Tactile Vectors for Omnidirectional Arm Guidance

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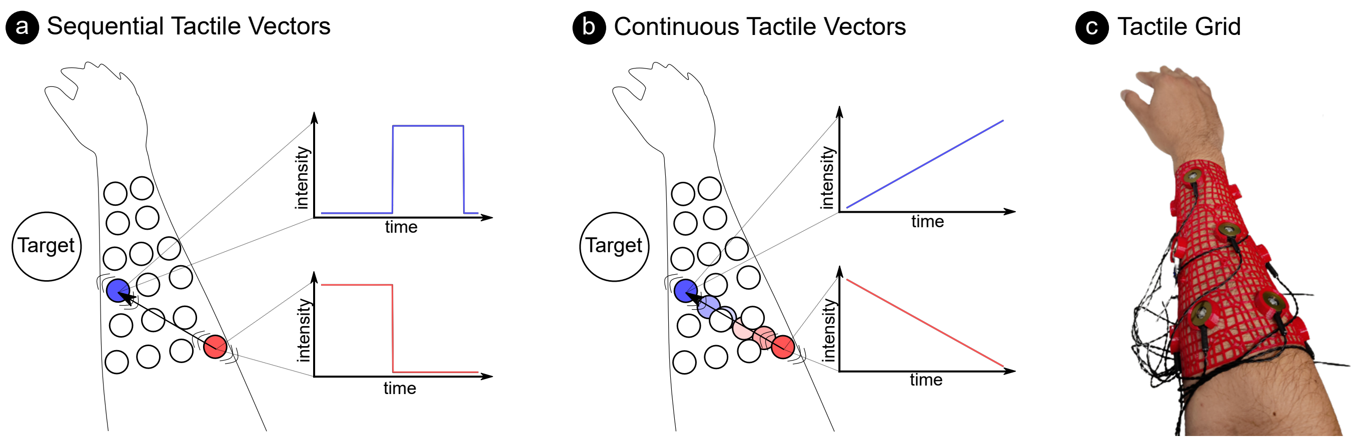

Figure 1: Motion guidance interaction techniques developed in this paper. We introduce (a) sequential tactile vectors (STV) and (b) continuous tactile vectors (CTV). (c) shows an example prototype used to conduct the user study.

ABSTRACT

We introduce and study two omnidirectional movement guidance techniques that use two vibrotactile actuators to convey a movement direction. The first vibrotactile actuator defines the starting point and the second actuator communicates the endpoint of the direction vector. We investigate two variants of our tactile vectors using phantom sensations for 3D arm motion guidance. The first technique uses two sequential stimuli to communicate the movement vector (*Sequential Tactile Vectors*). The second technique creates a continuous vibration vector using body-penetrating phantom sensations (*Continuous Tactile Vectors*). In a user study (N = 16), we compare these two new techniques with state of the art push and pull metaphors. Our findings show that users are 20% more accurate in their movements with sequential tactile vectors.

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CCS CONCEPTS

• **Human-centered computing** → **Human computer interaction (HCI)**; **Interaction techniques**; **Empirical studies in HCI**.

KEYWORDS

movement guidance, vibrotactile, wearables

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1 INTRODUCTION

In recent years, a line of research investigated augmenting humans with on-body vibrotactile feedback for motion guidance [1, 5, 11, 13, 32]. Vibrotactile displays have been shown beneficial, for instance, to teach novice users violin [31], choreographed dance [3, 23], to support with practicing and learning sports (e.g., snowboarding [28], rowing [24], and tennis [19]), and for various forms of physical rehabilitation such as gait retraining [16] and stroke rehabilitation [12].

Prior work [7, 10, 18, 26, 28] identified two main interaction techniques for vibrotactile motion guidance: *push* and *pull*. Both communicate a direction with a single actuator: In the *push* metaphor, vibrations on the user's body push the user in a particular direction. The *pull* metaphor pulls the user in the direction of the vibration. While useful and intuitive, these interaction techniques are limited in the accuracy of communicated directions as the interpretation of a pulling/pushing sensation can vary greatly. Primarily because it is difficult to interpret a direction from a single actuator, leading researchers to encode one direction per actuator [18, 31]. This is even more difficult for vibrotactile guidance in 3D as the space of possible movements expands greatly compared to 2D guidance.

To overcome these limitations, we propose increasing the precision and space of feasible directions by using two vibrotactile actuators to communicate movement directions, i.e., spanning a vector between two vibration points. We introduce two novel interaction techniques for tactile motion guidance: *Sequential Tactile Vectors (STV)* and *Continuous Tactile Vectors (CTV)*. In *STV*, consecutive activations of actuators create the required direction vector of the motion (see Figure 1a). The first actuator communicates to the user the starting point of the vector and the second actuator communicates the end point. Taken together, they can be interpreted as a movement vector in 3D space. Similarly, *CTV* also uses two actuators to communicate a direction vector. However, instead of sequential activation, the actuators vibrate at the same time with changing intensities to elicit a body-penetrating phantom sensation [14]. This gives the impression of one stimulus moving in the direction of the vector (Figure 1b). The start and end points of STV and CTV are not limited to physical actuators. Instead, the techniques utilize phantom sensations [22] to increase the resolution of the display and create vectors starting and ending from virtual actuators.

We compare the two interaction techniques in a user study to push and pull as a baseline for current state of the art from prior work. We quantitatively analyse the accuracy of users' movements using the different guidance methods and collected qualitative feedback through a NASA-TLX and a questionnaire. The results show that using *STV* users are 20% more accurate in their movements in comparison to *push*, *pull*, and *CTV*. Subjective quantitative results further support the viability of *STV* and show a clear user preference for *pull* over *push*.

In summary, this paper contributes two novel interaction techniques for omnidirectional movement guidance: STV and CTV. These techniques aim to expand the possible guidance space by enabling movements in more directions than possible with a single vibration and by increasing the accuracy of the feedback. In a user study we compare STV and CTV with the state of the art in movement guidance, i.e. the push and pull metaphor for tactile guidance of 3D arm movements. The findings of our user study show a high accuracy for the STV technique.

2 RELATED WORK

To better contextualize our research and contributions, we outline existing research on tactile motion guidance. Many technologies have been used for Human-Computer Integration [20, 21]. This work focuses on the use of wearable vibrotactile displays for movement guidance. Table 1 provides an overview of the different approaches.

2.1 Pull

Jansen et al. [10] used five vibrotactile actuators arranged around the arm to guide wrist rotations. In this work, the authors identified two basic interaction techniques for tactile motion guidance: *push* and *pull*. Using *push* vibrations are interpreted to push the user in the direction of the vibration. Conversely, vibrations using the *pull* interaction technique pull the user along the direction of the vibration. Jansen et al. measured reaction times to vibrotactile stimuli and concluded that pull should be favoured over push. Günther et al. [7] proposed and evaluated a vibrotactile glove that uses push and pull for spatial guidance in 3D. Findings of the user study indicated that pull resulted in a lower number of errors while guiding users to spatial targets, and was prefered by the majority of users over push. Weber et al. [32] used six vibrotactile actuators arranged around the wrist to guide translations of the hand following the pull interaction technique, and rotation in two directions. Similarly, Jin et al. [11] introduced VT-Ware, a wearable wrist device with six actuators that was used to guide users in six directions and two rotation directions. For directional guidance the authors use the pull interaction technique. Rotational guidance was achieved by using the cutaneous rabbit illusion to produce moving tactile sensations along the required rotation. In work by Salazar et al. [26], motion path efficiency using push and pull were compared and the findings showed improvements with pull, however, with no statistical significance. Aggravi et al. [1] used pull with four actuators around the wrist for motion guidance in human-robot teams. Tsai et al. [30] compared a similar setup to force-feedback guidance from a haptic device. In HapticHead [13], Kaul et al. used 22 vibrotactile actuators arranged in concentric ellipses around the head for spatial guidance, where actuators pull the user towards the target.

2.2 Push

Spelmezan et al. [28] used vibrotactile actuators placed across the body to guide users during physical activities into performing a particular movement instuction from a discrete set of 10 instructions. The authors stated that the interpretation of a vibration as either push or pull is a matter of preference and decided to use push. Salazar et al. [25] conducted a user study to evaluate the use of vibrotactile cues around the wrist for hand movement guidance in two dimensions. The authors used phantom sensations to be able to generate cues at all locations around the wrist with six vibrotactile actuators. In their work, Salazar et al. [25] used the push interaction technique. Lieberman and Breazeal [15] used push with eight vibrotactile actuators (four arranged around the wrist and four around the upper arm) to aid with performing complex 5 degrees of freedom arm motions. In MusicJacket [31], van der Linden et al. used the push interaction technique with seven actuators placed on the arm and torso to guide violin bowing techniques. Kapur et al. [12] presented a wearable tactile interface that uses magnetic motion tracking and eight vibration motors to provide feedback to apraxic stroke patients through a series of desired movements. They decided to use push as it is similar to a therapist pushing the patient's arm to perform the correct motion.

Table 1: Overview of approaches in related work.

	Jansen et al. [10]	Günther et al. [7]	Weber et al. [32]	Jin et al. [11]	Salazar Luces et al. [26]	Aggravi et al. [1]	Tsai et al. [30]	Kaul and Rohs [13]	Kaul and Rohs [13]	Salazar et al. [25]	Lieberman and Breazeal [15]	van der Linden et al. [31]	Kapur et al. [12]	Marquardt et al. [17]	McDaniel et al. [18]
Pull	✓	✓	✓	✓	✓	✓	✓	✓							✓
Push	✓	✓			✓				✓	✓	✓	✓	✓		✓
Other Interaction Technique							✓							✓	✓
Body part	Arm	Hand	Wrist	Wrist	Wrist	Wrist	Wrist	Head	Full body	Wrist	Arm	Arm	Arm	Hand	Arm
Number of tactors	5	10	6	6	6	4	4	22	34	6	8	7	8	27	12

2.3 Other interaction techniques

Besides push and pull, approaches were introduced that rely on moving tactile sensations for guiding movements. Marquardt et al. [17] developed a vibrotactile glove and forearm prototype that uses 27 actuators to guide hand movements and postures. Patterns were used to trigger movements such as pinching (vibrations from the back of the hand to the fingertips), forward (vibrations from forearm to fingers), and backward (vibrations from fingers to forearm) movements of the hand. In a similar approach, McDaniel et al. [18] introduced the "follow me" interaction technique, where the user is required to follow the movement of the tactile sensation, e.g vibrations from the back of the forearm to the front indicate bending the elbow. The authors compared the use of moving tactile sensations according to the "follow me", push and pull approaches for guidance of fundamental arm movements, and concluded that the naturalness of the interaction technique depended on the movement to be performed. Although these approaches are promising, reaction times of users depends on the duration of the vibrotactile stimuli and can reach 2.5 s to 4.5 s for stimuli with longer durations [18], rendering them unsuitable for real-time motion guidance. On the other hand, vibrotactile stimuli with shorter duration demonstrated reaction times of about 500 ms [29], making them more appropriate for real-time guidance. In this work, we therefore focus on interaction techniques that stimulate the user for short periods of time (1 s) to elicit faster reaction to feedback. Most similar to our work, Schönauer et al. [27] introduced the use of sequential activations to communicate eight directions, however, no user study was conducted to validate their approach. In this work, we introduce the concept of tactile vectors based on phantom sensations that can generate up to 2,652 directions with 15 physical actuators, thus enabling omnidirectional guidance in 3D. Figure 2 shows the different guidance possibilities developed in our work.

Prior work primarily focuses on the push and pull metaphors. However, there is no clear favorite in the community: some researchers use pull while others use push. In our work, we quantitatively and qualitatively compare the use of push and pull. Moreover, we introduce two new interaction techniques: *STV* and *CTV*. In contrast to the state-of-the-art these techniques allow for omnidirectional movement guidance by expanding the range of possible directions communicated through haptic feedback.

3 INTERACTION TECHNIQUES FOR VIBROTACTILE MOTION GUIDANCE

This section contributes two new interaction techniques – Sequential Tactile Vectors (STV) and Continuous Tactile Vectors (CTV) – for vibrotactile motion guidance. We describe their fundamental mechanism and detail on the chosen parameterization used in our implementation. Finally, we provide details on the parameters for the baseline techniques (pull and push). STV and CTV are visualized in Figure 1.

3.1 Sequential Tactile Vectors (STV)

The Sequential Tactile Vectors interaction technique uses two vibrations to convey a movement direction (see Figure 1a). The two vibrations are activated sequentially: the first vibration defines the starting point and the second vibration defines the endpoint of the direction vector in which the user should move. Both vibrations together produce a direction vector in which the person should move the body.

3.2 Continuous Tactile Vectors (CTV)

The Continuous Tactile Vectors interaction technique uses body-penetrating phantom sensations [14] to create omnidirectional vibration cues. The vectors are created through the same start- and endpoints as in STV. However, instead of sequential vibrations, CTV creates a single continuous stimuli moving from the start point towards the endpoint. CTV can create the same vectors as STV, but is perceived differently. We evaluate both techniques to better understand which tactile vector stimuli is preferred by participants and leads to a higher movement accuracy.

3.3 Tactile Vector Types

This work investigates three types of sequential and continuous tactile vectors (shown in Figure 2):

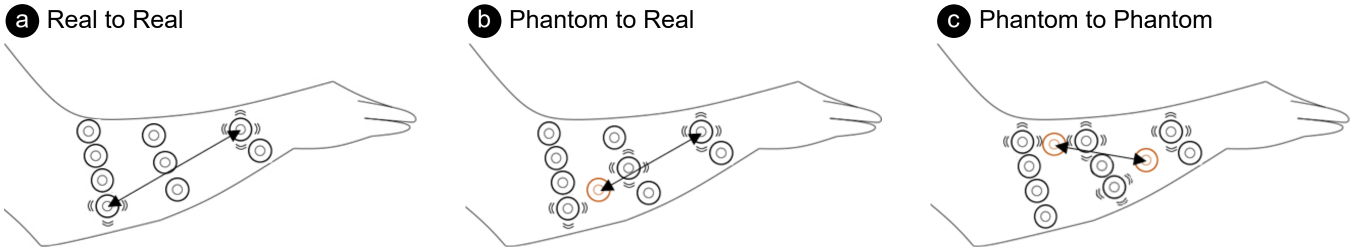

Figure 2: Tactile vectors for directional guidance: (a) using only real tactors, (b) using a combination of phantom and real tactors, and (c) using phantom sensations.

- **Real → Real** The most straight-forward possibility to create a sequential tactile vector is by vibrating a physical actuator and afterwards a second physical actuator (Figure 2a). Hence, both perceived vibrations are *real*, i.e., created by physical actuators. Although Schönauer et al. [27] described this concept for motion guidance, its accuracy has not been evaluated.
- **Real ↔ Phantom** We extend the idea of tactile vectors by adding a variation using one real vibration and one vibration through phantom sensation (Figure 2b). This variation has the potential to increase the resolution of tactile vectors. It can create vectors to arbitrary points between two or more physical actuators. Inverting this variation (*Phantom to Real*) allows for tactile vectors between a phantom sensation (start-point) and real vibration (endpoint).
- **Phantom → Phantom** Tactile vectors can consist of two vibrations created through phantom sensations (Figure 2c). This allows for a wider variety of direction vectors, since both start- and endpoint can be placed anywhere between two or more real actuators.

For best usage of STVs and CTVs, we recommend choosing the pair of supported (real and phantom) vibrations that span the vector with the lowest deviation from the target vector.

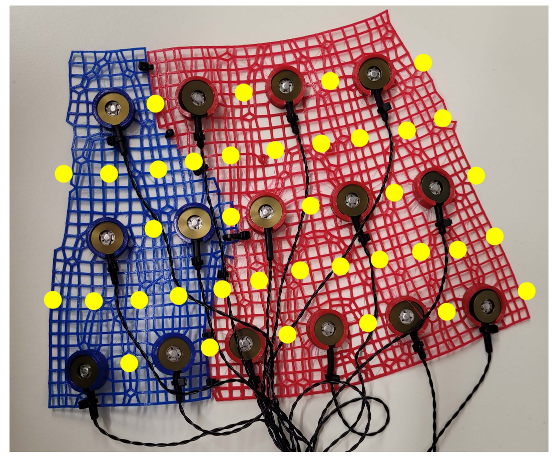

Figure 3: An unwrapped tactile grid with 15 actuators attached. The yellow points indicate the position of the vibrations created through phantom sensations.

3.4 Implementation of Tactile Vectors

Both techniques (CTV and STV) are implemented and evaluated on a 3D printed vibrotactile grid with 15 vibrotactile actuators (C-2 tactors from Engineering Acoustics). We extend the real actuators using phantom sensations to include virtual actuators placed in the middle of each pair of neighbouring physical actuators. This created 52 vibration points that could be chosen as start- or endpoint of the tactile vector (see Figure 3). In total, this allows for 2,652 possible tactile vectors. However, we limit the combinations of actuators to those placed at least 10 cm apart, because our pilot tests showed: (1) actuators that were too close to each other were difficult to distinguish and (2) close actuators created unintentional phantom sensations for continuous tactile vectors. The chosen 10 cm threshold exceeds the maximum distance for producing a phantom sensation [6].

For STV, each vibration (i.e., start- and endpoint) lasted 0.5 s. The physical actuators vibrated with 200 Hz at 10 dB over Sensation Level (SL). SL is the intensity at which a vibration became perceptible, as determined during our calibration. Phantom sensations were generated using a linear model.

For CTV, we use a linear function for the amplitudes of the actuators to generate body penetrating sensations. The first actuator starts at full intensity (10 dB over SL) and decreases linearly over 1 s to 0 dB, while the second actuator increases from 0 dB to 10 dB over SL. Similar to the other interaction techniques, the frequency of vibration was constant at 200 Hz and the amplitudes of the actuators were updated at 100 Hz.

3.5 Baselines: Pull and Push

Depending on the mental model of the user vibrations can be interpreted in different ways [7, 28]. Hence, we chose the *pull* and *push* interaction techniques as baseline interaction techniques. In our implementation, we actuate the real or phantom actuator that pushes or pulls the arm at the midpoint (midpoint of the middle row of motors) towards the target direction for one second (200 Hz at 10 dB over SL). For example, a push stimulus communicates the direction vector going from the position of the actuator to the midpoint of the arm. In contrast, a pull stimulus communicates the

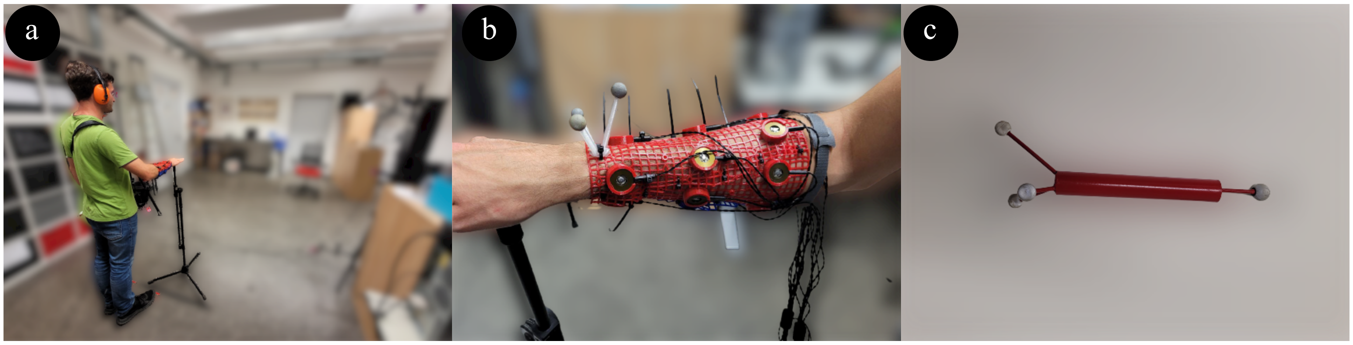

Figure 4: Experimental setup: (a) neutral pose used during our experiment, (b) vibrotactile grid with wrist trackable, and (c) pointer used for calibrating the position of the tactors.

direction vector from the midpoint of the arm to the position of the actuator.

4 USER STUDY: EVALUATION OF VIBROTACTILE MOTION GUIDANCE TECHNIQUES

To evaluate the interaction techniques introduced in this paper, we conducted a controlled user study that is described in the following. In particular, our user study aims to address the following hypotheses:

- **H1$_{STV/CTV}$:** STV/CTV results in higher accuracy in guiding arm movements compared to push and pull.
- **H2$_{STV/CTV}$:** STV/CTV reduces workload compared to push and pull.
- **H3$_{STV/CTV}$:** STV/CTV is more intuitive than push and pull.
- **H4$_{STV/CTV}$:** STV/CTV results in higher confidence ratings compared to push and pull.
- **H5$_{STV/CTV}$:** Willingness to use of STV/CTV is higher than push and pull.

4.1 Participants

16 right-handed individuals (11 male and 5 female) between 21 and 70 years old (M = 37.8) participated in our user study. Participation was voluntary, with no compensation offered. 14 of our participants had no experience with vibration based motion guidance. The remaining participants participated in prior experiments with vibrotactile feedback for purposes other than motion guidance.

4.2 Experimental Design

Throughout our experiment we varied the guidance method (pull, push, sequential tactile vectors, and continuous tactile vectors) and target. The targets were defined as equidistant points on a sphere with an angle of 45°. The sphere had a radius of one meter and was centered at the midpoint of the arm. The midpoint of the arm was defined to be in the center of the middle row of tactors in the grid. We group the targets in our analysis along the x, y, and z axes. Figure 5 shows the distribution of the targets in the sphere and their division along the main axes. We used a 4×4 balanced latin square to counterbalance the variable guidance method in a within subjects design. For each guidance method, the order of targets was randomized. Participants performed three repetitions resulting in a total of 312 movements per participant.

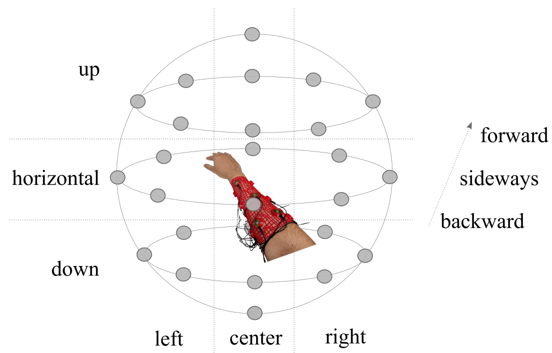

Figure 5: Targets used in our experiment

4.3 Procedure

After obtaining informed consent from the participants, we collected their demographic data. Then, we explained the task and provided a brief overview of the procedure. The task was to move the arm in the direction indicated by the vibrations.

At the beginning of the experiment, we calibrated the position of the vibrotactile actuators relative to the position of the wrist. Each actuator in the grid was activated and its position was recorded using the pointer in Figure 4c. The experimenter could choose which actuator to activate using a graphical user interface and then subsequently record the position when the tip of the pointer is in contact with the actuator. Furthermore, SL thresholds were determined for each actuator by increasing vibration amplitude until the participant indicated perceiving a vibration. Every trial started with the participant standing in a fixed location indicated by markings on the floor with their hands resting on a tripod (see Figure 4).

After finishing performing a movement, the participants returned their arm to the neutral position with their hands on the tripod. Upon reaching the neutral position, there was a 5 seconds

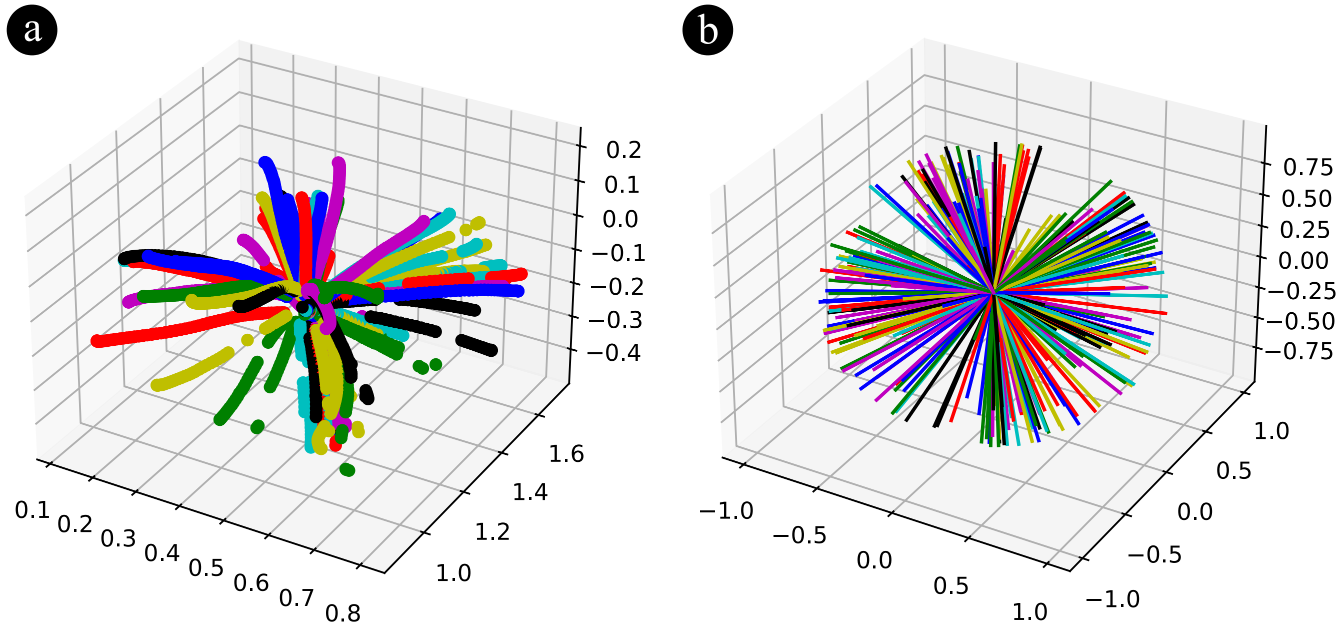

Figure 6: The Figure shows (a) example movements as measured by the motion capture system and (b) the normalized direction vectors of the computed best fit lines.

pause followed by the next trial. To reduce the amount of questionnaires, upon completing all targets in a guidance method, our participants filled out a short questionnaire with three 7-point Likert-scale statements followed by filling out a NASA-TLX. We consider this time as resting time. The total duration of the experiment was approximately 80 minutes.

4.4 Apparatus

We used a Prusa MK3 for printing the wearable grids using thermoplastic polyurethane (TPU) filament. The experiment was conducted on a i7 dual core 3.6 GHz, 16 GB RAM desktop PC with a NVIDIA GeForce GTX 970 graphics card. The vibrotactile actuators used were the C-2 tactors from Engineering Acoustics, Inc. The tactors were controlled by a tactor control unit connected to the desktop PC over USB. Additionally, an Optitrack V100:R2 motion capture system with six cameras (submillimeter accuracy) was used for tracking the markers placed at the wrist and the participants' movements.

4.5 Dependent Variables

Our main evaluation metric is the angle error. This is the angle between the target movement and the movement actually performed by the user. To obtain the movement vector of the user, we compute a best fit line with orthogonal regression based on the tracked points from our motion capture system. The angular difference in degrees between the target vector and movement vector is the angle error.

Additionally, we measured participants' ratings on a 7-point Likert-scale for each guidance method to the following three statements:

- Interacting with the system was intuitive.
- I am confident I could follow the direction cue correctly.
- I would like to use this type of guidance for movement guidance.

Finally, we collected participants' answers to a NASA-TLX questionnaire.

4.6 Data Analysis

We tested the data for normality with Shapiro Wilk's test and found no significant deviations. The recorded data was analyzed using a 2-way repeated measures ANOVA, followed by Bonferroni corrected pairwise t-tests where significant effects were present. We further report the eta-squared η^2 as an estimate of the effect size and use Cohen's suggestions to classify the effect size as small, medium or large [2]. For the Likert questionnaires, we performed an Aligned Rank Transformation as suggested by Wobbrock et al. [33]. For the analysis of the NASA-TLX questionnaires, we used the raw method, indicating an overall workload as described by Hart [8].

4.7 Results

In the following, we present the results of our user study in terms of the measured angle error, NASA-TLX, and questionnaire responses.

4.7.1 Angle Error. We calculated the R^2 over all movements and participants to estimate how well the best fit lines represent the measured data from participants. The average R^2 value indicated a good fit of 0.98. Figure 6 shows example movements of a participant and the computed best fit lines.

We found that STV (M = 34.58°, SD = 5.33°) resulted in the lowest angle errors in comparison to pull (M = 42.16°, SD = 6.43°), push (M = 43.96°, SD = 5.87°), and CTV (M = 44.19°, SD = 12.03°). The

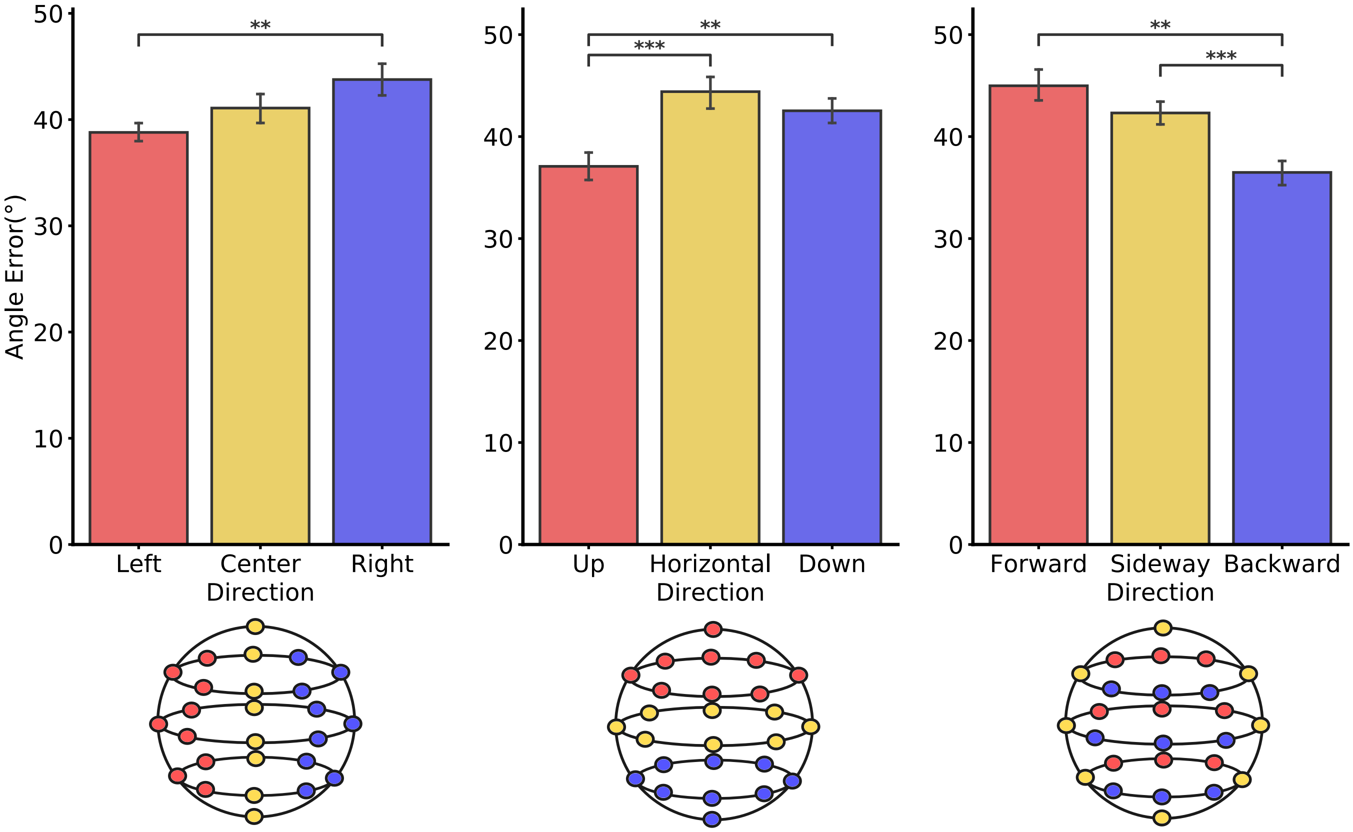

Figure 7: Angle error for the targets. All error bars indicate the standard error. Statistical significance of post-hoc pairwise contrast test are marked with asterisks (∗ = p < .05, ∗∗ = p < .01, ∗ ∗ ∗ = p < .001).

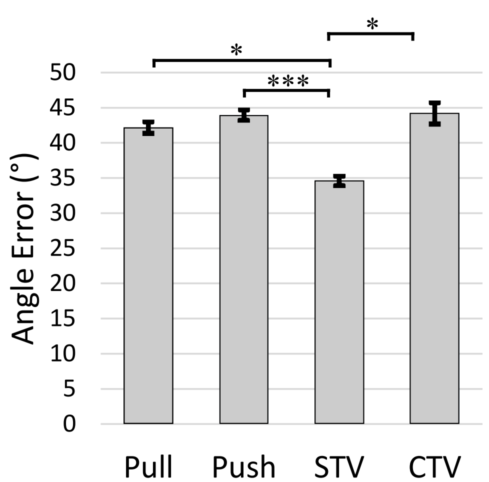

Figure 8: Angle errors for the guidance methods.All error bars indicate the standard error. Statistical significance of post-hoc pairwise contrast test are marked with asterisks (∗ = p < .05, ∗∗ = p < .01, ∗ ∗ ∗ = p < .001).

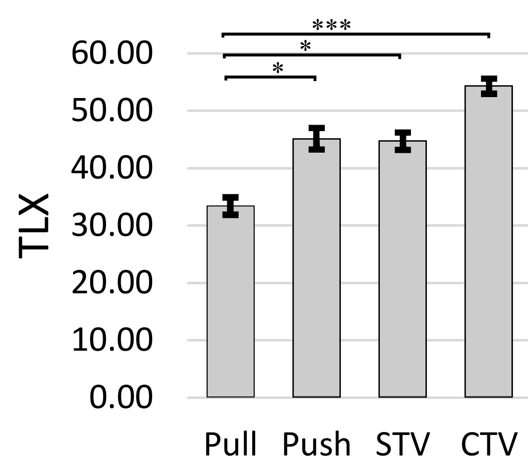

Figure 9: NASA-TLX scores for the guidance methods. All error bars indicate the standard error. Statistical significance of post-hoc pairwise contrast test are marked with asterisks (∗ = p < .05, ∗∗ = p < .01, ∗ ∗ ∗ = p < .001).

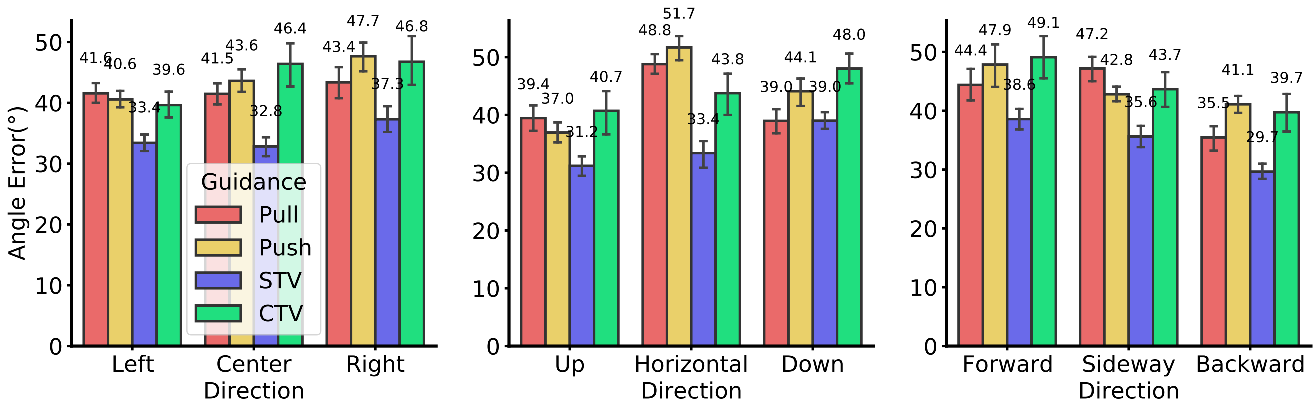

Figure 10: Angle error of the interaction between guidance method and target direction. All error bars indicate the standard error.

analysis showed a significant ($F_{3,45}$ = 6.19, p < .001) main effect of the *guidance method* on the angle error with a small η^2=.038 effect size. Post-hoc tests confirmed significant differences between STV and pull (p < .05), STV and push (p < .001), and between STV and CTV (p < .05).

For a more meaningful analysis of the effect of *target*, we clustered the targets along the x, y, and z axes to compare the following movement directions: (1) left, center and right (grouping along the x-axis), (2) up, horizontal and down (grouping along the y-axis), and (3) forward, sideway and backward (grouping along the z-axis). Figure 7 depicts the results.

Our analysis of targets left (M = 38.79, SD = 3.48), center (M = 41.09, SD = 6.13) and right (M = 43.77, SD = 7.67) revealed a significant ($F_{2,30}$ = 5.60, p < .01) main effect of *target* on the angle error with a medium η^2=.103 effect size. Post-hoc tests confirmed significantly lower angle errors for targets to the left in comparison to targets to the right (p < .01).

For the grouping up (M = 37.08, SD = 6.25), horizontal (M = 44.41, SD = 6.02) and down (M = 42.53, SD = 6.53), our analysis showed a significant ($F_{2,30}$ = 10.1, p < .001) main effect of *target* on the angle error with a large η^2=.197 effect size. Post-hoc tests confirmed significant differences between up and down (p < .05), and up and horizontal (p < .001).

The analysis of the grouping forward (M = 44.98, SD = 9.17), sideway (M = 42.32, SD = 4.65) and backward (M = 36.49, SD = 4.55) showed a significant ($F_{2,30}$ = 10.6, p < .001) main effect of *target* on the angle error with a large η^2=.230 effect size. Post-hoc tests confirmed significant differences between forward and backward (p < .01), and sideway and backward (p < .001).

Figure 10 shows the interaction between *guidance method* and *target*. Figure 12 displays heatmaps of the angle error for the different guidance methods and targets.

4.7.2 NASA-TLX. The analysis of the NASA-TLX questionnaires revealed a significant ($F_{3,45}$ = 10.8, p < .001) effect of *guidance method* on participants' ratings with a large η^2=.260 effect size. The pull (M = 33.39, SD = 12.16) condition resulted in the lowest overall workload, followed by STV (M = 44.69, SD = 11.96), push (M = 45.10, SD = 14.97), and CTV (M = 54.27, SD = 10.52). Post-hoc tests confirmed significant differences between pull and push (p < .05), pull and STV (p < .05), and pull and CTV (p < .001).

4.7.3 Questionnaire. Intuitiveness: we asked our participants to rate how intuitive interacting with the system was on a 7-point Likert-scale (1: strongly disagree 7: strongly agree). Our analysis showed a significant ($F_{3,45}$ = 5.53, p < .01) effect of *guidance method* on our participants' ratings of intuitiveness. The pull (MED = 6, MAD = 0.5) condition showed the highest ratings of intuitiveness, followed by STV (MED = 5, MAD = 1), CTV (MED = 4.5, MAD = 1.5), and finally push (M = 4, SD = 1). Post-hoc tests confirmed significantly higher ratings for pull than for push (p < .01), as well as significantly higher ratings for pull in comparison to the CTV condition (p < .01).

Confidence: our participants rated their confidence in following the direction cue correctly. The analysis revealed a significant ($F_{3,45}$ = 4.53, p < .01) effect of *guidance method* on the ratings of participants. Confidence ratings in decreasing order for the conditions were pull (MED = 5.5, MAD = 0.5), STV (MED = 5, MAD = 0), push (MED = 5, MAD = 0.5), and CTV (MED = 4, MAD = 1). Post-hoc tests confirmed significantly higher confidence ratings for the pull condition in comparison to CTV (p < .01).

Willingness to use: for the last statement in our questionnaire, we asked participants to rate if they would like to use this type of guidance. Our analysis showed a significant ($F_{3,45}$ = 6.23, p < .01) effect of *guidance method* on participants' ratings. Participants were most willing to use the pull (MED = 5, MAD = 1) condition, followed by STV (MED = 4, MAD = 1), push (MED = 3.5, MAD = 1.5), and CTV (MED = 2, MAD = 0.5). Post-hoc tests confirmed significantly higher willingness to use ratings for the pull condition in comparison to CTV (p < .001).

5 DISCUSSION

We introduced two new interaction techniques to improve the range of possible directions for movement that can be communicated to the user through vibrations. These interaction techniques were compared to the current state of the art push and pull metaphors.

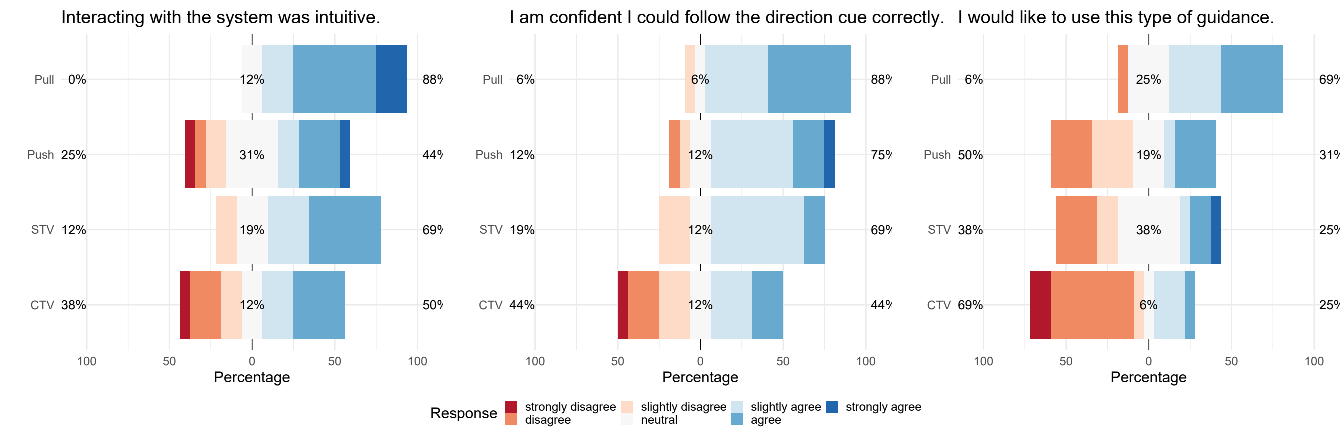

Figure 11: Participants' ratings to our statements.

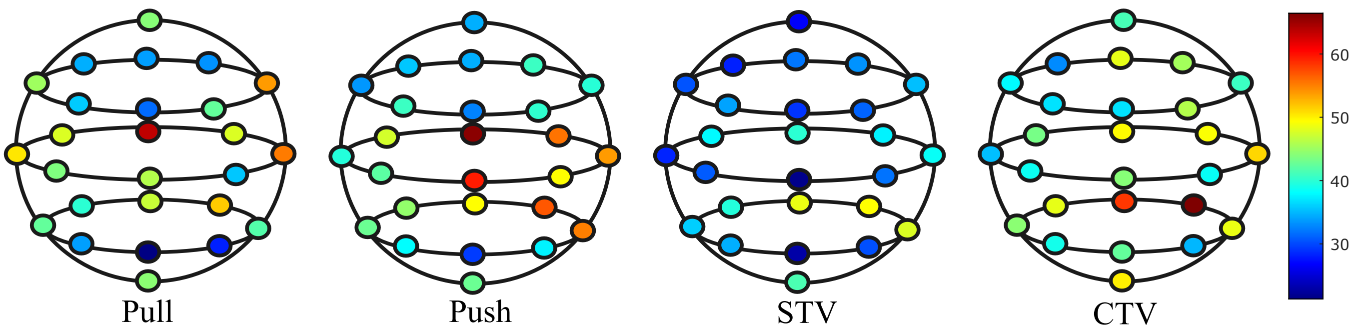

Figure 12: Heatmaps of angle error in ° for the different guidance methods.

While the results of our experiment demonstrate large errors 35° (STV), 42° (Pull), and 44° (Push & CTV) for 3D guidance of arm movements, this was to be expected based on more restricted prior work showing that vibrotactile 2D guidance has an upper limit of 23-25° [9] for guiding wrist movements. However, our results pave the way for investigating novel approaches to further reduce movement error, or to use our tactile vectors on more sensitive body locations such as the hand for improved accuracy.

Prior work has identified advantages for pull over push using error metrics, such as reaction time [10], number of errors in movements [7], and motion path efficiency [26]. Based on our findings, we found comparable performance in terms of angle error between the metaphors. However, pull was subjectively preferred by our participants, similar to findings by Günther et al. [7].

In the following we summarize and discuss the findings from our user study:

5.1 STV for higher accuracy

The results of our user study show that using STV, users achieved the highest accuracy in their movements compared to the other interaction techniques. Thus, we can accept $H1_{STV}$. Compared to current state of the art push and pull techniques, the advantage of STV is particularly evident for guiding movements where no actuator is present to push/pull the user, e.g forward and backward (Target 0 & 12, see Figure 12). In addition, STV had the highest accuracy for guiding upward and backward directions (see Figure 10). This information can be useful, e.g while designing gestures for interaction, where the user is guided by a wearable vibrotactile display.

Contrary to our initial hypothesis $H1_{CTV}$, CTV did not lead to an improvement in user accuracy compared to the other interaction techniques. CTV resulted in higher angular deviation compared to STV, and comparable angular deviation to pull and push. Thus, we cannot support $H1_{CTV}$. A possible explanation for this was provided by our participants where they expressed that it was difficult to determine which motor was first and which was second (P4, P11, P14, P15, P16). We used a linear function for determining the amplitude of the actuators that was shown to work on the hand and torso [14]. A possible solution can be the use of a higher order polynomial for determining the intensities of the actuators to allow for better differentiation of the start and endpoints.

Although subjective data collected from our participants showed higher median ratings for pull in comparison to STV regarding intuitiveness, confidence, and willingness to use, these differences were not significant and do not reflect the results of the angle error. A possible explanation for this behavior is that participants were inclined to overestimate their performance as demonstrated by the confidence ratings when the stimulus was a vibration at a single location. This finding further demonstrated that self-assessment with vibrotactile guidance is more difficult in comparison to visual guidance for example.

5.2 Pull for applications with low accuracy requirements

For applications that do not require high accuracy of guidance, e.g guidance of a discrete set of directions with a large angle between them such as right/left, up/down, and forward/backward, pull should be used. We hypothesized that STV and CTV reduce workload in comparison to push and pull. However, this was not reflected in our results, as pull resulted in lower workloads in comparison to all the other guidance methods. Hence, we cannot support $H2_{STV/CTV}$. Furthermore, pull was rated to be significantly more intuitive than push and CTV. Although intuitiveness ratings were lower for STV, this difference was not significant. Nevertheless, we cannot support $H3_{STV/CTV}$. Similarly, our initial hypotheses were that STV and CTV increase participants' confidence in the perceived direction. However, pull received the highest confidence ratings among the guidance methods, with a significant increase compared to CTV. Thus, we cannot support $H4_{STV/CTV}$. Regarding willingness to use of the guidance methods, participants were most willing to use pull. Thus, we cannot support $H5_{STV/CTV}$.

5.3 Pull instead of push

Although pull and push had comparable accuracy for motion guidance, there were significant differences between them. Pull was favoured by our participants in the qualitative results. It resulted in lower workload for our participants and was rated to be significantly more intuitive than push. This was reflected in the participants' comments where P6 expressed *"I preferred pulling for one motor guidance"*, *"pull is better than push"* (P12), and *"I found pull most intuitive"* (P10). Participants further mentioned that using both interaction techniques is *"confusing"* (P1, P10) after getting accustomed to one of them.

5.4 Movement direction affects accuracy of guidance

Based on prior work investigating vibrotactile guidance of 2D hand movements [9], we expected the movements of our participants to be biased towards the cardinal directions. This was, however, not the case for 3D movements as can be seen in Figure 12. We found differences in accuracy showing that users are more accurate in movements toward the body than movements away from the body. Moving the right arm to targets to the left (towards the body) was more accurate than targets to the right (away from the body). Similarly, targets requiring a forward (away from the body) movement were less accurate compared to targets requiring a backward (towards the body) movement.

When evaluating the influence of movement direction on the accuracy it is also important to note the guidance method and actuator arrangement used. Push and pull guide the user in the direction defined between the actuator location and the midpoint of the arm. Since the actuators are arranged around the arm, directions such as forward become more difficult to communicate. A possible solution for this could be the attachment of an actuator at the elbow/tip of the hand to push/pull the user forward. An overview of the effect of movement direction for all guidance methods and directions investigated can be seen in Figure 12.

6 LIMITATIONS & FUTURE WORK

We are confident that our results provide valuable insights into the influence of different interaction techniques on the accuracy and user experience of vibrotactile motion guidance systems. However, design as well as the results of our user study impose some limitations and starting points for future work.

6.1 Movement Direction

Consistent with prior work on spatial guidance [13], we chose to use targets for eliciting movements that are uniformly distributed on a sphere. This arrangement of targets appropriately covered the wide range of movement directions possible by the arm. However, other arrangements are possible, e.g., distributing targets in a cube [7] that can be investigated in future work.

6.2 Dynamic Tactile Guidance

For a more fundamental analysis independent of the use-case, our user study focused on guiding arm movements from a fixed neutral posture. However, this is not the case while performing activities such as physical rehabilitation, yoga or tai-chi, where the arm posture is dynamic. While our results provide a valuable baseline showing that our interaction technique outperforms current state of the art, further work is necessary to apply these findings to tasks where continuous guidance of user motion is required.

6.3 Real-World Applicability

In this paper, we investigated vibrotactile motion guidance in a lab setting. We chose this approach to focus on the mere influence of the factors and to exclude external influences. While we are convinced that our results make a strong contribution to the future of such systems, we also acknowledge that other settings might yield other results. Therefore, further work is necessary to understand how these results are transferable to in-the-wild settings. For example, by integrating the haptic sleeve with a visual posture guidance approach that uses a mobile motion capture system [4].

7 CONCLUSION

We presented two new omnidirectional guidance techniques for arm movements: Sequential Tactile Vectors and Continuous Tactile Vectors. We studied both techniques and compared them to the state of the art (push/pull) in a user study. The results of our evaluation show Sequential Tactile Vectors to be the most promising interaction technique of the four, outperforming push and pull, as well as Continuous Tactile Vectors in terms of accuracy. Qualitative results further support the viability of our interaction technique for accurate and intuitive vibrotactile motion guidance.

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