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The Effects of Vibrotactile Stimulation of the Upper Extremity on Sensation and Perception: A Study for Enhanced Ergonomic Design

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Abstract

Vibrotactile stimulation has applications in a variety of fields, including medicine, virtual reality, and human–computer interaction. Eccentric Rotating Mass (ERM) vibrating motors are widely used in wearable haptic devices owing to their small size, low cost, and low-energy features. User experience with vibrotactile stimulation is an important factor in ergonomic design for these applications. The effects of ERM motor vibrations on upper-extremity sensation and perception, which are important in the design of better wearable haptic devices, have not been thoroughly studied previously. Our study focuses on the relationship between user sensation and perception and on different vibration parameters, including frequency, location, and number of motors. We conducted experiments with vibrotactile stimulation on 15 healthy participants while the subjects were both at rest and in motion to capture different use cases of haptic devices. Eight motors were placed on a consistent set of muscles in the subjects' upper extremities, and one motor was placed on their index fingers. We found a significant correlation between voltage and sensation intensity (r = 0.39). This finding is important in the design and safety of customized haptic devices. However, we did not find a significant aggregate-level correlation with the perceived pleasantness of the simulation. The sensation intensity varied based on the location of the vibration on the upper extremities (with the lowest intensities on the triceps brachii and brachialis) and slightly decreased (5.9 ± 2.9%) when the participants performed reaching movements. When a single motor was vibrating, the participants' accuracy in identifying the motor without visual feedback increased as the voltage increased, reaching up to 81.4 ± 14.2%. When we stimulated three muscles simultaneously, we found that most participants were able to identify only two out of three vibrating motors (41.7 ± 32.3%). Our findings can help identify stimulation parameters for the ergonomic design of haptic devices.

Keywords: haptic feedback; perception; tactile sensation; vibrotactile stimulation

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1. Introduction

Vibrotactile feedback is a mechanical stimulation that is produced with actuators placed on the skin [1]. This form of stimulation has applications in gaming and virtual reality [2], movement training [3], rehabilitation after stroke [4], and neuromodulation in Parkinson's disease [5]. Research shows that investigating the specifics of vibration perception is essential for the usability of haptic interfaces, particularly in human–computer interaction applications [6]. For haptic feedback with vibrotactile stimulation to advance in these areas, it is necessary to understand how different parameters impact how people respond to the stimulation. Stimulating the upper extremities is interesting for applications like upper-extremity stroke rehabilitation (i.e., hemiparesis) and teaching new motor skills like playing a musical instrument.

How different parameters of vibrotactile stimulation applied to the upper extremities impact sensation and perception has not been previously investigated. In our study, we focused not only on sensation intensity but also on the participants' feedback on the vibration. Most prior studies did not examine how participants experience vibrotactile stimulation, which is important in developing human–computer interaction devices. In this work, we address the following questions: How does varying ERM motor parameters affect sensation and perception regarding upper-extremity muscles? How does upper-extremity movement affect sensation intensity? How does stimulating one versus multiple motors affect sensation? Our hypothesis was that ERM parameters would be strongly correlated with sensation intensity but not perceived pleasantness, for which more heterogeneous responses would be exhibited due to different factors, including age, gender, and skin temperature. We further hypothesized that movement would reduce sensation intensity and that most participants would be able to identify the locations of at least three simultaneously vibrating motors on their upper extremities. In this work, we present a study on 15 healthy participants that analyzed the effects of changing the vibration signal voltage on sensation and perception. Our contributions include (1) an analysis of sensation intensity and perceived pleasantness when changing the voltage stimulation parameter across the upper extremity, (2) a comparison of sensation intensity when the upper extremity is still and when it is actively in movement, and (3) an analysis of how accurately participants can identify the vibrating motors or the stimulated muscles from tactile feedback.

2. Related Work

Vibrotactile feedback has been shown to be effective for delivering tactile cues, as the small size of these systems enables them to be embedded in lightweight garments that do not hinder the movement of the participant [3]. This could help in developing tactile motion guidance for motor learning or rehabilitation therapy, so that participants can practice motions on their own without the presence of a coach or therapist. Previous work has studied the effects of some vibrotactile stimulation parameters in older adults with and without a history of stroke [1]. However, stimulation was limited to the hand and the forearm. Gtat et al. [7] found that a pulse width of 15 ms had an average perceptibility of 50%, thus making it the absolute detection threshold for the average participant. Ng et al. [8] found that high-amplitude and low-frequency stimuli were perceived more intensely than high-frequency and low-amplitude stimuli. Our study focuses on the effects of changing the voltage parameter of ERM motors when the stimulation is applied on the shoulder, upper arm, lower arm, and index finger. Other studies have focused on understanding the effect of the stimulation pattern on controlling an upper-limb prosthetic [9]. They found that the stimulation pattern had no significant effect on sensation intensity. Furthermore, they did not observe a significant difference between the effects of amplitude and frequency on sensation intensity. In our work, we used ERM motors, where voltage affects the rotational speed of the motors. The vibration frequency and vibration amplitude of ERM motors are linked and proportional to the voltage [10]. We chose ERM motors because of their common use in haptic devices [4,11]. We are interested in studying the effects of changing the voltage on sensation, perception, and motor identification in healthy adults. In future work, we plan to investigate different types of motors, where frequency and voltage are not linked.

It is known that tactile sensation in the hand decreases when it is in movement [12], and our work examines whether this effect can also be observed throughout the upper extremities. Bark et al. [3] evaluated the effect of vibrotactile feedback on the learning of arm motions. The vibrating motors were placed on the forearm without regard to placing the motors consistently on the same muscles. In our work, we placed the motors on important muscles in the upper extremity, which can help to study the effects of vibrotactile stimulation in teaching new muscle coordination patterns. Shah et al. [13] developed a study to distinguish stimuli thresholds in the upper extremities using both sequential and simultaneous vibration frequencies. They observed that the discrimination threshold in the front of the forearm was on average 10 Hz lower than the threshold for the back of the forearm. Their results showed that sequentially delivered stimuli were identified more accurately than simultaneously delivered stimuli. We investigated in our study if participants could identify simultaneous vibrating motors in different regions of their upper extremities and at what threshold values.

3. Materials and Methods

We present in this section the vibrotactile stimulation system developed for this study. The system consists of a microcontroller obtained from Arduino (Mega 2560) Shenzhen, China, that has 15 digital pins which can be used for pulse width modulation (PWM) signals. The maximum voltage value of the digital pins is 5 V. The pins are connected to ERM vibrating motors obtained from Seeed Technology (Model # 316040001). We used ERM vibrating motors, where vibration voltage and frequency are linked [10]. To verify the relation between voltage and frequency in ERM motors, we measured the vibration frequency using an accelerometer (SparkFun KX134, Boulder, CO, USA) fed into a Fourier transform function. In Figure 1, we show how the measured frequencies and voltages are linked in ERM motors based on a representative sample ERM motor. We placed 8 motors on specific muscles on the shoulder, upper arm, and lower arm and 1 vibrating motor on the index finger. Figure 2 provides a general description of the system components and shows the placement of the motors on the upper-extremity muscles and on the index finger. We chose these locations for motor placement based on the major muscles in the upper extremity. These muscles are often targeted in haptic devices for rehabilitation (e.g., after stroke), virtual reality training, and motor learning. We also added the index finger, which has dense skin receptors, for comparison with the muscle locations. The control unit of the vibrotactile system was developed in MATLAB (R2021/R2022b). The vibrotactile signal is generated with PWM sent to the Arduino digital pins connected to the vibrating motors. We controlled the vibrating signal voltage and duration in real time. We recorded the participant's verbal response to the changes in these parameters. The control unit communicates with the motors individually via serial communication. We changed the voltage value entered to the motors by changing the PWM duty cycle using the writePWMDutyCycle function in MATLAB [14].

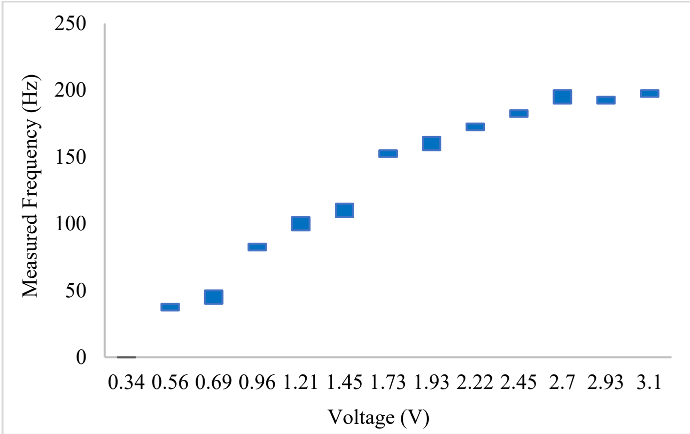

Figure 1. The relationship between measured voltage and frequency with the ERM motors. We observed how both frequency and voltage are linked: as we increase voltage, frequency increases. The bars denote the range of frequencies measured.

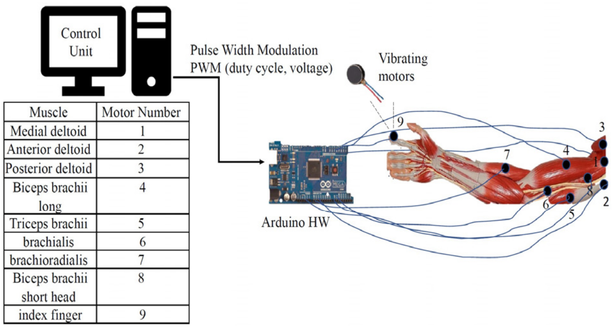

Figure 2. The vibrotactile stimulation system consists of two main components: the Arduino Mega device with attached vibrating motors (numbered 1–9) and the control unit software that sends the voltage values and records the subject's feedback in real time.

4. Sensation and Perception Studies and Protocol

We conducted three separate studies on each participant to investigate how they sensed and perceived the stimulation when the upper extremity was still, how they sensed the stimulation during movement, and to characterize their conscious awareness of which motor was vibrating. Throughout the paper we will use "sensation" to refer to the level of sensation intensity felt on a scale from 1 to 4 (1 = not felt, 2 = low, 3 = medium, 4 = high). We will use the term "perception" to refer to the perceived pleasantness of the stimulation. This will be rated on a scale from 1 to 3 (1 = unpleasant, 2 = neutral, 3 = pleasant). We chose those three values to gain a general understanding of perception as we changed the voltage from low to high. We describe more customized feedback by participants in the Discussion section. One of our objectives was to determine how changing the stimulus's voltage affects sensation intensity and perceived pleasantness. The studies were conducted on 15 healthy adults (13 males and 2 females) with an average age of 26.6 $\pm$ 5.2 years. Participants were recruited for this study voluntarily without consideration of sex or age (minimum age of 18 years old). Each participant participated in the three studies on the same day in consecutive sessions. Participants were given an opportunity to take a break between sessions. The total time for the experiments was an hour per participant. The sample size was chosen based on similar behavioral studies [1]. Participants understood and consented to the protocol approved by the Institutional Review Board of the University.

4.1. Initial Setup

At the start of the session, we asked the participant to be seated, and we placed the vibrotactile device on their dominant upper extremity. The vibrating motors were placed directly on the skin, and they were attached by an elastic tape. The motors were placed on the belly of the following muscles for all participants: anterior deltoid, medial deltoid, posterior deltoid, triceps brachii, brachioradialis, brachialis, biceps brachii long head, and biceps brachii short head. An additional motor was placed on the index finger. We acknowledge that we followed the best protocols in identifying the bellies of the muscles across all participants; however, human errors could have occurred due to variation in the participants' upper-arm weights and sizes. In addition, the use of plastic tape to attach the motors might have led to some variance in the locations. For haptic design, the use of fabric and textiles for the upper arm will be needed to ensure the right fit and stable attachment of the motors [15]. We started the session by applying random vibrotactile stimulations for two minutes with different voltage values to accustom the participants to the vibrations.

4.2. Still Upper Extremity Study

The objective of this study was to analyze how sensation and perception are affected by changes in vibrotactile voltage. We were also investigating whether participants could identify the locations on the upper extremity of the vibrating motors, without visual feedback.

Protocol

One motor (out of nine) was chosen at random and stimulated for 30 cycles, which lasted for about 10 s. We generated various voltage values, as shown in Table 1. After each motor vibrated, the participants were asked to rate the sensation intensity and the perceived pleasantness on a scale from 1 to 4 and 1 to 3, respectively.

Table 1. Values of generated voltage measured on the motors.

Duty Cycle Input out of 255 (DC)	Measured Voltage Output (V)
51	0.55–0.56
64	0.68–0.69
128	1.26–1.30
255	2.54–2.57

Participants were also asked if they could identify the location of the vibrating motor precisely, vaguely, or not at all, and without looking at the upper-extremity device. If the response was vague, they were asked to identify the upper-extremity region (i.e., the shoulder, upper arm, or lower arm). Participants answers were entered into the running application and recorded in a csv file for further processing.

4.3. Moving Upper Extremity Study

In this study, we aimed to determine the effects of a simple, everyday movement (i.e., reaching) on sensation and motor identification across the upper extremity.

Protocol

Participants performed reaching movements back and forth at their chosen pace for the duration of the study, which was less than 7 min. We focused in this study on the upper-extremity muscles, with a simple reaching movement that engages these muscles. Different voltage values were chosen randomly, using the same random values for voltage in the previous protocol. We applied vibration on the medial deltoid, triceps brachii, biceps brachii short head, and brachioradialis. A subset of the motors was chosen compared to the still study to reduce the duration of the experiment and reduce participant fatigue.

4.4. Multiple Vibrating Motors Study

In this last study, we vibrated multiple motors simultaneously across the upper extremity with the goal of determining whether participants could identify which motors were vibrating, or whether we could observe differences between certain upper-extremity muscles and regions.

Protocol

In this study, three motors vibrated simultaneously for 60 s, and participants were asked to identify which motors were vibrating. The three motors were chosen from one of the following sets: (1) the anterior deltoid, biceps brachii long head, and triceps brachii; (2) the medial deltoid, posterior deltoid, and biceps brachii short head; (3) the brachioradialis, brachialis and biceps brachii long head; and (4) the triceps brachii, brachioradialis, and biceps brachii short head. The sets were chosen so that the muscles spanned different regions in the upper extremity. For this experiment, we applied a voltage of 5 V, which corresponded to an average of 2.56 V ± 0.02 measured voltage, on all motors. After each set of motors stopped vibrating, the participant was asked to evaluate the motor locations (i.e., precisely, vaguely, or not at all). If they responded vaguely, then they were asked to identify the regions where the motors were vibrating (i.e., shoulder, upper arm, or lower arm). During this experiment, participants were asked not to look at their upper extremity to ensure they did not identify the vibrating motors with visual feedback instead of tactile feedback. All answers were recorded interactively in the running application and sent to a csv file for further processing.

5. Results

In the sub-sections below, we present our results along with an analysis for the three study outcomes.

5.1. Sensation and Perception Analysis in the Still Upper Extremity

Our first study focused on the effect of changing voltage on sensation and perceived pleasantness when the participant's upper extremity was at rest. The total data set has 1224 records. We grouped the results based on the average measured voltage value into LOW (0.63 V ± 0.01), MEDUIM (1.28 V ± 0.03), and HIGH (2.56 V ± 0.02). The motor vibration frequencies associated with these voltage values may stimulate a range of sensory receptors (especially as the motors ramp up and down), including the Pacinian corpuscles cutaneous mechanoreceptors preferentially at 200 Hz [8] and the muscle spindle receptors at 80 Hz [16]. In this work, we consider p values less than 0.05 to be statistically significant. We found a moderate positive correlation between voltage and sensation intensity (Pearson correlation coefficient of r = 0.39, with $p < 0.001$). Sensation intensity increased from 1.46 ± 0.54 (at low voltage) to 3.37 ± 0.87 (at high voltage) on average. The average increase in sensation intensity was 53.3 ± 2.9%. On the other hand, we found no significant correlation between perceived pleasantness and voltage. We can observe this in Figure 3, where the perception level remains stable in the neutral range, with an average value of 2.2 ± 0.05, and does not significantly change when the voltage is increased.

We also analyzed how sensation intensity varies depending on the location of the vibrating motor on the upper extremity (see Figure 4). We found that sensation intensity followed similar trends across the different motor locations when changing the voltage. However, we note that the motor locations have different baseline sensation intensities, meaning that, on average, participants will report different stimuli intensities for the same voltage depending on the location of the motor on the upper extremity. We observed that the brachioradialis and the index finger are the motor locations with the highest sensation intensities, while the triceps brachii and the brachialis are the motor locations with the lowest sensation intensities. Even when the motors were placed in the same region on the upper extremity, we found some differences in sensation intensity.

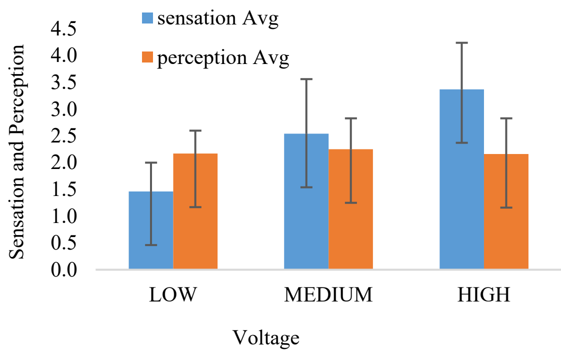

Figure 3. Effect of changing voltage on sensation and perception. We see that sensation intensity increases with voltage increase, while perceived pleasantness remains stable across the different values. We calculated the average sensation and perception for a given voltage value across the 15 participants and for all the motor locations. Error bars represent one standard deviation of the sensation/perception value.

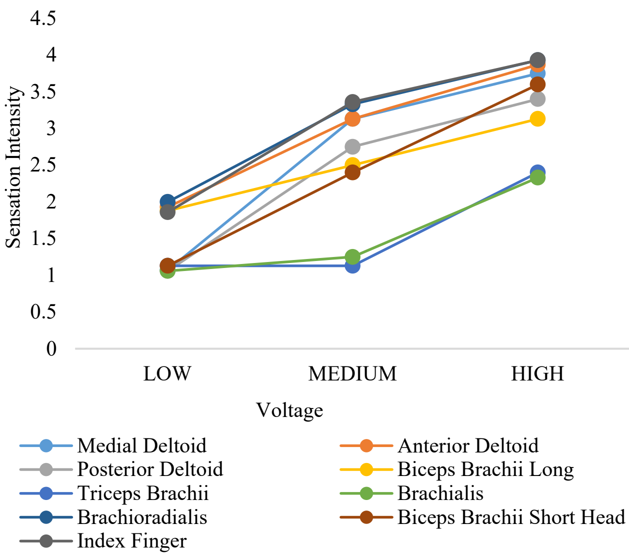

Figure 4. Average sensation intensity per motor location at different values of voltage for 15 participants in the still study.

For example, we found that the biceps brachii long head and biceps brachii short head have a slightly higher (by 0.89 ± 0.44) sensation intensity than the posterior triceps brachii and the anterior brachialis ($t(549) = 13.65$, $p < 0.0001$). Tables 2 and 3 show the description of the data sets and the results obtained.

Table 2. Description of the two data sets: set 1 (biceps brachii long head and biceps brachii short head) and set 2 (posterior triceps and anterior brachialis) for *t*-test.

Variable	Set 1	Set 2	Combined Sets
N	274	277	551
Mean	2.47	1.62	2.05
SD	0.78	0.68	0.85
SE	0.05	0.04	0.04

Table 2. *Cont.*

Variable	Set 1	Set 2	Combined Sets
95% Conf.	2.38	1.54	1.97
Interval	2.57	1.70	2.12

Table 3. Results of *t*-test performed on the two sets of muscles in Table 2.

Parameters	Value
Difference (set1–set2)	0.8535
Degrees of freedom	549.0
t	13.6535
Two side test p value	0.0000
Difference < 0 p value	1.0000
Difference > 0 p value	0.0000
Cohen's d	1.1633
Hedge's g	1.1617
Glass's delta1	1.0935
Point-biserial r	0.5035

In the shoulder, we observed that the medial and anterior deltoids have a slightly higher (by 0.41 ± 0.03) sensation intensity than the posterior deltoid ($t(413) = 3.91$, $p < 0.001$) (See Tables 4 and 5 for *t*-test results). All *t*-tests were performed on normally distributed data sets.

Table 4. Description of the two data sets: set 1 (medial and anterior deltoids) and set 2 (posterior deltoid).

Variable	Set 1	Set 2	Combined Sets
N	276	139	415
Mean	2.97	2.60	2.84
SD	0.91	0.91	0.93
SE	0.05	0.08	0.05
95% Conf.	2.86	2.45	2.75
Interval	3.08	2.75	2.93

Table 5. Results of *t*-test performed on the two sets of muscles in Table 4.

Parameters	Value
Difference (set1–set2)	0.3703
Degrees of freedom	413.0000
t	3.9113
Two side test p value	0.0001
Difference < 0 p value	0.9999
Difference > 0 p value	0.0001
Cohen's d	0.4068
Hedge's g	0.4061
Glass's delta1	0.4060
Point-biserial r	0.1890

5.2. Sensation Analysis of the Moving Upper Extremity

Our second study investigated the effects of changing voltage on sensation intensity while the participant performed reaching movements. As described in Section 4.3, we focused on a subset of the muscles in Figure 2, which were the medial deltoid, triceps brachii, biceps brachii short head, and brachioradialis. In Figure 5, we compare the sensation intensity in these muscles for the still and moving studies. We observed an average decrease of 5.9 ± 2.9% in sensation intensity in the moving study compared to the still study. Although the average decrease is slight, it is statistically significant ($t(1726) = 2.9$, $p < 0.005$). Most of the decrease occurs in the biceps brachii short head (9.6%) and the brachioradialis (6.7%). The decreases in the medial deltoid and triceps brachii are not statistically significant.

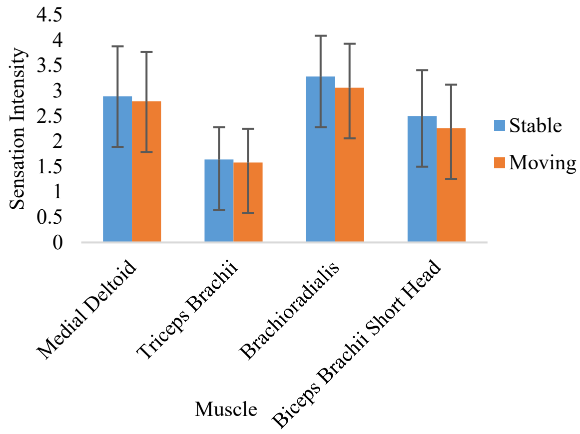

Figure 5. Average sensation intensity per motor location at different values of voltage for 15 participants. We observed a decline in sensation intensity in the moving study. Error bars represent one standard deviation of the sensation intensity.

5.3. Motor Identification Analysis

We analyzed the effect of increasing voltage on motor identification in both the still and the moving studies. We found that as we increased the voltage, motor identification accuracy in the still study increased from 33.3 ± 16.5% for low voltages to 80.9 ± 15.4% for high voltages. Similarly, in the moving study, motor identification accuracy increased from 19.6 ± 22.3% at a low voltage to 89.3 ± 12.8% at a high voltage (see Figure 6). Note that we had a smaller number of stimulated muscles in the moving study compared to the still study, which made the identification task easier. On average, participants were able to identify the right motors 72.0 ± 13.8% of the time in the still study (see Figure 7) and 72.5 ± 25.6% of the time in the moving study (see Figure 8).

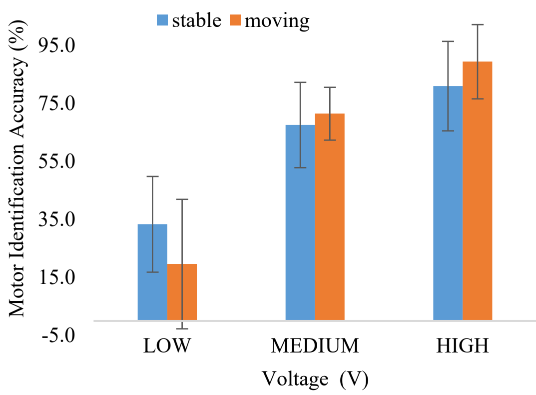

Figure 6. Motor identification accuracy at different voltage values in the still versus the moving studies. We observed an increase in accuracy with increased voltage values.

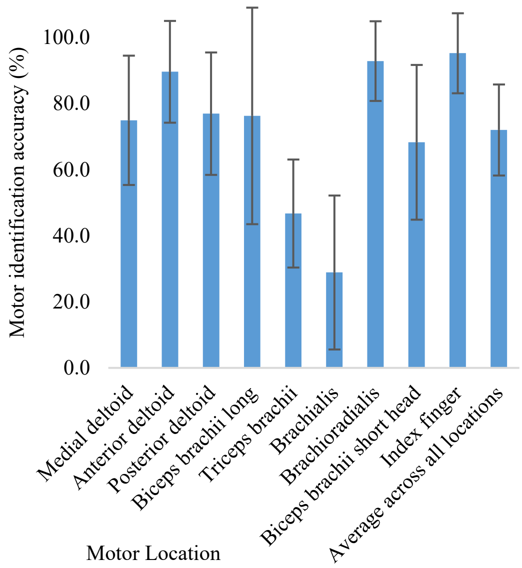

Figure 7. Average percentage of motor identification accuracy per motor location for 15 participants in still study. Error bars represent one standard deviation of the identification accuracy.

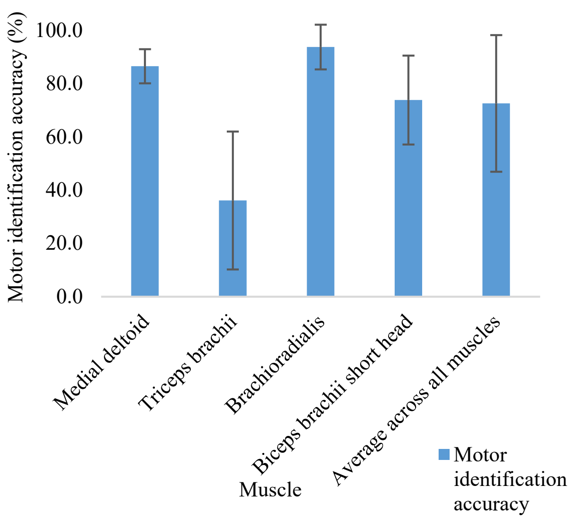

Figure 8. Average percentage of motor identification accuracy per muscle in the moving study.

We performed an analysis of motor identification per muscle in both the still and moving studies. We found that some locations, such as the index finger and the brachioradialis, have a higher motor identification accuracy at a low voltage compared to other locations, such as the triceps, brachialis, and biceps brachii short head, which require higher stimuli to be clearly recognized (see Figure 9). This also held in the moving study, where the same muscles had a lower identification accuracy at a lower voltage. For example, the biceps brachii short head, medial deltoid, and triceps brachii all require a high voltage intensity to be recognized with an accuracy above 60% (see Figure 10). Intuitively, we observed that muscles with lower sensation results (see Figure 4) have a lower motor identification accuracy.

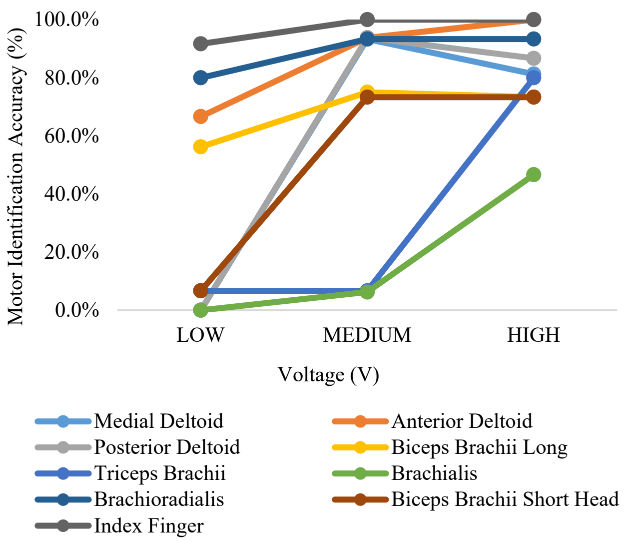

Figure 9. Motor identification accuracy per motor location in 15 participants in still upper extremity study over different values of voltage. The figure shows how different motor locations require different voltage values to reach a higher motor identification percentage.

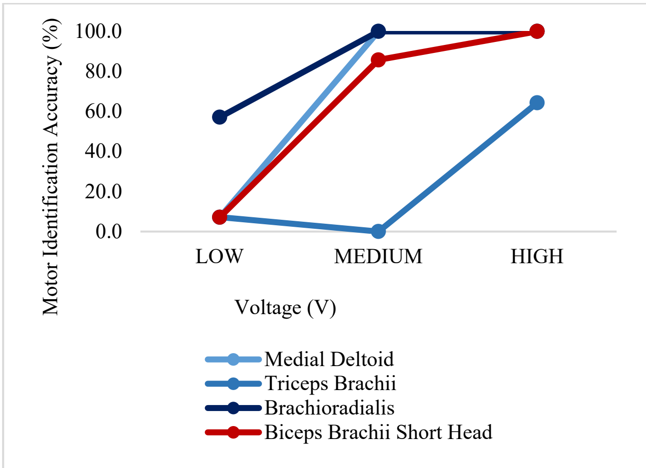

Figure 10. Motor identification accuracy per muscle in the moving upper extremity study over different voltage values.

5.4. Multiple Vibrating Motors Analysis

Our last study was focused on the accuracy of identifying simultaneous vibrating motors. We had three motors vibrating simultaneously with a high-voltage input value of 5V using four different sets of motor locations as described in Section 4.4. As shown in Figure 11, participants were able to identify all three vibrating motors 30.0 $\pm$ 33.0% of the time and two out of the three vibrating motors 41.7 $\pm$ 32.3% of the time. Participants were only able to vaguely identify the motor location 8.3 $\pm$ 20.4% of the time (i.e., by specifying the location as in the shoulder, upper arm, or lower arm) and were unable to identify all three motors 3.3 $\pm$ 8.8% of the time. Overall, participants were able to identify the right motors 64.4 $\pm$ 19.6% of the time. We also found that participants were able to identify an average of 2.5 $\pm$ 0.8 out of 3 vibrating motors.

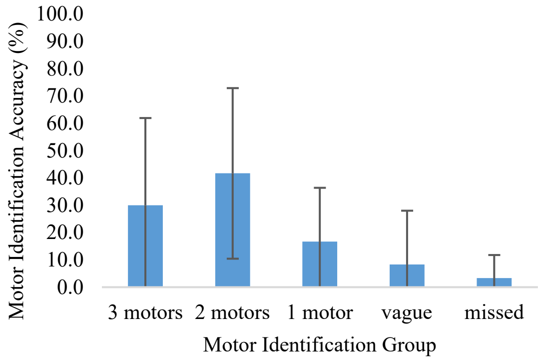

Figure 11. Motor identification accuracy in the three simultaneously vibrating motors study averaged over 15 participants. We observed that most participants accurately identified only two out of the three vibrating motors. Error bars represent one standard deviation of the motor identification accuracy.

6. Discussion

In the sensation study on the still upper extremity, we found that increasing the vibrotactile stimuli voltage resulted in higher sensation intensity, with moderate to strong positive linear correlations of r = 0.39. Previous work in psychophysics noted a power law relationship between stimulus amplitude and sensation intensity [17,18]. We did not observe a strong power law relationship in our data set (i.e., most of the variance in sensation intensity was not explained by the stimulus amplitude). We speculate that this may be due to our stimulus parameters not being discretized finely enough or their range of values being too restrictive. In prior work, it was found that sensation intensity increases with frequencies of up to 100 Hz and then plateaus [8]. Other authors found that high-amplitude and low-frequency stimuli were perceived more intensely than high-frequency and low-amplitude stimuli [8]. We could not investigate this in this work, as we used ERM motors, where frequency and voltage are linked together.

In future work, it would be interesting to investigate different kinds of motors, such as Linear Resonant Actuators for high-frequency stimulation [1], and examine the use of electrotactile feedback, where frequency and voltage can be controlled separately [19]. As for the perceived pleasantness, we did not see a significant difference (i.e., perception values stayed in the neutral range) when changing the voltage, on average.

Compared to other work in the area, Seim et al. [1] reported that subjects in both a stroke group and a healthy group were dissatisfied with a stimulation that they could not sense and enjoyed high-voltage stimuli. We did not see a significant correlation between high-voltage stimuli and perceived pleasantness on average. In our work, we found that participants on an individual level expressed different feelings with respect to the stimulation, some reporting neutral perception across the range of voltage values, others indicating a more pleasant feeling with a higher voltage, and others indicating an unpleasant feeling with high-voltage values. Some participants reported that the stimulation applied at certain locations on the upper extremity created a feeling of annoyance, tingling, or massaging. Because we did not find a strong aggregate-level correlation between these parameters and the perceived pleasantness of the simulation, this indicates the need for customizing the parameter tuning to the individual person. One limitation of our work is that we did not vary the vibration patterns or durations. In future work, it could be interesting to investigate the effects of these parameters on perception, as some subjects reported that they might have felt differently if the vibration duration was increased. Seim et al. [1] observed that participants reported a lower sensation intensity when the stimulation was applied in the lower arm (however, they did not target specific muscles in the lower arm). In contrast, we found that certain lower arm muscles such as the brachioradialis produce a high sensation intensity (see Figure 12). This finding can help in developing haptic devices and in understanding at what locations the stimulation should be applied.

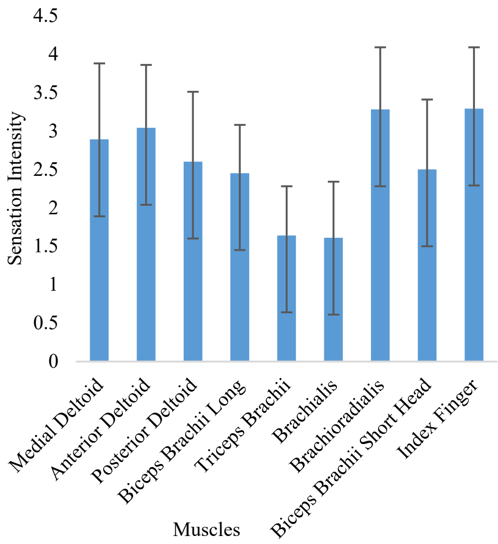

Figure 12. Average sensation intensity across the different motor locations averaged over the 15 participants and voltage values in the still study. Error bars represent one standard deviation of the sensation intensity.

In the moving upper extremity study, we found that sensation intensity also increased with increasing voltage, but on average the increase was less than the measured one in the still study by 5.9 $\pm$ 2.9% (see Figure 5). Related work in the field [12] found that sensation intensity in the hand decreases when it is moving. Our work confirms that we observed the same pattern across the upper extremity. One limitation of our work is that we asked participants to perform simple reaching movements in the moving study, which would have impacted certain muscles in the upper extremity more than others. A matter of potential interest in future work would be to determine whether other upper-extremity movements or the degree of fatigue produce significantly different sensation intensity results.

In the motor identification study, our goal was to determine whether participants were able to locate the vibrating motors in certain areas more than others, without visual feedback. We found that the brachioradialis muscle has a higher motor identification accuracy with low stimuli compared to other muscles like the triceps, brachialis, and biceps brachii short head (see Figure 9). This is consistent with our results shown in Figure 4 that indicate that participants reported a higher sensation intensity for the brachioradialis than for the other muscles. These differences in sensation intensity might be explained by differences in the densities of the mechanoreceptors across the upper extremities, but these have not yet been characterized [13]. Intuitively, we also found that motor identification accuracy broadly increased as we increased the voltage parameter, as shown in Figure 10. However, for the highest voltage value we observed that the motor identification accuracy decreased for most locations. This indicates that participants start losing motor identification accuracy when the stimulus intensity of the vibrating motor increases above a threshold value. One of the limitations of our work is that participants did not have noise-cancelling headphones to prevent them from using auditory feedback to identify the motors. Another limitation regarding the hardware of the vibrating motors is that we cannot guarantee that all motors gave the same stimuli intensity with the same set of parameters. It is known that ERM motors exhibit various frequencies as they accelerate and decelerate during a given activation [20]. It would be interesting to examine other muscles and locations in the upper extremity to stimulate in addition to those examined in this work (see Figure 2). We should also add that variation in participants' skin temperature or hydration can affect sensation intensity and perception.

Our final study focused on motor identification accuracy with simultaneously vibrating motors. We found that participants were able to accurately identify two out of three vibrating motors 41.7% of the time compared to 30% of the time for identifying all three motors. Examining the cases where only two motors were identified accurately, we observed that participants were able to more easily identify the motors at different regions on the upper extremity (see Figure 13). Shah et al. [13] found that sequential vibrotactile stimuli result in better intensity discrimination than simultaneous stimuli, independently of whether the pair of motors were located within the same dermatome or across dermatomes. In our work, we found that simultaneous stimulation across the upper extremity decreases motor identification accuracy compared to single-motor stimulation (see Figure 13). Bark et al. [3] found that vibrotactile stimulation can help in learning simple arm movements involving one degree of freedom, but no significant effect was found in more complex movements involving two or three degrees of freedom. The results are consistent with those of our study showing that most participants could only identify two vibrating motors at a time, such that the ability to teach complex movements could be limited. Teaching complex movements would likely require more vibrating motors, which could indicate the need to investigate new vibrotactile stimulation strategies that only activate a small number of motors simultaneously and that use sequential vibration strategies to teach new muscle coordination patterns. While we focused in this study on the effects of vibration parameters on sensation and perceived pleasantness, we acknowledge the lack of exploration of interaction effects between participants and the stimulation. We believe that this issue is worth investigating as it may be critical for practical applications and the design of customized haptic devices. Two additional limitations are worth mentioning. Firstly, our sample size was small, consisting of 15 participants. Secondly, we recruited participants blindly with regard to sex, resulting in an imbalanced sample set, with the majority of participants being male. The small sample size and imbalanced data set could have affected the generalizability of our findings. Prior studies indicate no statistically significant difference in sensation between males and females [21]. Future work could involve a more diverse group and thoroughly investigate the effects of gender, age, and other physiological factors on sensation and perception.

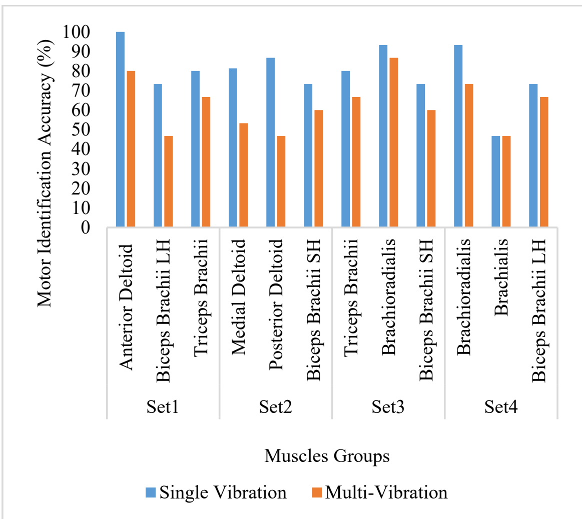

Figure 13. Exact motor identification percentages across the four sets of muscles comparing simultaneous versus single stimuli effects on motor identification. The chart also shows how motor identification accuracy increased for muscles of different groups in the multi-vibrating study.

7. Conclusions

We have developed a vibrotactile stimulation system designed for the upper extremities. In this work, we conducted three studies on 15 participants to evaluate the effect of changing the ERM motor stimuli voltage on sensation intensity, perceived pleasantness, and motor identification. We found a significant correlation between voltage and sensation intensity, but no significant aggregate-level correlation between voltage and the perceived pleasantness of the simulation, which indicates the need to customize the parameters for individual subjects. This could be investigated with human-in-the-loop optimization in future work [22]. Our work identifies which motor locations in the upper extremities produce a greater sensation intensity and are easier to identify without visual feedback. We also investigated how movements impact sensation intensity and whether subjects were able to identify simultaneously vibrating motors (without visual feedback). We expect our results to hold for other types of vibrating motors, but future experiments would need to confirm this. Our results will aid in designing haptic vibrotactile stimulation devices for the upper extremities and in developing vibrotactile stimulation patterns for applications in human–computer interaction, motor learning, and rehabilitation.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data for this research can be found at https://github.com/abeerk/SensationStudy (accessed on 1 August 2025).

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