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Studying the Perception of Vibrotactile Stimulation on the Arm via a Modular Wearable Sleeve

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***Abstract*—This study investigates the perception of vibrotactile stimulation on the human arm using a modular wearable sleeve equipped with vibrotactile actuators. We examined three perceptual aspects: vibration localization, apparent haptic motion (AHM), and two-point discrimination (2PD). Our findings indicate that users can accurately identify the location of four distinct vibrotactile stimuli with over 95% accuracy across the wrist, forearm, upper arm, and shoulder. Additionally, participants demonstrated reliable perception of apparent motion, though minor misclassifications in directional cues were observed in the upper arm and shoulder regions. The two-point discrimination results revealed that spatial acuity decreases from the wrist to the upper arm, with the shoulder exhibiting better discrimination than expected. These findings provide preliminary insights for the design of wearable haptic feedback systems in applications such as rehabilitation, virtual reality, and assistive navigation.**

***Index Terms*—haptics, vibrotactile, arm, mapping.**

I. Introduction

The human sense of touch plays a critical role in perceiving and interacting with the physical world. Advances in haptic technologies have opened new avenues for enhancing sensory feedback in applications ranging from rehabilitation to virtual reality [6], [10]. One key area of research within haptics is vibrotactile stimulation [4], which leverages vibrations to communicate information through the skin. Many studies have investigated the responses of various regions of the arm to vibrotactile stimuli. However, a comprehensive study examining the entire arm, spanning from the wrist to the shoulder, remains unexplored.

The objective of this paper is to provide a preliminary analysis of the arm's response to vibrotactile stimuli across its full length. To achieve this, we focus on four key regions of the arm: wrist, forearm, upper arm, and shoulder. Our investigation includes three experiments. The first evaluates whether participants can accurately identify the location of vibrotactile stimuli applied to different regions of the arm. The second focuses on pattern recognition capabilities through the apparent haptic motion illusion, while the final experiment examines two-point discrimination thresholds across dorsal and ventral regions. To do this, we developed a wearable vibrotactile sleeve for the arm, featuring housing pockets to position the vibrotactile actuators along the user's arm. The sleeve can be adapted to best match the morphology of the user's arm.

II. Related Works

The sense of touch allows humans to interact with the external environment, with sensations arising from mechanoreceptors embedded in the skin. These mechanoreceptors can be categorized into fast-adapting (FAI, FAII) and slow-adapting (SAI, SAII) types [7]. Meissner's corpuscles (FAI), located predominantly in glabrous skin such as the palms, are sensitive to low-frequency stimuli (5-50 Hz), while Pacinian corpuscles (FAII), found in hairy skin like the forearm, respond to high-frequency stimuli (40-400 Hz) [5], [22], [26]. Understanding the sensory mapping of the human arm is essential for advancing vibrotactile feedback systems in applications such as rehabilitation, industrial training, and robotics [1], [2], [21]. Prior research has explored various aspects of vibrotactile stimulation, including localization, intensity perception, spatial resolution, and directional feedback. However, most studies have focused on specific regions of the arm or limited aspects of sensory responses, leaving gaps in the understanding of the arm's tactile capabilities. A characterization of tactile sensitivity along the entire length of the arm would enable more flexible placement of haptic devices, allowing adaptation to specific application needs, for example, in cases involving individuals with limb amputation or sensory deficits due to neurological conditions.

A. Vibration localization

The first step in understanding sensory responses in the arm is to evaluate whether users can accurately identify the location of vibrotactile stimuli. This involves determining if participants can perceive vibrations as originating from, e.g., the dorsal, ventral, lateral, or medial regions of the arm. Accurate localization is particularly useful in haptic-assisted navigation and feedback systems for visually impaired individuals [30]. Previous research has demonstrated that users can reliably distinguish between different stimulation sites. Prabhu et al. [25] showed that users could identify vibrotactile stimuli on the forearm with high accuracy. Similarly, Pardo et al. [23] found that participants could discern between vibrations applied to the lateral and medial regions of the wrist, forearm, and upper arm. Additionally, research on torso-based vibrotactile displays has indicated that even untrained users can achieve rapid adaptation to directional cues provided via vibration [32]. Building on these findings, our study extends previous work by evaluating localization accuracy across the entire arm, including the wrist, forearm, upper arm, and shoulder , an area not previously examined in related work, and by evaluating all four anatomical sides. Although some prior studies have investigated various arm locations, they have typically been limited to the lateral and medial sides, with the dorsal and ventral aspects largely neglected. This approach is designed to account for variations in skin properties (e.g., differences between hair-covered and hairless areas) and the distribution of mechanoreceptors along the arm, both of which can influence perceptual accuracy. By investigating these aspects, we aim to improve the efficiency of vibrotactile communication for wearable haptic devices.

B. Apparent Haptic Motion (AHM)

Apparent haptic motion (AHM) is an illusion allowing for the perception of continuous motion through sequential activation of discrete stimuli [28]. AHM has been studied in various contexts, including its application in navigation aids, robotic feedback systems, and immersive virtual environments [11], [33], [34]. Prior research has demonstrated that AHM can effectively guide users along predefined paths, even in the absence of visual feedback [31]. Studies by Israr et al. [12] have shown that adjusting inter-stimulus timing and intensity can significantly affect the perception of continuous movement. Additionally, recent work by Lacôte et al. [15]–[18] has explored the use of "tap" stimulations as an alternative to traditional vibrotactile cues, finding that tap-based feedback can generate motion illusions comparable to vibrotactile stimulation at 120 Hz. While AHM has been well studied in torso and hand applications, its effectiveness in full-arm mapping remains less explored. Our research investigates how different stimulation parameters influence the perception of motion along the arm, contributing to a more comprehensive understanding of AHM in wearable haptic devices.

C. Spatial acuity and tactile resolution

Two-point discrimination (2PD) is used for assessing spatial acuity and tactile resolution. The ability to distinguish between two closely spaced points of stimulation varies across different areas of the body and is influenced by mechanoreceptor density and neural processing [29]. Prior research has established that 2PD thresholds for pressure stimulation are smallest in regions with a high density of Merkel cells, such as the fingertips, and increase significantly in areas with lower receptor density, such as the upper arm [14]. Focusing on pressure stimulation, Shibin et al. [29] examined 2PD variations along the arm and found significant differences between the dorsal and ventral regions. Similar studies have shown that vibrotactile 2PD thresholds are generally larger than those for pressure stimuli, suggesting that spatial resolution differs between tactile modalities [24]. Additionally, frequency-dependent effects on vibration propagation have been observed, influencing how users perceive vibrotactile patterns at different stimulation points [27]. Understanding spatial acuity is of course important for designing wearable haptic devices. Research has shown that good actuator spacing and vibration intensity can improve discrimination thresholds [3]. Our study aims to extend this knowledge by examining 2PD variations along the entire arm and how they may influence vibrotactile feedback systems.

III. Methods

A. Areas of interest

Mechanoreceptors in the skin exhibit differential responses to variations in frequency, with their density increasing from the proximal to the distal regions of the limb [13], [19]. Additionally, variations in skin properties have been shown to influence intensity perception [8], [25]. To investigate these variations across different regions of the arm and better understand how skin mechanics and mechanoreceptor distribution impact intensity perception, we selected four arm areas for our analysis (see Fig. 1): wrist, forearm, upper arm, and shoulder. Furthermore, to examine the potential influence of hairless skin on the ventral side of the arm, both dorsal and ventral surfaces were analyzed for each region, with the exception of the shoulder, which lacks space on the ventral side.

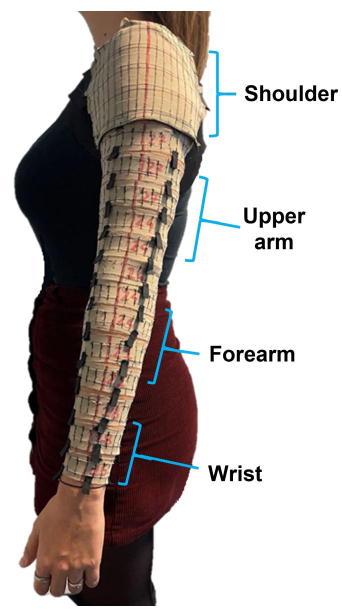

Fig. 1. Modular wearable sleeve. User wearing the modular sleeve to test four locations of the arm: wrist, forearm, upper arm, and shoulder. The sleeve can be adapted to best match the morphology of the user's arm.

B. Modular wearable sleeve

To conduct our experiments, we required a system that facilitated the quick and precise placement of vibromotors across the entire arm, adaptable to individuals of varying arm morphology, and that ensured high repeatability in the tested areas. To achieve these objectives, we developed a modular sleeve constructed from elastic fabric, comprising a shoulder-covering piece and several armbands of varying sizes that can be easily attached to one another using Velcro strips (see Fig. 1). The shoulder piece is secured to a band that encircles the chest and the portion of the shoulder near the neck. The number and size of the armbands are adjusted based on the length and circumference of the participant's arm. Additionally, to ensure consistent positioning of all components, a red line is marked at the center of the shoulder, and each armband is positioned such that its corresponding red line aligns with that of the shoulder piece. Each component of the system is designed with a variable number of 1-cm pockets (e.g., a 15 cm armband contains 15 pockets), into which the vibromotors can be easily placed. This design ensures precise positioning and modularity. The system holds potential for applications requiring detailed analysis of skin sensitivity across the arm with high repeatability, particularly in scenarios where arm sizes vary considerably. An example is haptic perception research on phantom limb sensations in amputees, which serves as a future objective for our applications.

C. Vibrotactile actuators

We used 7-mm-diameter Eccentric Rotating Mass (ERM) motors[1], with the number of vibromotors varying from 4 to 8 depending on the specific experiment (see the following Sections). Vibration stimuli were generated as constant signals with a fixed frequency of 200 Hz, selected to fall near the mid-point of the Pacinian corpuscles' sensitivity range [5], while the duration of each stimulus varied depending on the specific experimental condition. Motor control was implemented using an ESP32 microcontroller interfaced with two L293D motor driver shields, each independently operating four vibromotors.

D. Participants

In all the three experiments, 15 participants were involved (6 female and 9 male, age mean 27, SD:$\pm$ 6, 12 right hand and 3 left hand). Both male and female participants were included, as gender does not significantly influence skin sensitivity [20], [29]. On a scale from 1 to 5, 60% of the participants reported an experience rating of 3 or higher, with only one participant indicating zero experience with haptic feedback. All participants provide informed consent to join the study.

IV. Experiment #1: Vibration Localization

We began by evaluating whether a vibration stimulus enables users to accurately identify its location as being in the dorsal, ventral, lateral, or medial part of the examined region.

A. Setup

During the experiment, the participant was seated in front of a computer, with the right hand free to move and respond to the test using a mouse, while the left arm was wearing the sleeve. The four regions of the arm were examined sequentially, starting from the wrist and progressing up to the shoulder. In each region four motors were positioned at 90-degree intervals on the medial, dorsal, ventral, and lateral sides (see Fig. 2), with the exception of the shoulder, which lacks space on the ventral side. For the wrist and forearm regions, the participant rested the left elbow on the table and placed the hand on a box, ensuring that the ventral motor did not come into contact with the table, thus avoiding interference with the perception of the stimulus. During the tests for the arm and shoulder regions, both the forearm and hand were also placed on the table. Each motor was activated individually, and the participant was instructed to indicate, at the end of each stimulation, which side they felt the vibration. The activation order was randomized, and each side was activated four times.

The stimulus was a vibration burst of 200 Hz that lasted 1000 ms.

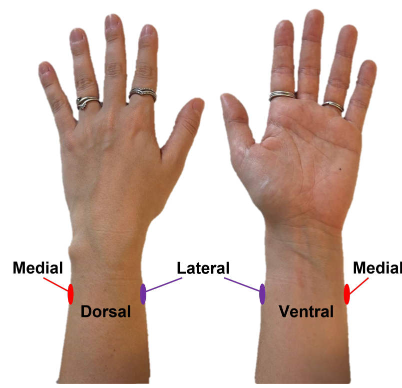

Fig. 2. Sides of the arm: medial, dorsal, ventral, lateral.

B. Results

To obtain an overview of the data, we constructed four confusion matrices, each corresponding to one of the arm positions, based on the participants' responses. Due to space constraints, only the confusion matrix for the upper arm is shown, as an example of all the matrices (see Fig. 3). From these matrices, we calculated the accuracies for identifying each target location, as presented in Table I. Considering the different positioning along the arm, stimulations at the wrist achieved an overall accuracy of 98.7%, the forearm 97.1%, the upper arm 98.3%, and the shoulder 98.3%; considering the different sides around the arm, stimulations on the medial side exhibited an accuracy of 99.6%, the dorsal side 96.7%, the lateral side 98.3%, and the ventral side 97.8%.

To assess potential statistically significant differences, we used a logistic regression model on the collected data with respect to the two conditions: the arm positions (wrist, forearm, upper arm, shoulder) and the sides of stimulation (medial, dorsal, ventral, lateral). Participants were considered as a random effect in the model. An analysis of deviance for the side answers showed a significant effect on the sides of the stimulation ($p = 0.02$). We did not find any interaction effect between the two conditions. Overall, the skin sensitivity across the entire arm was sufficient to enable participants to

[1] https://www.vybronics.com/erm-cylindrical-vibration-motors/encapsulated/v-z6dl2b0055211

accurately identify the vibration location, with accuracy levels consistently exceeding 95%. This suggests that it would be interesting to study more complex localization tasks, e.g., asking users to recognize the location of eight (or more) vibration stimulations across the arm.

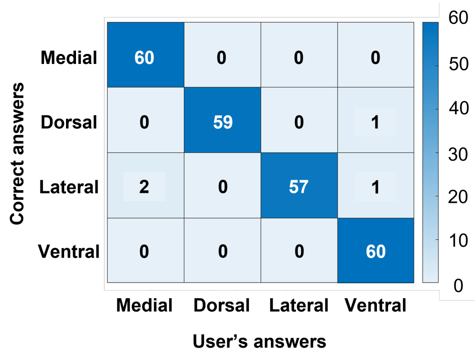

Fig. 3. Confusion matrix for the localization test around the upper arm.

TABLE I
ACCURACY OF THE LOCALIZATION TEST

Location	Medial	Dorsal	Lateral	Ventral
Wrist	98.3%	98.3%	100%	98.3%
Forearm	100%	95%	98.3%	95%
Upper arm	100%	98.3%	95%	100%
Shoulder	100%	95%	100%	-

V. EXPERIMENT #2: APPARENT HAPTIC MOTION

The second experiment focused on studying whether a sequence of vibratory stimuli allows participants to accurately identify the direction of vibration movement on both the dorsal and ventral sides of the examined regions.

A. Setup

During the experiment, the participant was seated in front of a computer, with the right hand free to move and respond to the test using a mouse, while the left arm, which was wearing the sleeve, rested on the table. The four regions of the arm were examined sequentially, starting from the wrist and progressing toward the shoulder. In each region, testing was conducted first on the dorsal side, followed by the ventral side, with the exception of the shoulder, which lacks a ventral side. The examined side was always positioned upwards to prevent interference from the motors coming into contact with the table. In each tested area, five motors were positioned in a cross configuration (see Fig. 4-right). A sensation of movement was elicited each time three motors were activated sequentially, according to the AHM paradigm [17]. Figure 4-right illustrates the specific motors activated and their order depending on the direction of vibration intended. At the end of each sequence, the participant was asked to indicate the direction of the vibration they perceived. To avoid confusion between forward/backward and right/left, a picture with four arrows representing the possible directions was displayed on the screen for both dorsal (see Fig. 4-left) and ventral (see Fig. 4-center) conditions. This setup was inspired from [17]. Each stimulus was a vibration burst of 200 Hz that lasted 300 ms.

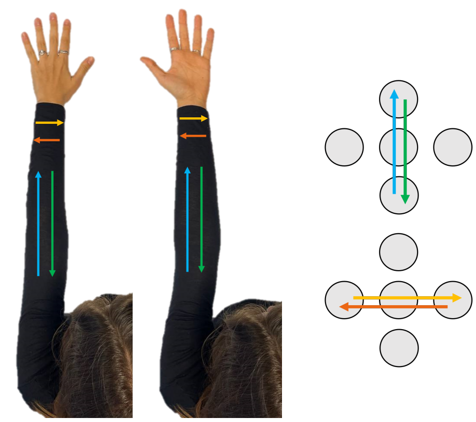

Fig. 4. Directions of the stimulation for the AHM test. Images showed to the users during the execution of the experiment in the dorsal (left) and ventral (center) condition. Position of the vibromotors and activation sequence for each direction: forward (right-up blue arrow), backward (right-up green arrow), right (right-down yellow arrow), and left (right-down orange arrow)

B. Results

To obtain an overview of the data, we considered seven confusion matrices, each corresponding to one of the arm positions and sides, based on participants' responses. Due to space limitations, only the confusion matrix for the ventral side of the wrist is presented as an example (see Fig.5). From these matrices, the accuracies for identifying each direction at each side and position were calculated, and the results are summarized in Table II. Regarding the locations, the wrist achieved an overall accuracy of 91.7%, the forearm 90.4%, the upper arm 85.4%, and the shoulder 84.2%. In terms of the sides of stimulation, the dorsal side exhibited an accuracy of 88.2%, while the ventral side achieved 88.7%. Regarding the directions of the apparent motion, the forward movement had an accuracy of 86.9%, the backward movement 88.6%, the right movement 89.8%, and the left movement 88.6%. To assess potential statistically significant differences, we used a logistic regression model on the collected data with respect to the three conditions: the arm positions (wrist, forearm, upper arm, shoulder), the sides of stimulation (ventral, dorsal) and the directions of apparent movement (forward, backward, right, left). Participants were considered as a random effect in the model. An analysis of deviance for the motion direction answers showed a significant effect on the arm position ($p = 0.001$). We did not find any interaction effect between the conditions. We performed a post-hoc analysis using a Tukey test adapted to the logistic generalized regression model. Regarding the arm positions, we found a significant effect between the upper arm and the forarm ($p = 0.03$), between the upper arm and the wrist ($p = 0.01$), between the shoulder and the forarm ($p = 0.02$) and between the shoulder and the wrist ($p = 0.01$).

It is important to highlight certain misclassifications that occurred in more than 10% of the cases. For instance, when examining the dorsal side of the shoulder, the forward movement was misclassified as a right movement 13% of the time, while the left movement was misclassified as a right movement 15% of the time. On the ventral side of the forearm, the forward movement was misclassified as right 13% of the time. For the upper arm, the backward movement was identified as right nearly 22% of the time, while the right movement was identified as left approximately 12% of the time. Additionally, on the dorsal side of the upper arm, the left movement was misclassified as right 15% of the time. Other misclassifications occurred less frequently. Among these errors, 61% were due to the correct motor sequence being detected but with the wrong direction, such as mixing left with right or forward with backward. The remaining 39% of errors involved confusing longitudinal movements (forward or backward) with transversal movements (right).

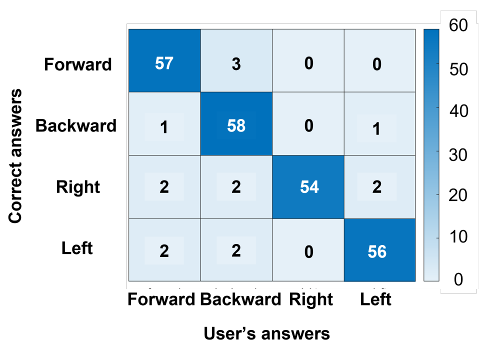

Fig. 5. Confusion matrix for the AHM test on the ventral side of the wrist.

TABLE II
ACCURACY OF THE APPARENT HAPTIC MOTION EXPERIMENT

Location	Side	Forward	Backward	Right	Left
Wrist	Dorsal	80%	86.6%	95%	96.6%
Wrist	Ventral	95%	96.6%	90%	93.3%
Forearm	Dorsal	90%	90%	93.3%	96.6%
Forearm	Ventral	83.3%	88.3%	90%	91.6%
Upper arm	Dorsal	85%	96.6%	88.3%	76.6%
Upper arm	Ventral	95%	73.3%	78.3%	90%
Shoulder	Dorsal	80%	88.3%	93.3%	75%

VI. Experiment #3: Two-Point Discrimination

The third experiment focused on investigating the two-point discrimination (2PD) threshold across the arm.

A. Setup

During the experiment, the participant was seated in front of a computer, with the right hand free to move and respond to the test using a mouse, while the left arm, which was wearing the sleeve, rested on the table. The four regions of the arm were examined sequentially, starting from the wrist and progressing toward the shoulder. In each region, testing was conducted first on the dorsal side, followed by the ventral side, with the exception of the shoulder, which lacks a ventral side. The examined side was always positioned upwards to prevent interference from the motors coming into contact with the table. Following the methodology of Elsayed et al. [9], we activated two vibromotors at 7 cm apart and then progressively reduced the distance of 1 cm until participants reported perceiving a single vibration. The process was reversed to confirm the threshold. Each cycle of decreasing and increasing the distance was repeated four times, and the results were averaged. The motors vibrate at 200 Hz for 500 ms.

B. Results

The mean values of the 2PD test for each location and side of the arm are presented in Table III. While no clear pattern emerges between the dorsal and ventral sides of the arm, we observe that, at least from the wrist to the upper arm, spatial acuity decreases from distal to proximal. This finding supports the results for the dorsal side reported by Elsayed et al. [9], which we found to be also applicable to the ventral side. Interestingly, the shoulder does not follow this pattern, exhibiting better spatial acuity than the upper arm.

To assess potential statistically significant differences, we used a linear regression model on the collected data with respect to the two conditions: the arm positions (wrist, forearm, upper arm, shoulder) and the sides of stimulation (ventral, dorsal). Participants were considered as a random effect in the model. An analysis of deviance for the distance answers showed a significant effect on the arm position ($p < 0.001$). We did not find any interaction effect between the conditions. We performed a post-hoc analysis using a Tukey test. Regarding the arm positions, we found a significant effect between the upper arm and the forarm ($p = 0.001$) and between the upper arm and the wrist ($p < 0.001$).

TABLE III
DISTANCES OF THE 2PD (MEAN pm STAND. DEVIATION)

Location	Side	2PD (cm)
Wrist	Dorsal	4.4±1.6
Wrist	Ventral	4.2±1.7
Forearm	Dorsal	4.5±1.8
Forearm	Ventral	4.8±1.6
Upper arm	Dorsal	5.4±1.7
Upper arm	Ventral	5.1±1.7
Shoulder	Dorsal	4.8±1.8

VII. Discussion

The findings of this study, although preliminary, contribute to the understanding of vibrotactile perception across different regions of the human arm. By evaluating localization accuracy, apparent haptic motion perception, and two-point discrimination thresholds, we provide insights that can inform the design of wearable haptic interfaces.

The results from the vibration localization experiment indicate that participants were able to accurately identify the site of vibrotactile stimulation across all four tested regions—wrist, forearm, upper arm, and shoulder—with accuracy levels consistently exceeding 95%. This suggests that the mechanoreceptors distributed along the arm, particularly the highly responsive Pacinian corpuscles, are sufficiently sensitive to distinguish between spatially distinct vibrotactile stimuli. While these findings are promising, they also motivate the exploration of more complex localization tasks. For instance, future studies could involve asking participants to identify eight or more stimulation points, while simultaneously performing a cognitive or physical task to introduce potential distractions. Such studies may further reveal the limits (and potential) of spatial encoding using vibrotactile feedback.

In the second experiment, which examined the perception of apparent haptic motion (AHM) across the arm, accuracy levels remained high (above 84% for all conditions) although a slight decrease in performance was observed in the upper arm and shoulder regions. A common misclassification involved confusion between longitudinal and transverse directions. This result suggests that the ability to perceive sequential vibrotactile stimuli as continuous motion may be influenced by variations in skin properties, mechanoreceptor density, or other biomechanical factors. Indeed, the observed decrease in accuracy corresponds with the progressive reduction in the density of Pacinian corpuscles along the arm from distal to proximal regions. Notably, most errors (61%) occurred when the correct motor sequence was detected but the perceived motion direction was incorrect. This agrees with previous research indicating that both the temporal and spatial parameters of stimulation are critical for AHM perception. Optimizing interstimulus intervals and motor spacing could indeed improve directional clarity. Furthermore, integrating vibrotactile feedback with other modalities (such as auditory or visual cues) might help to resolve ambiguities in directional information, particularly in complex real-world scenarios.

The third experiment assessed spatial acuity using a two-point discrimination test. As expected, spatial resolution was highest at the wrist and decreased progressively toward the upper arm, a trend that is consistent with the known distribution of mechanoreceptors. Interestingly, the shoulder exhibited better spatial acuity than the upper arm, suggesting that factors beyond receptor density may influence vibrotactile discrimination. Statistical analysis revealed significant differences in 2PD thresholds between the upper arm and both the wrist and forearm, reinforcing the notion that distal regions of the arm exhibit finer tactile resolution. At the same time, the absence of significant differences between dorsal and ventral regions indicates that vibrotactile spatial acuity is relatively uniform across different arm surfaces.

These experimental results might have implications for the design of wearable haptic feedback systems. The high localization accuracy observed suggests that vibrotactile cues can be effectively employed for spatial encoding on the arm, while the results on AHM indicate that sequential stimulation can create a convincing illusion of motion, which is a feature that may be leveraged in applications such as navigation aids, virtual reality, and assistive technologies. Moreover, the differences in spatial acuity along the arm highlight the need for careful actuator layout design. For instance, regions with lower tactile resolution (e.g., the upper arm) might require wider spacing or more pronounced stimulation, whereas areas with higher spatial acuity may benefit from denser actuator arrangements and finer control of vibration parameters.

In addition to these design considerations, our findings suggest ideas for future research. First, the sample size is quite small (15 participants), meaning that we should re-run these experiments with a larger and more diverse population. Moreover, additional studies should investigate more localized effects within each arm region and explore individual differences such as skin thickness, age, and prior haptic experience. Adaptive systems that adjust vibration parameters in real time based on user-specific feedback (e.g., sensor measurements of skin contact pressure) could enhance the reliability of haptic feedback in varying conditions. Additionally, a more detailed investigation into the temporal dynamics of AHM, possibly involving irregular timing sequences, could identify better parameters for inducing clear haptic motion sensations, while additional studies may reveal how repeated exposure or training influences tactile perception over time. Finally, while the sleeve itself is lightweight and comfortable, the cabling for the vibrotactile actuators currently restricts arm mobility. Future work should address this limitation by analyzing power consumption and exploring wireless solutions that would support greater freedom of movement and enable tactile feedback to be studied during dynamic arm use.

VIII. Conclusion

This study examined vibrotactile perception across the human arm, focusing on localization accuracy, apparent haptic motion, and spatial acuity. Our results show that vibrotactile feedback is reliably perceived across all tested regions, with high accuracy in localization and direction recognition. The findings contribute to the development of wearable haptic technologies, with potential applications in rehabilitation, virtual reality, and assistive navigation. Future research should build upon these insights to further refine haptic feedback strategies and optimize actuator designs for better user experience.

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