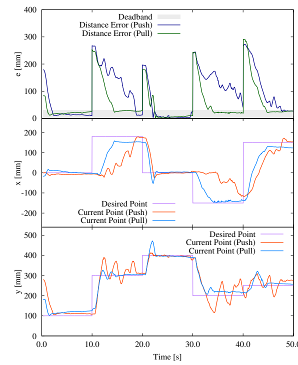
$$ME(\%) = \frac{E_P}{U_P}, \tag{3}$$

where E_P is the Euclidean distance between the start of the motion and the desired position (the shortest route) and U_P is the distance traveled by the user's wrist. The wrist position when a new target position is presented defines the start point of the motion. The distance E_P is measured from the start point to the deadband boundary, and U_P is calculated by summing the Euclidean distances between consecutive data points of the subject's traveled path until reaching the deadband (sampled at 50 Hz):

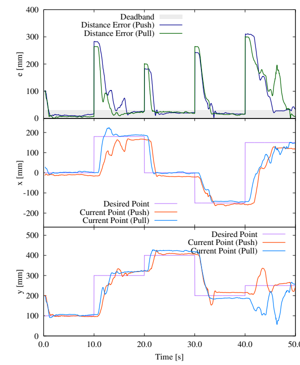
$$U_P = \sum_{i=0}^{n} \sqrt{|X_i - X_{i+1}|^2 + |Y_i - Y_{i+1}|^2}. \tag{4}$$

The calculated MEs for each user under both conceptual mappings are displayed in Fig. 12. The average MEs in the "push" and "pull" approaches were 44.26% and 52.41%, respectively.

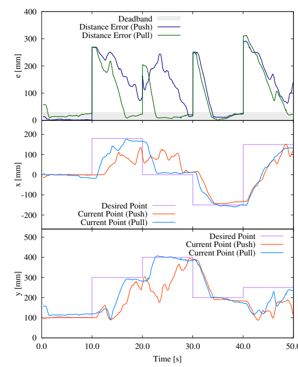
2) Qualitative results: After completing the tasks, the subjects were asked to comment on each mapping. Four participants preferred the "push" approach, whereas five preferred the "pull" approach. The remaining participant did not state a preference. Four out of the five subjects preferring the "pull" approach showed a larger ME under



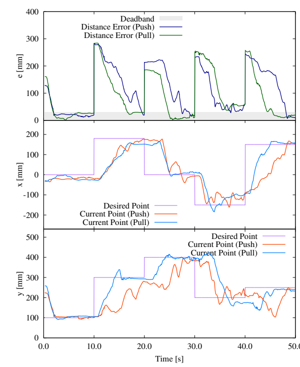
(a) Subject A



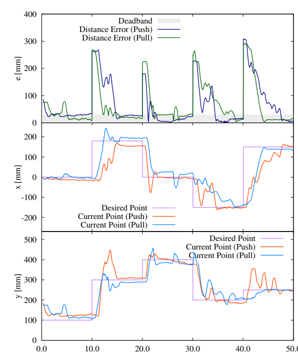
(b) Subject B



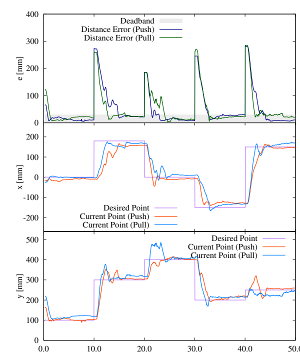
(c) Subject C



(d) Subject D



(e) Subject E



(f) Subject F

Fig. 11: Experimental results of the wrist guidance experiment

their favored mapping. Only one out of the four participants favoring the "push" approach performed better under this mapping. When inquired of the reasons for their preference, users who favored the "pull" approach commonly stated that under the "push" mapping, they needed to determine the opposite direction of the vibration, which required some time. Those who favored the "push" approach seemed to concur that moving to where no vibration was felt was easier than recognizing the exact position of the vibration.

V. CONCLUSIONS AND FUTURE WORK

We proposed a vibrotactile feedback method that guides the subject's wrist through space. The proposed approach is based on a vibrotactile illusion known as "Phantom Sensa-

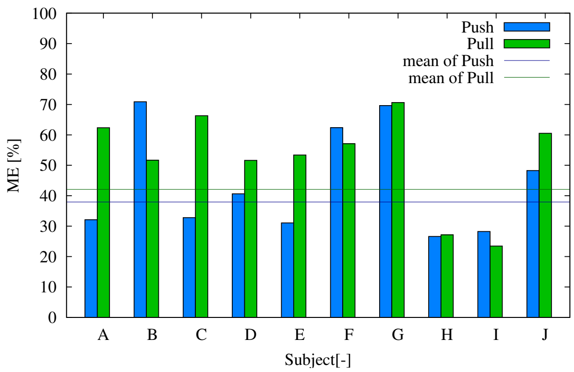


Fig. 12: ME of wrist guidance under both conceptual mappings

tion", which creates vibrotactile cues at any point around the wrist by using only six vibrotactile actuators. Subjects correctly identified the direction of the vibrotactile cue at various positions around the wrist and used this information to reach arbitrary positions around a two-dimensional plane.

Under the proposed approach, a multiple-DOF motion can be guided by a single vibrotactile cue near the end-effector. However, because the conveyed directions must be perpendicular to the wrist, the guidance is limited to 2D space. Therefore, the concept and feedback cues must be extended to guidance in three-dimensional space or to guidance of both position and orientation of the end-effector. The guidance effectiveness of the proposed paradigm should also be tested with more responsive actuation devices, such as linear resonant actuators or piezoelectric motors.

In this paper, the sample size of the experimental subjects was relatively small. To determine whether the performance significantly differs between the two mappings, we require further experiments with more subjects. A numerical comparison against existing approaches would also provide more insight on the effectiveness of the proposed paradigm.

In future work, we hope to correct sports motions (such as tennis swings) by using the proposed paradigm and evaluate the impact of the paradigm in motor learning.

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