Vibrotactile Phantom Sensations in Haptic Wrist Rotation Guidance

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***Abstract*—Haptic motion guidance has the potential to advance assistive technologies that support humans in movement tasks. This study systematically evaluates wrist rotation guidance methods in a 2 $\times$ 2 repeated measures design using a wearable vibrotactile feedback device. In two tasks, we investigate the benefits of encoding the current target distance in the cue strength and conveying additional information about the target location by incorporating a tactile illusion known as phantom sensation. For a directional response task, we analyze reaction times and error rates, and for an angle targeting task, we examine rise time, settling time, and maximum overshoot of the normalized step responses. These objective criteria are complemented by subjective user ratings that assess the intuitiveness and ease of interpreting the vibrotactile cues. Feedback methods incorporating an adaptive amplitude perform significantly better in the angle targeting task compared to those using a constant amplitude. Additional improvements can be achieved by combining the adaptive amplitude with phantom sensations, including an average additional 24.3% reduction in rise time. Furthermore, more than half of the participants rate this combination as their favorite method. Altogether, the results underline the potential of incorporating phantom sensations in vibrotactile wrist guidance, thereby contributing to the advancement of wearable haptics in assistive applications.**

***Index Terms*—Wearable haptics, vibrotactile, motion guidance, forearm, tactile illusion, human-machine interaction.**

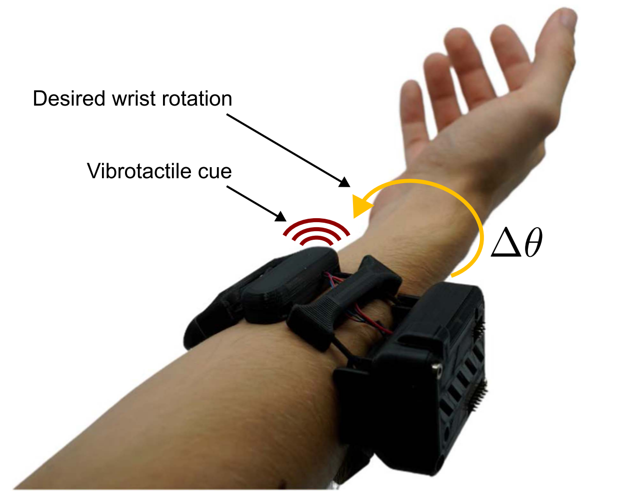

Fig. 1. Vibrotactile wrist rotation guidance. The wearable haptic device applies vibrotactile cues to communicate the desired wrist rotation $\Delta\theta$ to the human user.

I. Introduction

Motion guidance provides human users with information about how to move their body, which can be useful in application areas such as learning and refining motor skills, assistive technologies, and human-robot interaction. The necessary information can be provided by sensory feedback of different modalities, including visual [1], auditory [2], and haptic [3], [4] stimuli. Haptic feedback can be particularly helpful to provide additional information when the other channels are already in use [5]. The versatile applicability of haptic guidance has been demonstrated in a wide spectrum of applications. For instance, haptic guidance for learning and training motions includes rehabilitation [6] and medical procedures, such as needle insertion [7]. Furthermore, assistive technologies incorporating haptic information can provide sensory substitution as well as sensory augmentation [8], e.g., guiding reaching movements of visually impaired [9] as well as unimpaired [10] users or enhancing ergonomics by providing postural feedback [11], [12].

Humans solve many of their tasks using their upper limbs. Consequently, guiding the hand in 3D space, which includes position as well as orientation, seems particularly useful to assist in various activities. However, haptic feedback to support manual tasks does not necessarily need to be applied directly to the hand. Instead, the haptic information can also be conveyed at the wrist or forearm [13], keeping the hands themselves free for more natural interactions. Several studies have demonstrated the potential of vibrotactile cues for positional wrist guidance in 2D [14], [15] and 3D [10], [16], and investigated the effectiveness of different feedback strategies, such as indicating the desired movement direction either by "push" or "pull" mappings [14], [16], providing only corrective feedback [15], and presenting vibrotactile cues in different spatial reference frames [17]. While most haptic wrist guidance studies focused on positional guidance, Stanley and Kuchenbecker [18] investigated wrist rotation guidance, focusing on supination and pronation. In three different tasks, they compared five different wearable haptic devices as well as two feedback strategies, i.e., the way the devices were controlled to convey the guidance information, resulting in ten different device-strategy combinations. Their results underlined that the optimal device-strategy combination depends on the specific task. However, relatively simple vibrotactile feedback, using only two actuators to indicate the direction of wrist rotation through a steady vibration with an amplitude proportional to the current target distance, yielded good results across all tasks investigated. Furthermore, the same devices exhibited significantly different performance depending on the feedback strategy implemented, emphasizing the importance of appropriate feedback methods for haptic wrist guidance.

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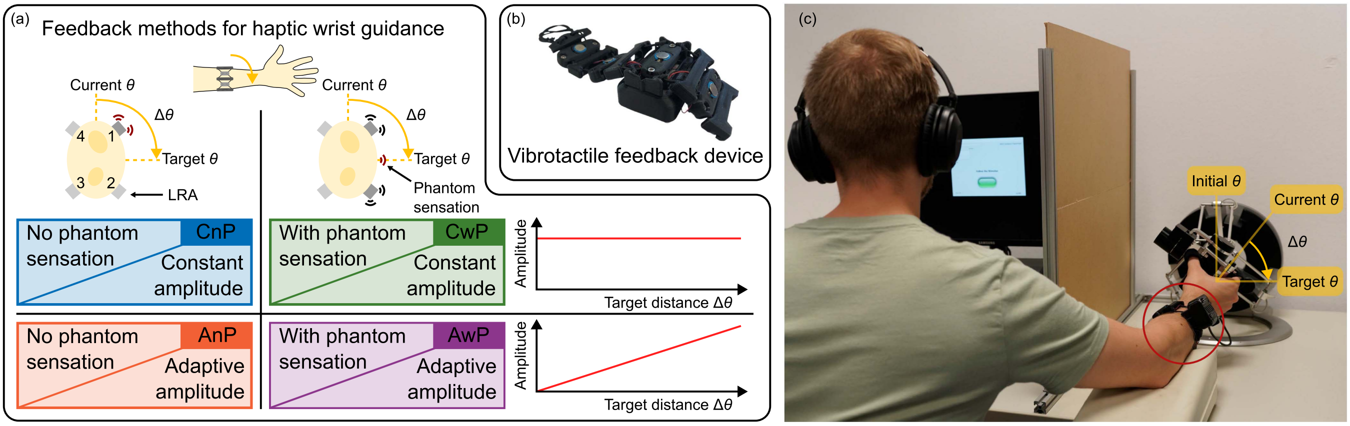

Fig. 2. Haptic feedback and experimental setup. (a) Four feedback methods for haptic guidance of the wrist orientation θ are tested, which are combinations of two different amplitude settings and whether or not phantom sensations are incorporated to indicate the exact location of the target angle. The amplitude is either independent (constant) or proportional (adaptive) to the current target distance $\Delta\theta$. Phantom sensations are generated by simultaneously activating two adjacent linear resonant actuators (LRAs), which is perceived as a single vibration between them. (b) The vibrotactile feedback device comprises four LRAs, which are arranged equidistantly around the forearm circumference. (c) In the haptic wrist guidance experimental setup, the participant conducts two tasks (directional response, angle targeting) for each of the four feedback methods. The wearable vibrotactile feedback device (red circle) provides guidance cues, while the wrist angle is measured using a tabletop device.

Wearable devices for vibrotactile feedback at the forearm often take the form of armbands or bracelets with a number of vibrotactile actuators arranged around the arm circumference [19], [20], [21], [22]. While high-density feedback is assumed to feel more natural, the number of actuators is often limited by hardware constraints [23]. The spatial resolution of vibrotactile feedback devices can be increased by control algorithms making use of tactile illusions [24]. In particular, vibrotactile phantom sensations can be used to increase the spatial resolution of vibrotactile cues around the arm circumference generated by a limited number of actuators [14], [25], which has already been applied for 2D wrist position guidance [14]. However, making use of vibrotactile phantom sensations in wrist rotation guidance has not yet been systematically investigated to the best of the authors' knowledge.

In this paper, we evaluate different vibrotactile feedback methods for wrist rotation guidance (Fig. 1). In particular, we investigate the effects of modulating the cue strength and leveraging an increased spatial resolution making use of phantom sensations. For this purpose, we design a user study inspired by Stanley and Kuchenbecker's systematic evaluation of different haptic devices for wrist rotation guidance [18]. Our study evaluates the performance of four different feedback methods in a directional task and an angle targeting task, thereby contributing to the advancement of vibrotactile wrist guidance technologies.

II. Methods

We investigate feedback methods for haptic wrist guidance in a 2×2 repeated measures design, varying the amplitude approach (constant versus adaptive) and whether phantom sensations are incorporated or not (Fig. 2(a)). The combination of these two independent variables with two levels each results in four feedback methods. Each of these four conditions is tested in two tasks, in which the participants need to identify target directions and orientations, respectively, and rotate their wrist accordingly.

A. Vibrotactile Device and Feedback Methods

The vibrotactile feedback device used in this study (Fig. 2(b)) is a further development of our demonstrator presented in previous work [25]. We use a custom printed circuit board to reduce the weight and size, which is particularly important in dynamic use cases such as movement tasks. The main components are a microcontroller module (ESP WROOM-32E, Espressif, Shanghai, China) and haptic drivers (DRV2605L, Texas Instruments, Dallas, TX, USA) to control the four linear resonant actuators (VG1036002D, Vybronics, Wanchai, Hong Kong, China). We implement four feedback methods for haptic wrist guidance based on the combination of the two factors amplitude type and phantom sensation usage (Fig. 2(a)). The strength of the vibrotactile cue can be set to be either constant or adaptive, i.e., linearly proportional to the current distance to the target. When no phantom sensation is used, only actuators 1 and 4 are used to indicate the direction of the target. In contrast, the feedback methods making use of phantom sensations can activate two actuators simultaneously to simulate a virtual actuator in between [26], indicating not only the direction but the specific location of the target. We use the following acronyms for the four feedback methods: CnP (constant amplitude, no phantom sensation), AnP (adaptive amplitude, no phantom sensation), CwP (constant amplitude, with phantom sensation), and AwP (adaptive amplitude, with phantom sensation). In particular, the method AnP corresponds to the device-algorithm combination "vibration steady" used in the study by Stanley and Kuchenbecker [18]. Further details on the implementation of phantom sensations in our vibrotactile interface, which uses the energy model proposed by Israr and Poupyrev [26], can be found in our previous work [25].

B. Wrist Rotation Guidance Experiment

1) Experimental Setup: In our experimental setup (Fig. 2(c)), participants sat in front of a monitor with the right elbow lying on an armrest, holding the end-effector of a haptic device (omega.7, Force Dimension, Nyon, Switzerland) with a passive rotational degree of freedom for wrist angle measurement. Note that this device was used for measurement purposes only, which means it behaved completely passive over the whole experiment. We defined the vertical orientation of the handle as the initial wrist orientation. Before the experiment, participants tested their range of motion (supination/pronation) and the device's end-effector was fixed at a comfortable position. The vibrotactile feedback device was worn on the right forearm, irrespective

TABLE I
QUESTIONNAIRE ITEMS

Item	Visual analog scale labels
Intuitiveness	Using the device was... not intuitive at all ——— very intuitive
Direction	Discerning the directions was... very difficult ——— very easy
Location	Locating the target angles was... very difficult ——— very easy

TABLE II
PERFORMANCE CHARACTERISTICS

Task	Characteristics
Directional response	Reaction time, initial direction accuracy, error rate
Angle targeting	Rise time, settling time, maximum overshoot

of the participant's dominant hand. The device was positioned at about one-third of the forearm length, measured from the wrist, with the circumference of the device being aligned to ensure a tight fit without causing discomfort. Although our vibrotactile feedback device offers wireless connectivity, we used a wired serial communication in this experiment to reduce delays. A visual shielding prevented participants from seeing their right arm during the experiment, and they were wearing headphones playing pink noise to cover acoustic cues from the device and avoid potential distractions. The experimental procedure was implemented on a PC using Qt (5.12.9, Qt Group, Espoo, Finland), with the software running at a rate of 1 kHz. The monitor showed a simple graphical user interface, which informed the participants about the current status of the experiment.

2) Participants and Experimental Procedure: Twelve participants (two female and ten male, eleven right-handed and one left-handed, age 23.3 $\pm$ 2.3 years) took part in this study. The study received a positive vote from the Ethics Committee of Technische Universität Darmstadt (EK 04/2022) and the participants provided written informed consent. Each participant tested all four feedback methods in two different tasks, corresponding to the directional response task and the angle targeting task in the study by Stanley and Kuchenbecker [18]. For each feedback method, the participants started with the directional response task before conducting the more complex angle targeting task, with each task comprising two sets of trials. Before the actual test set, participants performed a practice set with half the number of trials, which served for gaining intuition of how to respond to the tactile stimuli, as we did not provide any explanation of how the device and the feedback methods worked. After the completion of each condition the participants were presented with a questionnaire (Table I) inspired by [18] to rate the intuitiveness as well as the distinguishability of direction and location, respectively. Responses were collected using visual analog scales implemented as unnumbered sliders with a length of 10 cm and labeled endpoints (Table I), where the indicated position was normalized to a value from 0 to 100. After completing the final condition, participants were additionally asked to name the feedback method that they liked best overall, while still being unaware of the implementation details. The order of conditions was counterbalanced across participants using a Latin square [27].

3) Directional Response Task: In the directional response task, the vibrotactile stimulus indicated a direction in which the wrist was supposed to be rotated (supination/pronation). Starting from the initial wrist orientation, the goal was to quickly rotate the wrist in the direction that was indicated by the vibrotactile cue after a random delay ranging from 1 to 3 s. The vibrotactile cue stopped as soon as a wrist rotation of 45° in the respective direction was reached, and the participant initiated the next trial by returning to the initial wrist orientation and staying there for 3 s. For conditions making use of phantom sensations, the vibrotactile cues were placed at $\pm 90°$ instead, as $\pm 45°$ coincide with the locations of actuators 1 and 4. For conditions using the adaptive amplitude, the initial cue strength was equal to the strength used in the constant amplitude conditions, which was about 50% of the actuator maximum. Each test set of the directional task consisted of 12 trials, with six trials for each direction in randomized order. Participants were instructed that the indicated directions were randomized, but they were not informed about the equal number of trials for each direction. Furthermore, they were instructed that moving in the right direction was more important than speed to avoid anticipatory behavior.

4) Angle Targeting Task: In the angle targeting task, the vibrotactile cues indicated eight specific target angles ($\pm 22.5°$, $\pm 45°$, $\pm 67.5°$, $\pm 90°$) to which the participants were asked to rotate their wrist. As in the directional response task, the participant started from the initial wrist orientation and the vibrotactile cue started after a random delay ranging from 1 to 3 s. The vibration stopped as soon as a tolerance band of $\pm 7.5°$ around the target angle was reached, and the participant needed to keep the wrist within the tolerance band for 1 s to finish the trial [18]. If the tolerance band was left early, i.e., before the 1 s had elapsed, the vibration started again and the trial continued. After trial completion, the participant initiated the next trial as in the directional response task by returning to the initial wrist orientation. For the conditions using a constant amplitude, the cue strength was set to about 50% of the actuator maximum. The slope of the adaptive amplitude was chosen so that the cue strength was 25% of the actuator maximum at the edge of the tolerance band and 100% at a target distance of 90°. During individual trials, the phantom sensation cue remained at the same location on the skin. Each target angle was tested twice, resulting an a total number of 16 trials per test set, which were presented in a randomized order. Participants were not informed about the specific target angles and were instructed to reach the randomly-selected targets as fast as possible, with an emphasis on a direct path to avoid random search behavior.

C. Data Analysis and Statistics

We analyze the same characteristics as in Stanley and Kuchenbecker's study [18] to ensure comparability (Table II). For the directional response data, we calculate the reaction time, which is defined as the duration from the start of the vibrotactile cue to the first angular deviation from the initial wrist orientation by more than 1°. We calculate the median reaction time and the interquartile range (IQR) of the reaction times for each participant. In addition, we determine the initial direction accuracy, i.e., the rate of trials in which the wrist is initially moved in the right direction, and the error rate, i.e., the percentage of trials in which the participant crossed the 45° threshold on the wrong side. For the angle targeting task, we normalize the step responses by the respective target angle. We extract the characteristics rise time, settling time, and maximum overshoot, and calculate the median of these characteristics for each participant. The rise time is defined as the duration from 0.1 to 0.9 of the normalized step response or from 0.1 to the beginning of the tolerance band, where the vibration stopped, depending on which value is reached earlier. The settling time is the duration from the start of the vibrotactile cue until the participant finally reached the tolerance band. The maximum overshoot is the furthest position beyond the target angle.

We analyze the calculated characteristics using a two-way repeated measures analysis of variance (ANOVA) with the fixed effects of

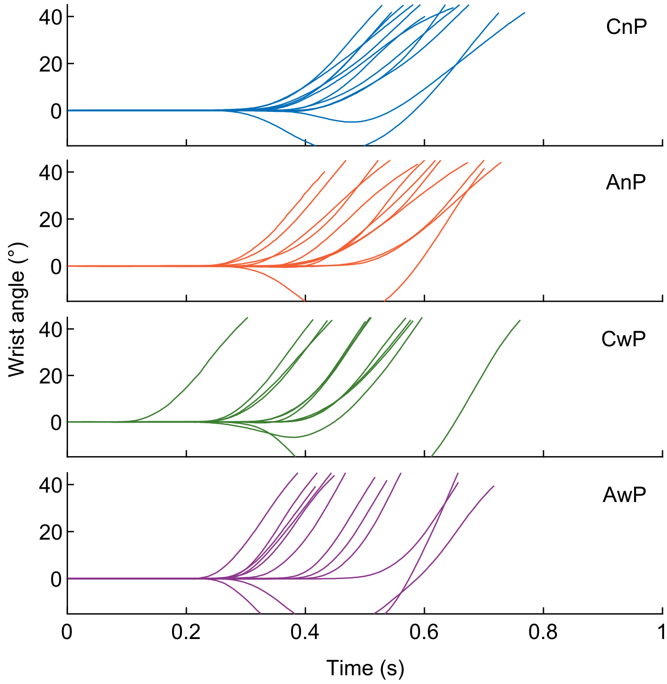

Fig. 3. Directional responses by one participant. Reaction time is measured from the start of the vibrotactile cue at 0 s to the first deviation by more than 1° in either direction. Both movement directions are illustrated using the positive axis for the target direction, and movements in the opposite direction are truncated.

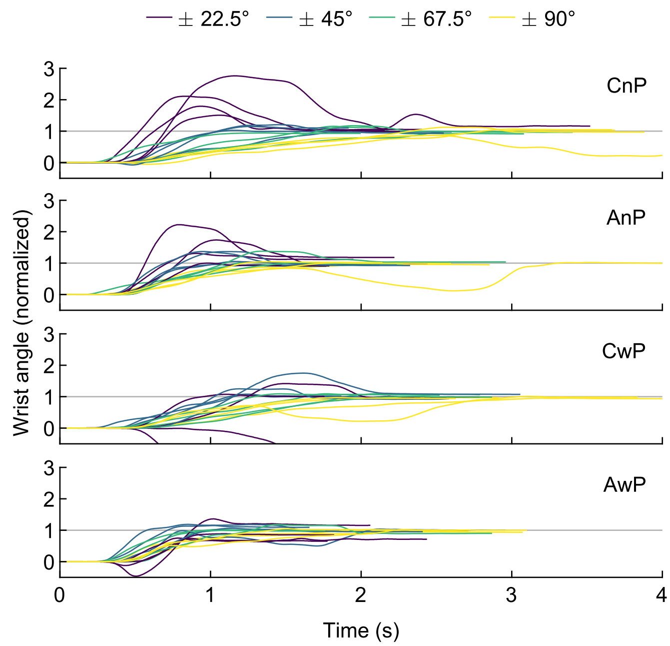

Fig. 4. Normalized step responses from the angle targeting task by one participant. Rise time is the duration from 0.1 to 0.9. Settling time is the duration from start of the vibrotactile cue at 0 s until the participant finally reaches the target. Maximum overshoot is the furthest position beyond the target. Overshooting mainly occurs for the smallest target angles of ±22.5°. Different colors depict different target distances.

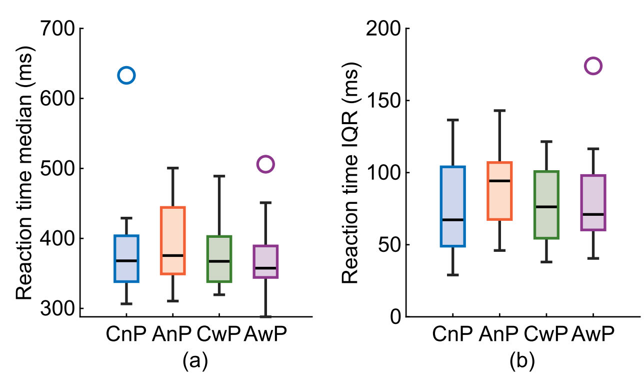

Fig. 5. Directional response characteristics. Reaction time (a) medians and (b) interquartile ranges (IQRs) of the individual participants are similar for all feedback methods. The four feedback methods are combinations of the two factors amplitude type and phantom sensation usage, denoted as constant amplitude (C), adaptive amplitude (A), no phantom sensation (nP), and with phantom sensation (wP).

incorporating an adaptive amplitude and making use of phantom sensations, a first-order interaction, and the participant as random effect. The normality assumption is checked using the Shapiro-Wilk test and Q-Q plots [28]. Since reaction time data is usually not normally distributed, we transform the reaction time, rise time, and settling time data using the decadic logarithm [29] before conducting the ANOVA. Pairwise comparisons are performed using two-sided paired samples t-tests with the Bonferroni correction for multiple comparisons. Unless otherwise stated, averaging is done by calculating the mean and uncertainties are indicated by the standard deviation.

III. Results

Figs. 3 and 4 show the directional responses and the normalized step responses of an exemplary participant, illustrating the data from which the performance characteristics analyzed in the following sections were derived.

A. Directional Response

The reaction time metrics do not significantly differ across conditions (Fig. 5). The reaction time medians of the individual participants range from 325 to 534 ms (381 ± 56 ms), while the individual IQRs range from 51 to 146 ms (88 ± 25 ms). The initial direction accuracies are similar for all conditions ranging from 91.7 to 95.1%, and the error rates are all below 2.1%.

B. Angle Targeting

The rise time differs across feedback methods, as the ANOVA reveals significant effects of both the type of amplitude and the use of phantom sensations, but no significant interaction (Table III). Averaging the rise time medians of the individual participants results in means of 0.96 s, 0.83 s, 0.8 s, and 0.64 s for the methods CnP, AnP, CwP, and AwP, respectively (Fig. 6(a)).

For the settling time, the ANOVA indicates a significant effect of the amplitude type, while incorporating phantom sensations and the interaction are non-significant (Table III). In particular, the pairwise comparison of the conditions CwP and AwP exhibits a significant difference ($p = 0.007$). The averages of the individual settling time medians are 1.74 s, 1.58 s, 1.75 s, and 1.43 s for the methods CnP, AnP, CwP, and AwP, respectively (Fig. 6(b)).

The observed maximum overshoot values are found to be non-normally distributed. Therefore, we refrain from conducting an

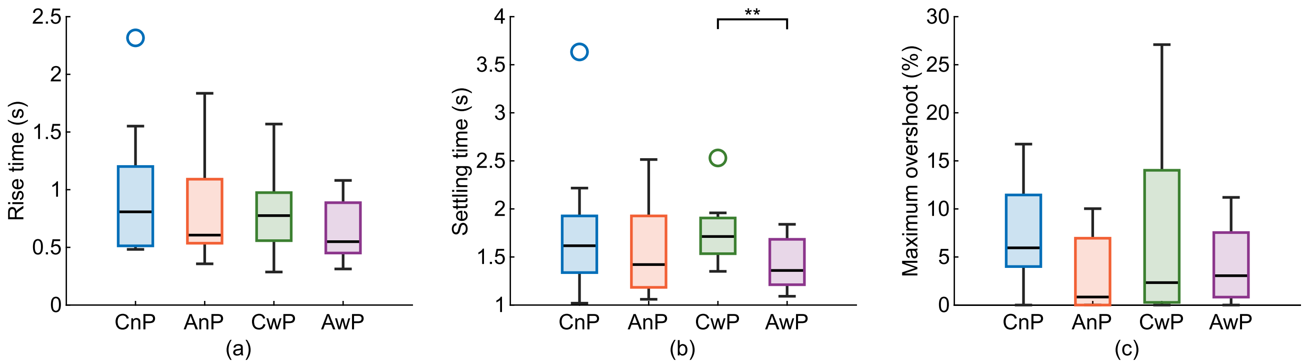

Fig. 6. Angle targeting characteristics. (a) Rise time, (b) settling time, and (c) maximum overshoot for each feedback method. The four feedback methods are combinations of the two factors amplitude type and phantom sensation usage, denoted as constant amplitude (C), adaptive amplitude (A), no phantom sensation (nP), and with phantom sensation (wP). Double asterisks denote statistical significance with $p < 0.01$ (paired samples t-test).

TABLE III
ANOVA Results of Angle Targeting Task

Characteristic	Factor	$F(1,11)$	p	η_p^2
Rise time	Amplitude	**5.121**	**0.045**	**0.318**
	PS	**7.339**	**0.020**	**0.400**
	Interaction	0.198	0.665	0.018
Settling time	Amplitude	**7.966**	**0.017**	**0.420**
	PS	0.048	0.830	0.004
	Interaction	1.852	0.201	0.144

PS: phantom sensation

TABLE IV
ANOVA Results of Subjective Ratings

Characteristic	Factor	$F(1,11)$	p	η_p^2
Intuitiveness	Amplitude	**6.941**	**0.023**	**0.387**
	PS	0.848	0.377	0.072
	Interaction	3.434	0.091	0.238
Discerning direction	Amplitude	0.078	0.785	0.007
	PS	**5.027**	**0.047**	**0.314**
	Interaction	0.019	0.892	0.002
Locating	Amplitude	3.308	0.096	0.231
	PS	**8.855**	**0.013**	**0.446**
	Interaction	2.090	0.176	0.160

PS: phantom sensation

ANOVA and descriptively analyze the data instead. The average maximum overshoot medians are 7.1%, 3.1%, 7.9%, and 4.1% for CnP, AnP, CwP, and AwP, respectively (Fig. 6(c)). For target angles $\pm 22.5^\circ$, overshoot was observed in 83.9% of all cases, while for the target angles $\pm 45^\circ$, $\pm 67.5^\circ$, and $\pm 90^\circ$ participants exceeded the tolerance band around the target angle in 65.6%, 58.9%, and 44.3% of all cases, respectively.

Participants initially moved in the correct direction in 91.3% of all trials, with initial direction accuracies of 91.7%, 94.3%, 87.5%, and 91.7% for the feedback methods CnP, AnP, CwP, and AwP, respectively. However, a notably larger number of incorrect initial movements can be observed for the target angles $\pm 22.5^\circ$, with 33 occurrences, compared to the other three target distances that lead to 10 to 13 initial direction errors. Ten of the 33 erroneous initial directions for the target angles $\pm 22.5^\circ$ occurred without the use of phantom sensations, while 23 occurred when making use of phantom sensations.

C. Subjective Ratings

The ANOVA results of the subjective ratings are given in Table IV. The ratings of intuitiveness exhibit a notably larger range and a lower median for CwP, while the ratings for the other three methods are similar (Fig. 7(a)). In particular, pairwise comparisons exhibit a significant difference between CwP and AwP ($p = 0.039$). Directional distinguishability ratings are in similar ranges for all four methods, while the medians tend to be slightly lower for the methods using phantom sensations (Fig. 7(b)). The ratings of distinguishability of location are lower for CwP compared to the other three methods (Fig. 7(c)), with statistically significant differences compared to CnP ($p = 0.026$) and AnP ($p = 0.049$). When being asked to select their favorite feedback method, only two participants selected more than one method, naming two each. AwP is rated as favorite in 50% of all selections, followed by AnP, CnP, and CwP with 28.6%, 14.3%, and 7.1%, respectively.

IV. Discussion

A. Directional Response

All observed reaction times are larger than 120 ms, which is above the minimum physiologically plausible value (100 ms) based on the time required for stimulus perception and motor response [29]. Furthermore, the reaction time medians are consistent with the results reported for the steady vibration feedback by Stanley and Kuchenbecker [18], where medians range from about 400 to 680 ms, with a tendency of slightly shorter reaction times in our experiment (325 to 534 ms). Another study investigating vibrotactile guidance of elbow flexion and extension observed reaction times of 379 ± 62 ms [30], which closely aligns with our results (381 ± 56 ms). The reaction time IQRs fall into the range observed in [18] and demonstrate consistency across trials. While there are a few trials where participants corrected their movement after initially moving into the wrong direction, participants correctly initialized their movement in 93% of all trials, which is consistent with the observations in [30] and underlines that the direction cues can be reliably detected. The absence of statistically significant differences across the feedback methods appears plausible, as the adaptive amplitude and the phantom sensation convey additional information regarding the target location, which might not be crucial for the decision in which direction to move.

B. Angle Targeting

The significant reductions in rise time observed when incorporating an adaptive amplitude and making use of phantom sensations underline that both effectively convey information about target location, allowing participants to move faster. While the feedback method based

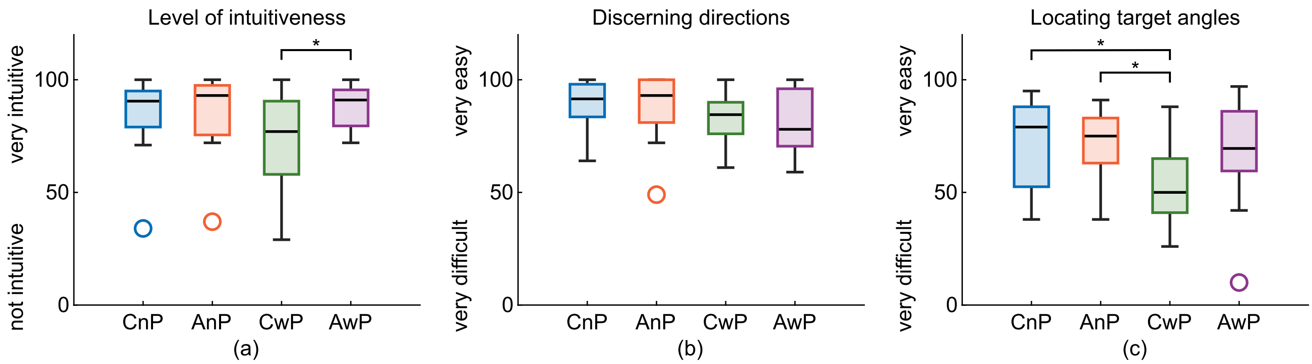

Fig. 7. Subjective ratings. (a) Level of intuitiveness and ease of (b) discerning directions and (c) locating targets are rated for each feedback method. The four feedback methods are combinations of the two factors amplitude type and phantom sensation usage, denoted as constant amplitude (C), adaptive amplitude (A), no phantom sensation (nP), and with phantom sensation (wP). Single asterisks denote statistical significance with $p < 0.05$ (paired samples t-test).

on an adaptive amplitude alone encodes the information about the target location using a combination of direction (actuator location) and distance (actuator amplitude), the method making use of phantom sensations in combination with an adaptive amplitude communicates the target location directly (phantom sensation location). The rise time medians observed for AnP in our study are comparable to the medians observed by Stanley and Kuchenbecker [18] for the feedback "vibration steady", which was among the device-algorithm combinations with the smallest rise times in their study. Additionally incorporating phantom sensations further reduces the rise time (median reduction 24.3%). It is possible that participants became faster due to the added redundancy, which may have benefited information transfer [31]. Compared to the baseline CnP, the reduction achieved when using an adaptive amplitude in combination with phantom sensations is in the same order of magnitude as the reaction times observed in the directional task, which may be particularly beneficial in time-critical tasks.

The significant reduction in the settling time median when using an adaptive amplitude, is consistent with the performance observed for the rise time. In contrast, incorporating phantom sensations shows no clear effect, which can be explained by the opposite tendencies in CwP and AwP. Still, method AwP exhibits the smallest settling times, thus, it appears plausible that making use of phantom sensations in combination with an adaptive amplitude can result in a further reduction compared to using an adaptive amplitude alone.

The results indicate that methods using an adaptive amplitude are less prone to overshoot than methods using a constant amplitude, which we expected since the adaptive amplitude encodes the current distance to the target angle. While the quantitative amount of overshoot may be affected by the chosen tolerance band width, the observed tendencies are expected to be consistent since the same width was used across all conditions. The notably increased occurrence of overshoot for the smallest target distance is plausible as the targets are close to the initial wrist orientation, which requires stopping already shortly after initiating the wrist rotation.

Although previous studies have found the average error in locating vibrotactile stimuli around the forearm circumference to be less than 10° [14], [25], our results imply difficulties in discerning the two target angles right next to the initial wrist orientation, in particular for the feedback methods using phantom sensations. We assume this is due the fact that inducing a phantom sensation at ±22.5° involves one actuator on each side of the forearm, i.e, actuators 1 and 4, which might have negatively impacted the participants' accuracy in locating these stimuli. As both of the involved actuators are placed in proximity of the radial bone (Fig. 2(a)), structure-borne propagation of the vibrations might have resulted in more diffuse vibrotactile stimuli [32], making a precise locating more difficult. Since these difficulties are more prevalent with the method CwP, where even small target distances are indicated at full strength, the effect appears to be more pronounced at stronger vibrations. Furthermore, slight misalignment of the vibrotactile device might have contributed to perceiving the stimulus on the wrong side of the forearm.

C. Subjective Ratings

The lower ratings of CwP, in particular for intuitiveness and distinguishability of location, are consistent with the reduced performance observed in the angle targeting task. The similar ratings for the distinguishability of direction correspond to the performance in the directional task, where no significant differences in reaction time appear. The tendency of a slightly lower median for the methods using phantom sensations may be explained by the observed difficulties for the target angles ±22.5°. These difficulties are also reflected by comments of multiple participants who reported they found it difficult to discern the target angles next to the initial wrist orientation. Nevertheless, more than half of the participants chose AwP as their favorite feedback method, which indicates that this potential drawback is outweighed by the benefits of combining an adaptive amplitude with vibrotactile phantom sensations.

V. Conclusion

In this study, we systematically evaluated feedback methods for vibrotactile wrist rotation guidance. While there were no significant performance differences across feedback methods in the directional response task, encoding the target distance in the stimulus strength proves to be beneficial with respect to all investigated performance metrics and appears particularly important to avoid excessive overshoot. Communicating target locations in a more differentiated way using the vibrotactile phantom sensations, in particular when combined with an adaptive amplitude, can further improve the performance. While it appears that the phantom sensation implementation can be improved for small target distances, still more than half of the participants chose the feedback method making use of an adaptive amplitude and phantom sensations as their overall favorite method. This underlines that incorporating phantom sensations not only leads to performance improvements but also to an enhanced user experience. Further improvements to the control algorithm may involve dynamically adjusting the phantom sensation cue location in real-time to maintain its alignment in the world reference frame and exploring alternative nonlinear mappings between target distance and cue strength. Future work may also test the vibrotactile wrist rotation guidance in application-oriented scenarios and in combination with wrist position guidance, where it may be particularly interesting to evaluate the user's cognitive load under different feedback methods. Altogether, the results of this study contribute to the advancement of vibrotactile wrist guidance, thereby promoting the development of wearable devices for haptic guidance in assistive scenarios and human-robot interaction.

References

[1] Y. A. Sekhavat and M. S. Namani, "Projection-based AR: Effective visual feedback in gait rehabilitation," *IEEE Trans. Hum.-Mach. Syst.*, vol. 48, no. 6, pp. 626–636, Dec. 2018.

[2] F. Bevilacqua et al., "Sensori-motor learning with movement sonification: Perspectives from recent interdisciplinary studies," *Front. Neurosci.*, vol. 10, Aug. 2016, Art. no. 385.

[3] J. Lieberman and C. Breazeal, "TIKL: Development of a wearable vibrotactile feedback suit for improved human motor learning," *IEEE Trans. Robot.*, vol. 23, no. 5, pp. 919–926, Oct. 2007.

[4] F. Chinello, C. Pacchierotti, J. Bimbo, N. G. Tsagarakis, and D. Prattichizzo, "Design and evaluation of a wearable skin stretch device for haptic guidance," *IEEE Robot. Autom. Lett.*, vol. 3, no. 1, pp. 524–531, Jan. 2018.

[5] L. R. Elliott, M. D. Coovert, and E. S. Redden, "Overview of meta-analyses investigating vibrotactile versus visual display options," in *Proc. Hum.-Comput. Interaction. Novel Interaction Methods Techn., 13th Int. Conf., HCI Int. 2009*, Berlin, Heidelberg, 2009, pp. 435–443.

[6] K. Bark et al., "Effects of vibrotactile feedback on human learning of arm motions," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 23, no. 1, pp. 51–63, Jan. 2015.

[7] C. G. Corrêa, F. L. Nunes, E. Ranzini, R. Nakamura, and R. Tori, "Haptic interaction for needle insertion training in medical applications: The state-of-the-art," *Med. Eng. Phys.*, vol. 63, pp. 6–25, Jan. 2019.

[8] P. B. Shull and D. D. Damian, "Haptic wearables as sensory replacement, sensory augmentation and trainer–A review," *J. Neuroeng. Rehabil.*, vol. 12, 2015, Art. no. 59.

[9] S. A. Satpute, J. R. Canady, R. L. Klatzky, and G. D. Stetten, "FingerSight: A vibrotactile wearable ring for assistance with locating and reaching objects in peripersonal space," *IEEE Trans. Haptics*, vol. 13, no. 2, pp. 325–333, Apr.–Jun. 2020.

[10] M. Aggravi, G. Salvietti, and D. Prattichizzo, "Haptic wrist guidance using vibrations for human-robot teams," in *Proc. 25th IEEE Int. Symp. Robot Hum. Interactive Commun.*, New York, NY, USA, 2016, pp. 113–118.

[11] S. Fani, S. Ciotti, and M. Bianchi, "Multi-cue haptic guidance through wearables for enhancing human ergonomics," *IEEE Trans. Haptics*, vol. 15, no. 1, pp. 115–120, Jan.–Mar. 2022.

[12] W. Kim, V. Ruiz Garate, J. M. Gandarias, M. Lorenzini, and A. Ajoudani, "A directional vibrotactile feedback interface for ergonomic postural adjustment," *IEEE Trans. Haptics*, vol. 15, no. 1, pp. 200–211, Jan.–Mar. 2022.

[13] A. Dwivedi, S. Yu, C. Hao, G. Salvietti, D. Prattichizzo, and P. Beckerle, "How positioning wearable haptic interfaces on limbs influences virtual embodiment," *IEEE Trans. Haptics*, vol. 17, no. 2, pp. 292–301, Apr.–Jun. 2024.

[14] J. V. Salazar Luces, K. Okabe, Y. Murao, and Y. Hirata, "A phantom-sensation based paradigm for continuous vibrotactile wrist guidance in two-dimensional space," *IEEE Robot. Automat. Lett.*, vol. 3, no. 1, pp. 163–170, Jan. 2018.

[15] J. Salazar, K. Okabe, and Y. Hirata, "Path-following guidance using phantom sensation based vibrotactile cues around the wrist," *IEEE Robot. Automat. Lett.*, vol. 3, no. 3, pp. 2485–2492, Jul. 2018.

[16] S. Günther, F. Müller, M. Funk, J. Kirchner, N. Dezfuli, and M. Mühlhäuser, "TactileGlove: Assistive spatial guidance in 3D space through vibrotactile navigation," in *Proc. 11th PErvasive Technol. Related Assistive Environments Conf.*, Corfu, Greece, Jun. 2018, pp. 273–280.

[17] S. Basu, J. Tsai, and A. Majewicz, "Evaluation of tactile guidance cue mappings for emergency percutaneous needle insertion," in *Proc. 2016 IEEE Haptics Symp.*, Philadelphia, PA, USA, 2016, pp. 106–112.

[18] A. A. Stanley and K. J. Kuchenbecker, "Evaluation of tactile feedback methods for wrist rotation guidance," *IEEE Trans. Haptics*, vol. 5, no. 3, pp. 240–251, Third Quarter 2012.

[19] S. Schätzle, T. Ende, T. Wüsthoff, and C. Preusche, "VibroTac: An ergonomic and versatile usable vibrotactile feedback device," in *Proc. 19th Int. Symp. Robot Hum. Interactive Commun.*, Viareggio, Italy, 2010, pp. 670–675.

[20] M. Aggravi, F. Pausé, P. R. Giordano, and C. Pacchierotti, "Design and evaluation of a wearable haptic device for skin stretch, pressure, and vibrotactile stimuli," *IEEE Robot. Automat. Lett.*, vol. 3, no. 3, pp. 2166–2173, Jul. 2018.

[21] E. Pezent et al., "Tasbi: Multisensory squeeze and vibrotactile wrist haptics for augmented and virtual reality," in *Proc. 2019 IEEE World Haptics Conf.*, Tokyo, Japan, 2019, pp. 1–6.

[22] J. Kindel, D. Andreas, Z. Hou, A. Dwivedi, and P. Beckerle, "A wearable bidirectional human–machine interface: Merging motion capture and vibrotactile feedback in a wireless bracelet," *Multimodal Technol. Interaction*, vol. 8, no. 6, May 2024, Art. no. 44.

[23] P. Beckerle, C. Castellini, and B. Lenggenhager, "Robotic interfaces for cognitive psychology and embodiment research: A research roadmap," *Wiley Interdiscipl. Rev., Cogn. Sci.*, vol. 10, no. 2, Mar./Apr. 2019, Art. no. e1486.

[24] A. Barghout, J. Cha, A. El Saddik, J. Kammerl, and E. Steinbach, "Spatial resolution of vibrotactile perception on the human forearm when exploiting funneling illusion," in *Proc. IEEE Int. Workshop Haptic Audio Vis. Environments Games*, Lecco, Italy, 2009, pp. 19–23.

[25] J. Seiler et al., "Wearable vibrotactile interface using phantom tactile sensation for human-robot interaction," in *Proc. Haptics, Sci., Technol., Appl., 12th Int. Conf.*, Cham, Switzerland, 2020, vol. 12272, pp. 380–388.

[26] A. Israr and I. Poupyrev, "Tactile brush: Drawing on skin with a tactile grid display," in *Proc. SIGCHI Conf. Hum. Factors Comput. Syst.*, Vancouver, BC, Canada, 2011, pp. 2019–2028.

[27] J. V. Bradley, "Complete counterbalancing of immediate sequential effects in a Latin square design," *J. Amer. Stat. Assoc.*, vol. 53, no. 282, pp. 525–528, Jun. 1958.

[28] M. B. Wilk and R. Gnanadesikan, "Probability plotting methods for the analysis of data," *Biometrika*, vol. 55, no. 1, pp. 1–17, Mar. 1968.

[29] R. Whelan, "Effective analysis of reaction time data," *Psychol. Rec.*, vol. 58, pp. 475–482, Jul. 2008.

[30] P. B. Shull, X. Zhu, and M. R. Cutkosky, "Continuous movement tracking performance for predictable and unpredictable tasks with vibrotactile feedback," *IEEE Trans. Haptics*, vol. 10, no. 4, pp. 466–475, Oct.–Dec. 2017.

[31] C. E. Sherrick, "A scale for rate of tactual vibration," *J. Acoust. Soc. America*, vol. 78, no. 1, pp. 78–83, Jul. 1985.

[32] C. E. Sherrick Jr., "Variables affecting sensitivity of the human skin to mechanical vibration," *J. Exp. Psychol.*, vol. 45, no. 5, pp. 273–282, 1953.