VibroMap: Understanding the Spacing of Vibrotactile Actuators across the Body

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In spite of the great potential of on-body vibrotactile displays for a variety of applications, research lacks an understanding of the spacing between vibrotactile actuators. Through two experiments, we systematically investigate vibrotactile perception on the wrist, forearm, upper arm, back, torso, thigh, and leg, each in transverse and longitudinal body orientation. In the first experiment, we address the maximum distance between vibration motors that still preserves the ability to generate phantom sensations. In the second experiment, we investigate the perceptual accuracy of localizing vibrations in order to establish the minimum distance between vibration motors. Based on the results, we derive VibroMap, a spatial map of the functional range of inter-motor distances across the body. VibroMap supports hardware and interaction designers with design guidelines for constructing body-worn vibrotactile displays.

CCS Concepts: • **Human-centered computing → Human computer interaction (HCI)**; *Haptic devices*; User studies.

Additional Key Words and Phrases: vibrotactile interfaces; actuator spacing; phantom sensation; haptic output; ERM vibration motors; wearable computing; design implications.

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1 INTRODUCTION

Vibrotactile displays on the body are increasingly used in situations where interaction with visual or audio displays is not possible or recommended, e.g., while driving, holding conversations, riding a bike, and countless other forms of physical activities [5, 7, 44, 59]. Prior research in HCI studied haptic feedback for many applications, ranging from navigation [16], motion coaching [50, 55], passive motor skill learning [53], driving [22, 28], and human-robot interaction [1]. Depending on the use-case, haptic feedback is proposed on many different body locations, e.g., upper arm [3, 4, 58], forearm [37, 38, 45, 47, 51, 70], wrist [7, 14, 30, 31, 35], stomach [28], thigh [56], legs [9], and feet [61].

Although a multitude of systems and application scenarios using vibrotactile actuators are proposed, the HCI community still lacks a systematic understanding of the required spacing of vibrotactile actuators. This is crucial to the effectiveness of vibrotactile feedback and can have a huge effect on the haptic perception, as the amount of mechanoreceptors and the thickness of the human skin varies across the body [26].

This paper aims to systematically study the accuracy of vibrotactile perception and the illusion of phantom sensations on different body parts (see Figure 1). Phantom sensations are a tactile illusion where the perceived location of a vibration is controlled by two or more neighbouring tactors [2]. Phantom sensations have been commonly used in HCI to generate high resolution tactile sensations using a low resolution tactile display. From these findings, we derive *VibroMap*, a first attempt to map vibrotactile perception across different body parts from an HCI perceptive.

In particular, this paper contributes the findings of two controlled experiments:

- A first experiment on *phantom sensations* at different body locations. Our findings detail on the maximum distance of two physical tactors that still allows for continuous vibrotactile feedback to allow for an efficient tactor placement.
- A second experiment on the *perceived accuracy* of vibrotactile stimulation on different body parts. These findings help to understand the minimum distance between two tactors without a loss of precision in the haptic perception.

These findings are combined together in the form of *VibroMap*. VibroMap is a map of the ideal tactor spacing across the human body (see Figure 6). It provides an understanding on the *minimum and maximum distance* of tactors across body locations. HCI researchers and practitioners can use this map as a design guideline to gain insights into the perception on different body parts in order to design efficient future haptic devices and user studies.

2 RELATED WORK

Our work aims to systematically investigate the spacing of vibrotactile actuators on the body. Therefore, we discuss in this section prior work using vibrations as an interaction modality, the human body's ability to resolve spatial tactile stimulation and work leveraging phantom sensations to generate continuous vibrotactile stimulation.

2.1 On-body Vibrotactile Interfaces

On-body computing opens up a wide variety of opportunities for interaction, e.g., leveraging the skin as a platform for interaction [21, 63, 64], using electrical muscle stimulation to move users' limbs [36] and providing feedback for prosthetic limbs [34]. Vibrotactile interfaces on the body for output are particularly attractive as they are not restricted to body locations that are visible, which leads to their use across a diverse range of body locations, e.g., on the hand [18–20, 33, 42], wrist [7, 30, 31, 35], forearm [37, 38, 45, 47, 51, 70], upperarm [3, 4, 58], back [23, 41, 60], stomach [28], thigh [56] and lower leg [9]. Their usage spans a wide range of interaction scenarios, such as speech communication [46, 67, 70], affective communication [43], progress monitoring [7], learning gestures [20], spatial guidance [19, 33], motion guidance [51, 56] and navigation [13, 15, 24].

Table 1. Body locations for vibrotactile feedback in related work ↕ indicates a longitudinal arrangement, ⟳ indicates a transverse arrangement, ⊞ indicates a grid and ∘ indicates a single actuator.

	Srikulwong and O'Neill [57]	Meier et al. [40]	Konishi et al. [27]	Israr and Poupyrev [23]	Tam et al. [59]	Cauchard et al. [7]	Leong et al. [34]	Lee et al. [30]	Lee and Starner [31]	Liao et al. [35]	Zhao et al. [70]	Luzhnica and Veas [38]	Luzhnica et al. [37]	Pfeiffer et al. [45]	Schönauer et al. [51]	Reinschluessel et al. [47]	Stratmann et al. [58]	Bark et al. [4]	Alvina et al. [3]	Spelmezan et al. [56]	Chen et al. [9]	Wong et al. [67]	Dobbelstein et al. [13]	Karuei et al. [25]	Cholewiak and Collins [12]	Cholewiak et al. [11]	Schneider et al. [49]	Krüger et al. [28]	Spelmezan [55]	Ertan et al. [16]	Aggravi et al. [1]	Ho et al. [22]	Elvitigala et al. [14]
Wrist		⊞			⟳	∘		⊞	⊞	⊞			⟳								⟳		⟳	∘									⊞
Forearm			↕								⊞	⊞	↕	∘	⊞	⟳		⟳			⟳	↕			↕						⟳		
Upperarm			↕				⟳						⟳				⟳	⟳	⊞					∘									
Back	⟳	⟳	⊞																	⊞						⟳	⊞	⟳		⊞		∘	
Stomach	⟳	⟳	⊞																⊞	⊞				∘		⟳		⟳				∘	
Thigh			↕				⟳												⊞	⊞				∘					↕				
Legs			↕																		∘												

While a large body of work explored vibrotactile interfaces (see Table 1) that are limited to a particular body location, prior work has also explored vibrotactile interfaces spanning across body locations. In OmniVib [3], recognition rate of vibrotactile notifications across the palm, upperarm, waist and thigh using a mobile phone form factor are investigated. Karuei et al. [25] investigated the influence of movement and visual load on the detection rate and reaction time of vibrations at different body locations. Spelmezan et al. [56] investigated full-body vibrotactile patterns for physical activities. Meier et al. [40] investigated vibrotactile feedback on several body locations for pedestrian navigation. In this work, we aim to gain a systematic understanding of the effect of inter-actuator distance across body locations. Thus, we contribute VibroMap, a map of the minimum and maximum inter-actuator distances for vibrotactile actuators across body locations.

2.2 Spatial Acuity of the Human Body

Spatial acuity of the human body's sense of touch is investigated in previous research [54, 62, 65]. Results of earlier studies by Weber and Ross [62] with a metal compass show that spatial acuity varies across body regions, with the tongue being most sensitive followed by the fingers, toes and forehead; and that spatial acuity increases when the stimulus is oriented along the transverse rather than the longitudinal body axis. Weinstein [65] extended upon this by investigating two-point discrimination thresholds, i.e., the distance at which two stimuli applied to the skin are detected as distinct; and localization errors across a larger number of body locations. The findings of these studies show that spatial acuity of touch varies across the body. Sensitivity to touch stimulation has been shown to be higher at the limbs, e.g. the fingertips and lower going towards the body center, e.g. forearm, upper arm and back [54].

In contrast to touch stimulation, vibration propagates for larger distances on the skin, which makes localization of vibrations harder [12]. For designs using closely-spaced tactors, vibrotactile localization accuracy on the skin is important. If vibrotactile actuators are placed too close to each other that their signals cannot be distinguished, information will be lost. Prior work investigated vibrotactile localization accuracy on body locations, such as the arm [12] and the torso [11]. These studies however measure discrete identification of a vibration location in a set of candidate locations, e.g., 6, 8, or 12 locations on the torso [11]. In this work, we aim to provide a map of *continuous* vibrotactile localization accuracy across body locations.

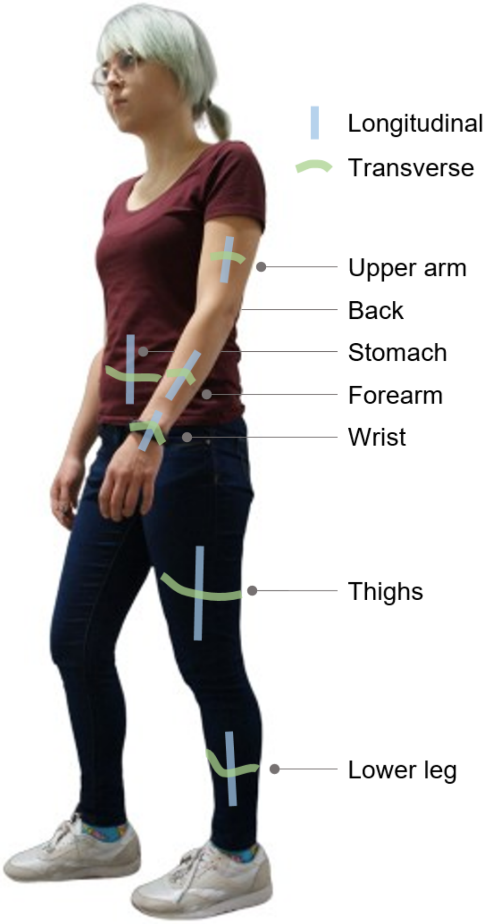

Fig. 1. Locations studied in our experiments

2.3 Vibrotactile Phantom Sensations

Phantom sensations refer to one of many tactile illusions [29], where the perceived location of a vibration is controlled by varying intensity (funneling) or time delay (saltation) between two (1D phantom sensations) or more (2D phantom sensations) neighbouring vibrotactile actuators [2, 42]. Phantom sensations are extremely useful for HCI applications as they enable rendering high resolution spatial vibrotactile stimuli using a low resolution grid of tactors [8, 17, 23, 48]. Mango [49], an authoring tool for creating vibrotactile patterns, uses direct manipulation of phantom sensations for designing and rendering expressive 2D patterns. In Tactile Brush [23], an algorithm is proposed and validated that uses phantom sensations and apparent motion to generate high resolution 2D vibrotactile strokes. While prior work investigated the control parameters for rendering phantom sensations, such as interpolation models, a systematic understanding of the effect of inter-tactor distance across the body needs to be investigated. As this has a direct influence on the design of vibrotactile displays. With VibroMap we investigate maximum inter-tactor distance across body locations while preserving the ability to generate phantom sensations.

3 EXPERIMENTS

To better understand the maximum and minimum spacing between vibration motors, we conducted two controlled experiments to measure vibrotactile perception across body parts. The maximum distance is defined to be the biggest distance, where generating phantom sensations is possible. The minimum distance is defined to be the distance, where distinguishing between 2 vibrotactile actuators is possible. We conducted 2 psychophysical experiments to measure these values at different body locations. This section details on the participants, apparatus, locations and analysis both studies have in common.

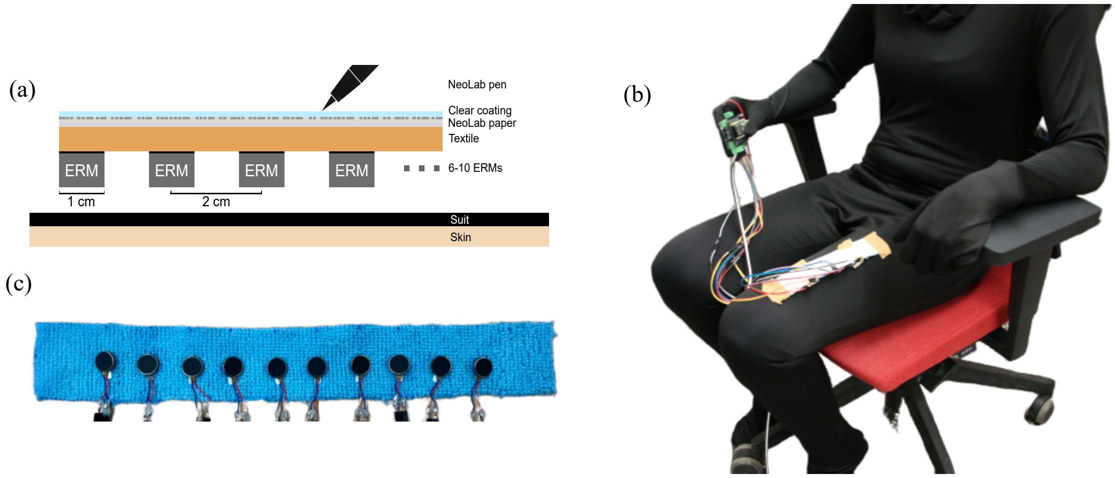

Fig. 2. (a) cross-section of vibrotactile strip with input, (b) experimental setup and (c) vibrotactile strips used in our experiments

3.1 Participants

We recruited 24 voluntary participants between 21 and 34 years old (12f, 12m; mean age 25.9 y; median age 27 y). None of the participants had experience with haptic feedback on the body beyond every day use of smartphones.

3.2 Apparatus

To study the perception of vibrations with different spacings, we built a textile stip (microfiber polyester cloth) with eccentric rotating mass (ERM) vibration motors (see Figure 2). The tactors have a diameter of 10 mm and were placed with a distance of 2 cm between each other. There are two versions of the strips, differing only in their length and the amount of tactors: one with 10 tactors and one with 6 tactors attached. The strip with 6 tactors was used on the wrist to account for the smaller area. The tactors are powered with 3 V, which leads to a maximum rotation speed of 12.000 rpm (200 Hz) and a maximum current draw of 60 mA. The experiments were controlled and logged on a computer that sends the tactor intensities over Serial connection to an ESP32 microcontroller. The ESP32 sends these commands over I^{2}C to a custom PCB to control the individual tactors.

Clothing influences the perception of vibrations, e.g., it can dampen the vibration. We standardized the clothing worn in the experiments to control for these effects by asking participants to wear a morphsuit (Polyester 91%, Elastane 9%). The strip was attached on top of the suit and centered on the location using an adhesive bandage.

In one experiment, participants were asked to mark the location of the vibration. For precise measurement of the input, we used a Neo smartpen [1] as an input device. The pen localizes its tip position on NeoLab paper attached on the top of the textile strip. Location of touch events on the paper were transmitted to the computer over Bluetooth. A clear coating on top of the NeoLab paper prevented abrasion and visible marks of prior inputs. A cross-section of the complete strip is shown in Figure 2a.

3.3 Design

We evaluate participants' perception of vibrotactile stimuli on 7 body locations: the *wrist*, *forearm*, *upper arm*, *stomach*, *back*, *thigh* and *lower leg*. All locations are evaluated in two orientations: arranged along the *transverse* and *longitudinal* body axis. Both experiments follow a within-subject design with body location and orientation

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[1] https://www.neosmartpen.com/en/neosmartpen-m1/

as independent variables. In experiment 2, we excluded the back location, since all body locations need to be reachable by the participants' hands.

To keep experiment time short and avoid excessive switching of locations, we used a 6x6 balanced latin square for counterbalancing body location (without wrist) and alternate starting or ending with the wrist condition between participants. Switching to the 6 tactor strip used for the wrist increased experiment time due to plugging and unplugging of motor connections to the board. By starting or ending with the wrist condition this change had to be done only once during the experiment. We expect this not to have an influence on our results.

3.4 Procedure

Participants were welcomed into the lab and given a brief explanation of the purpose of the experiment and the procedure. Once participants agreed to take part in the experiments, participants were asked to fill a short demographic questionnaire and to wear the morphsuit. For each condition the experiment started by placing the vibrotactile strip on the body. A calibration procedure was performed to find the voltage at each tactor where a stimulus becomes perceptible for the user. The driving voltage was increased gradually using the keyboard until a vibration became perceptible by the user. To ensure a quicker tactor response we used a 5ms overdrive cycle at 70% maximum voltage. This procedure was performed for all tactors on the strip. During the experiment all vibrations were performed at double the voltage from the calibration procedure, we ensured that vibrations were clearly perceived by participants. After successful completion of the calibration procedure, the participant proceeded with the task.

3.5 Data Analysis

We analyzed the recorded data using a two-way repeated measures ANOVA with *body part* and *orientation* as the two independent factors. For the Likert questionnaires, we performed an Aligned Rank Transformation as proposed in [66]. We tested the data for normality with Shapiro Wilk's test and found no significant deviations. Where Mauchly's test indicates a violation of the assumption of sphericity, we corrected the tests using the Greenhouse-Geisser method and report the ϵ. When significant effects are revealed, we use Bonferroni corrected pairwise t-tests for post-hoc analysis. We further report the eta-squared η^2 as an estimate of the effect size. As an estimate of the influence of the individual factors, we report the estimated marginal mean (EMM) as proposed in [52].

4 EXPERIMENT 1: MAXIMUM DISTANCE FOR PHANTOM SENSATIONS

In experiment 1 we investigated the *maximum* threshold distance between vibration motors, where participants could still experience phantom sensations. Using a larger distance between tactors results in losing the ability to generate continuous vibrotactile stimuli between the motors. We therefore used the lower 95% confidence interval as the *maximum distance*.

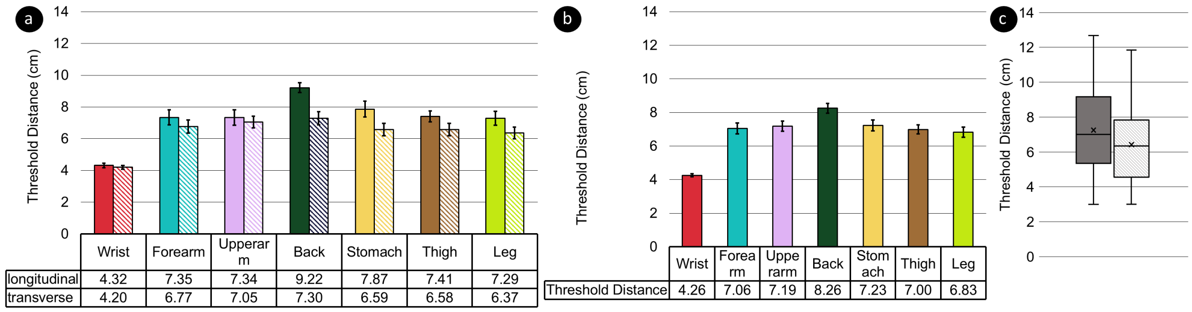
4.1 Research Questions

We aim to answer the following research questions with our experiment:

RQ 1 How do 2-point thresholds differ between touch and vibration?
RQ 2 How does stimulus orientation affect 2-point thresholds for vibration?

4.2 Task

In line with related work [23, 32], we used a one-interval two-alternative forced-choice paradigm using a one-up one-down adaptive staircase procedure to determine thresholds for phantom sensations. Participants start by feeling the first and last tactor (18 cm apart) on the strip vibrating simultaneously. The participants are asked if



	Wrist	Forearm	Upperarm	Back	Stomach	Thigh	Leg
longitudinal	4.32	7.35	7.34	9.22	7.87	7.41	7.29
transverse	4.20	6.77	7.05	7.30	6.59	6.58	6.37

	Wrist	Forearm	Upperarm	Back	Stomach	Thigh	Leg
Threshold Distance	4.26	7.06	7.19	8.26	7.23	7.00	6.83

Fig. 3. Average threshold distance of phantom sensations for each body location and orientation (a), body location (b), and orientation (c). Error bars are the standard errors. Data tables are displayed below each plot.

they feel vibration at a single position or more than one position. For every response of feeling distinct vibration points the distance is decreased until the participants respond with feeling a single vibration point, at this point a reversal occurs and distance is increased. We used a constant step size of 2 cm. After 6 reversals a measurement of *threshold distance* was taken to be the average of the reversals.

For every body location and orientation we conducted 2 series of trials, resulting in a total of 28 trials per participant. After completing a body location, participants answered questions regarding their experiences on a 7 point Likert scale.

4.3 Dependent Variables

In addition to the questionnaire, we used *threshold distance* as a dependent variable. Threshold distance is the maximum distance where the participants still perceive two neighbouring vibrations at a single location.

4.4 Results

This section presents the results for *threshold distance* using the tested body locations (see Figure 3(b)), orientations (see Figure 3(c)) and their combination (see Figure 3(a)). Analysis procedures are described in section 3.5.

4.4.1 Body Location. A 2-way repeated measures ANOVA showed a significant main effect of body location on threshold distance ($F_{3.89,89.39} = 22.48$, $p < .001$, $\epsilon = .648$, $\eta^2 = 0.252$). Post-hoc tests revealed significant differences between wrist and all other body locations ($p < .001$), forearm and back ($p < 0.05$), back and thigh ($p < 0.05$) and back and leg ($p < 0.01$).

We found a larger threshold distance going from wrist to all other body locations, from thigh to back, as well as a larger threshold distance of the back location compared to the forearm. All of these differences were significant. In connection to *RQ1*, these results demonstrate that the relative 2-point thresholds follow a similar pattern to touch, i.e increasing thresholds going to less sensitive body locations, however vibration thresholds show a larger absolute value [65]. An overview of the results can be found in Figure 3(b).

4.4.2 Orientation. A 2-way repeated measures ANOVA showed a significant main effect of the orientation of vibrotactile stimulation ($F_{1,23} = 15.27$, $p < .001$, $\eta^2 = 0.035$). Post-hoc tests confirmed the significantly lower threshold distance using the *transverse* orientation in comparison to the *longitudinal* orientation ($p < .001$).

Regarding *RQ2* (How does stimulus orientation affect 2-point thresholds for vibration?), our tests show that a longitudinal orientation always results in a significantly larger threshold distance in comparison to the transverse orientation. An overview of the results can be found in Figure 3(c).

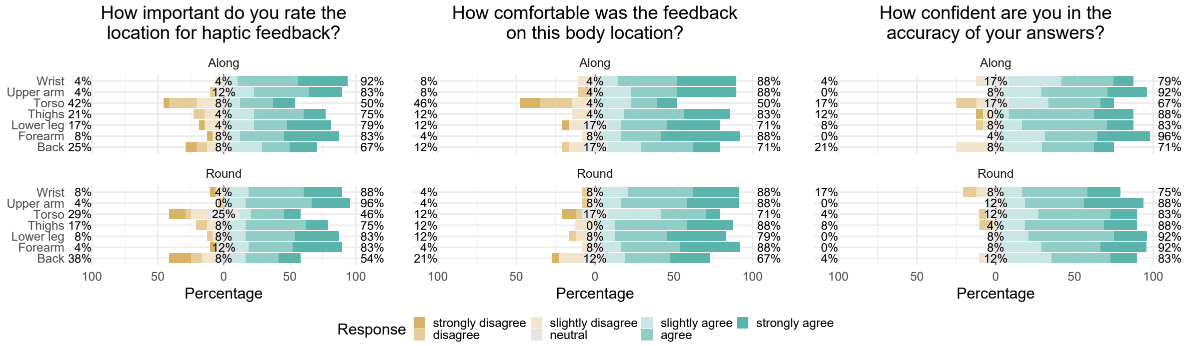


Fig. 4. Participant's questionnaire answers about vibrations on different body locations and orientations on a 7-point Likert-scale.

4.4.3 Body Location x Orientation. A 2-way repeated measures ANOVA revealed no significant interaction effects between body location and orientation ($F_{6,138} = 1.60$, p > .05). An overview of the results can be found in Figure 3(a).

4.4.4 Questionnaire. Participants were asked questions relating to the importance, comfort and confidence experienced using the different locations and orientations. The questions and participants'answers are depicted in Figure 4.

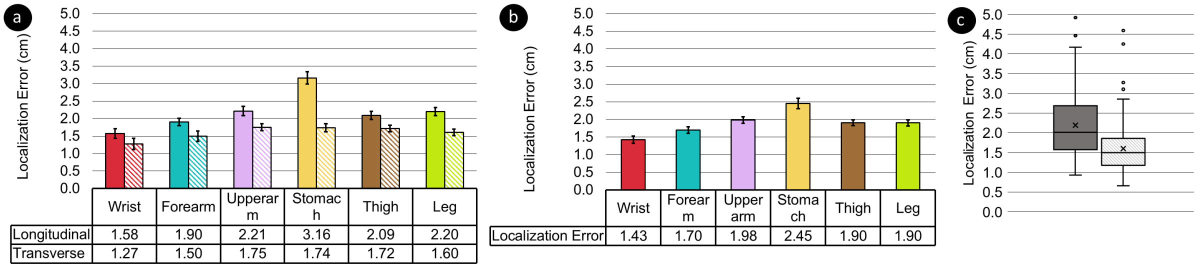
Importance. We asked participants to rate how important they find the different body locations for haptic feedback. Analysis of participants' answers showed a significant effect for body location ($F_{6,138} = 4.82$, p < .001) and no significant effects for orientation ($F_{1,23} = 0.00$, p > .05) as well as no interaction between body location and orientation ($F_{6,138} = 1.40$, p > .05). Post-hoc tests reveal significantly higher ratings of *wrist* (p < .01), *forearm* (p < .01) and *upper arm* (p < .05) in comparison to the *stomach* location. Similarly, we found significantly higher ratings of the *wrist* (p < .05) and *forearm* (p < .05) in comparison to the *back* location.

Comfort. We further asked participants how comfortable they found the different body locations. Our analysis showed both location ($F_{6,138} = 6.17$, p < .001) and orientation ($F_{1,23} = 6.30$, p < .05) as well as their interaction ($F_{6,138} = 2.34$, p < .05) to be significant. For the body location, post-hoc tests showed that participants found the forearm (p < .001), leg (p < 0.01), thigh (p < .01), *upper arm* (p < .001) and *wrist* (p < .001) more comfortable than the *stomach*. Regarding the orientation, our participants found the *transverse* orientation to be significantly more comfortable than a *longitudinal* orientation (p < .05).

Confidence. Participants were lastly asked to rate how confident they were with their answers. Our analysis showed that body location ($F_{6,138} = 3.45$, p < .01) as well as orientation ($F_{1,23} = 7.76$, p < .05) have a significant effect on participants' ratings. We could not find any interaction effects between the two factors ($F_{6,138} = 1.24$, p > .05). For the body location, post-hoc tests revealed significantly higher ratings for *forearm* (p < .05) in comparison with the *stomach* location. For the different orientations, participants' were more confident using the *transverse* orientation (p < .05) in comparison to the *longitudinal* orientation.

5 EXPERIMENT2: MINIMUM TACTOR DISTANCE

Experiment 2 investigates the minimum distance to use when placing vibrotactile actuators on the body. We use the upper 95% confidence interval as the localization error for a vibrotactile actuator. The minimum distance between 2 actuators, that does not lead to confusion is then the upper 95% confidence interval multiplied by a factor of 2 to account for the localization errors of both actuators.



	Wrist	Forearm	Upperarm	Stomach	Thigh	Leg
Longitudinal	1.58	1.90	2.21	3.16	2.09	2.20
Transverse	1.27	1.50	1.75	1.74	1.72	1.60

	Wrist	Forearm	Upper arm	Stomach	Thigh	Leg
Localization Error	1.43	1.70	1.98	2.45	1.90	1.90

Fig. 5. Average localization error for body location and orientation (a), body location (b) and orientation (c). Error bars are the standard errors. Data tables are displayed below each plot.

5.1 Research Questions

In this experiment, our goal is to answer these research questions:

- *RQ3* Are localization errors for vibration different than touch?
- *RQ4* How does stimulus orientation affect localization error?

5.2 Task

Participant's task was to indicate using the digital pen the location of vibration. The input was collected from the participants' after experiencing the vibration, so that the pen touching the surface does not influence the participants' perception of the vibrations. Participants were instructed to perform a light press on the paper which was also controlled visually by the experimenter. A light press avoids (1) markings being made by the pen despite the tape coating and (2) that the participant feels where the pen is located in comparison to the vibration locations previously felt. Every tactor on the vibrotactile strip is vibrated twice, resulting in 20 trials (12 at the wrist) per body location and orientation for a total number of 224 trials per participant.

5.3 Dependent Variables

We measured *localization error* as our only dependent variable. Localization error is the *absolute* distance between where the participant feels the vibration and the location of vibrotactile actuator.

5.4 Results

This section details on the results for *localization error* using the tested body locations (see Figure 5(b)), orientations (see Figure 5(c)) and their combination (see Figure 5(a)). Analysis procedures are described in section 3.5.

5.4.1 *Body Location.*

A 2-way repeated measures ANOVA reveals a significant effect of body location on localization error ($F_{3.60,82.70} = 10.79$, $p < .001$, $\epsilon = .719$, $\eta^2 = 0.159$). Post-hoc tests showed significant differences between wrist and upper arm ($p < .01$), wrist and stomach ($p < .001$), wrist and thigh ($p < .05$), wrist and leg ($p < .05$), forearm and stomach ($p < .001$), upper arm and stomach ($p < .05$), stomach and thigh ($p < .01$) and stomach and leg ($p < .01$). Similar to touch, body locations which have been shown to be more sensitive to touch stimulation resulted in lower localization error with vibrotactile stimulation. Significant differences supporting this have been found between wrist and all other locations except forearm, between forearm and stomach, upper arm and stomach, thigh and stomach and between leg and stomach. For *RQ3*, we can infer that localization errors follow a similar trend, but demonstrate larger absolute error values. [10, 65] The results are illustrated in Figure 5(b).

5.4.2 *Orientation.*

A 2-way repeated measures ANOVA showed this effect to be significant ($F_{1,23}$ = 117.71, p < .001, η^2 = 0.147). Post-hoc tests confirmed the significantly lower localization error using the *transverse* orientation in comparison to the *longitudinal* orientation (p < .001).

Participants were significantly more accurate in localizing vibrations with a transverse orientation in comparison to a longitudinal orientation. With regards to *RQ4*, we can infer that localization errors are reduced using the transverse body axis. The results are illustrated in Figure 5(c)

5.4.3 *Body Location x Orientation.*

A 2-way repeated measures ANOVA revealed a significant interaction effect between body location and orientation ($F_{5,115}$ = 8.27, p < .001, η^2 = 0.060). Post-hoc tests confirmed significant differences between wrist transverse and all other body locations in longitudinal orientation (p < .05), stomach longitudinal and all 13 other combinations of body location and orientation (p < .001), leg longitudinal and leg transverse (p < .01), forearm transverse and each of upper arm longitudinal (p < .01) and leg longitudinal (p < .01), and wrist longitudinal with upper arm (p < .05) and leg (p < .05) in longitudinal orientation. Significant differences found between orientations at the same body location for leg and stomach indicate a more prominent difference at these locations. The results are illustrated in Figure 5(a)

		Wrist		**Forearm**		**Upperarm**		**Back**		**Stomach**		**Thigh**		**Leg**	
		Longitudinal	Transverse	Logitudinal	Transverse	Longitudinal	Transverse	Longitudinal	Transverse	Longitudinal	Transverse	Longitudinal	Transverse	Longitudinal	Transverse
Localization Error	Mean	1.58 cm	1.27 cm	1.90 cm	1.50 cm	2.21 cm	1.75 cm	-	-	3.16 cm	1.74 cm	2.09 cm	1.72 cm	2.20 cm	1.60 cm
	95% CI	[1.32 , 1.83]	[1.02 , 1.53]	[1.65 , 2.16]	[1.24 , 1.75]	[1.96 , 2.47]	[1.50 , 2.0]	-	-	[2.91 , 3.41]	[1.48 , 1.99]	[1.84 , 2.35]	[1.46 , 1.97]	[1.95 , 2.46]	[1.35 , 1.86]
Threshold Distance	Mean	4.32 cm	4.20 cm	7.35 cm	6.77 cm	7.34 cm	7.05 cm	9.22	7.30	7.87 cm	6.59 cm	7.41 cm	6.58 cm	7.29 cm	6.37 cm
	95% CI	[3.55 , 5.10]	[3.43 , 4.98]	[6.57 , 8.12]	[6.00 , 7.54]	[6.56 , 8.11]	[6.27 , 7.82]	[8.44 , 9.99]	[6.52 , 8.07]	[7.09 , 8.64]	[5.82 , 7.36]	[6.64 , 8.18]	[5.81 , 7.36]	[6.52 , 8.07]	[5.59 , 7.14]

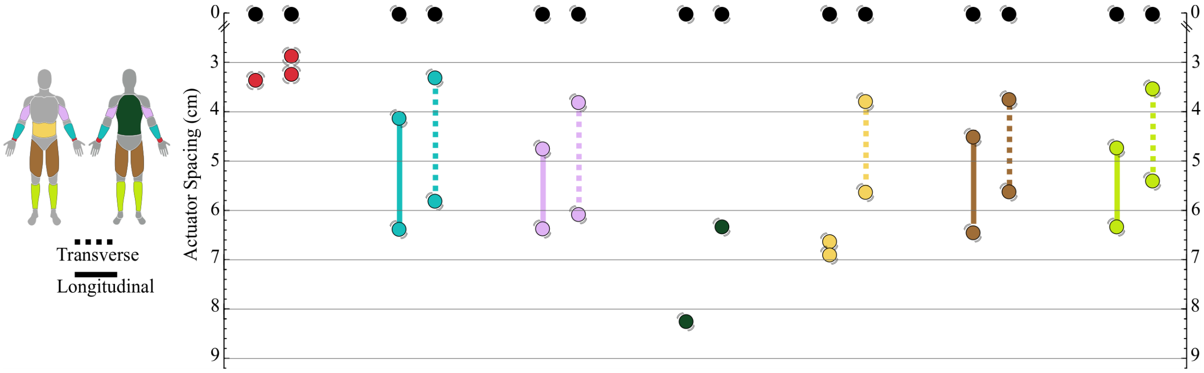


Fig. 6. VibroMap shows the ideal tactor spacing for different body parts. It combines the minimum and maximum distances from both experiments.

6 DISCUSSION AND IMPLICATIONS

In this section, we summarize the main findings of our experiments and discuss their implications on vibrotactile interfaces.

6.1 Summary

In general, locations towards the body extremities showed higher sensitivity to vibrotactile stimulation, and hence smaller localization error between vibration actuators. This is evident by the increasing minimum distance going from wrist, forearm and upper arm to stomach and similarly from thigh and leg to stomach. Considering the maximum distance between vibrotactile actuators where the generation of phantom sensations is still possible, a similar trend is observed. Locations at the limbs show a higher sensitivity to vibrotactile stimulation and therefore a smaller maximum distance. This is evident by the decreasing maximum distance possible going from back and stomach to other body locations. With regards to orientation, participants showed higher sensitivity when using a transverse orientation, this resulted in lower minimum and maximum values over body parts in comparison to a longitudinal arrangement of vibrotactile actuators. These findings are in line with experiments on touch sensitivity, however the absolute values for vibrotactile stimulation differ considerably, as shown in Figure 7. Qualtitatively, our participants rated *wrist* to be significantly more important and more comfortable than *stomach*. However, in comparison to other body locations *wrist* was not rated significantly higher and was rated comparably to *forearm* and *upper arm*.

6.2 Design Implications for Vibrotactile On-Body Interfaces

The results of our experiments provide valuable information on the required spacing between vibrotactile actuators at various body locations. In the following, we discuss implications for the design of on-body vibrotactile interfaces based on our results.

6.2.1 Favour Distal Over Proximal Placement. An important question faced by designers of wearable devices is where to place these devices on the body [69]. For vibrotactile devices our results show that distally (going away from the torso) placing vibration motors should be preferred over a proximal (going towards the torso) placement. Participants perceived vibrotactile stimulation on the wrist, forearm and upperarm to be significantly more important than on the stomach. Participants further rated the wrist and forearm to be of higher importance than the back.

With regards to comfort, our participants rated the wrist, forearm, upper arm, leg and thigh as a more comfortable location for vibrotactile feedback than the stomach.

In line with the participants' ratings, results of localization error show a clear trend and significant differences. Distal locations such as the wrist have shown a higher localization accuracy compared to proximal locations (e.g. the stomach). The body locations in ascending order of localization error are: wrist, forearm, leg, thigh, upper arm and stomach.

6.2.2 Favour Transverse Over Longitudinal. If given the choice between a transverse and a longitudinal arrangement of vibrotactile actuators on the same body part, our results show that a transverse orientation should be favoured for delivering accurately localized vibrotactile stimulation. Since for each body part, a transverse arrangement resulted in higher accuracy in comparison to a longitudinal arrangement. However, a transverse orientation (e.g on the forearm) is not necessarily more accurate than a longitudinal orientation (e.g on the wrist) of another body location.

Using a transverse orientation consistently resulted in significantly lower localization errors across body locations. Our participants further reported higher confidence ratings when using a transverse arrangement of vibrotactile actuators. We expect this to be of particular relevance for applications such as navigation and motion coaching where directions encoded spatially need to be accurately distinguished.

6.2.3 Design for the Correct Mechanoreceptor. Results of both our experiments show considerable deviation of localization and two-point thresholds for vibrotactile stimulation in comparison to touch stimulation. These differences could arise due to the mechanoreceptors in the skin targeted by touch (Merkel disc) and vibration (Pacinian corpuscle) that are different in the size of their receptive fields. They could also be due to the nature of stimulation, where vibrations cause displacements that propagate for larger distances on the skin [12].

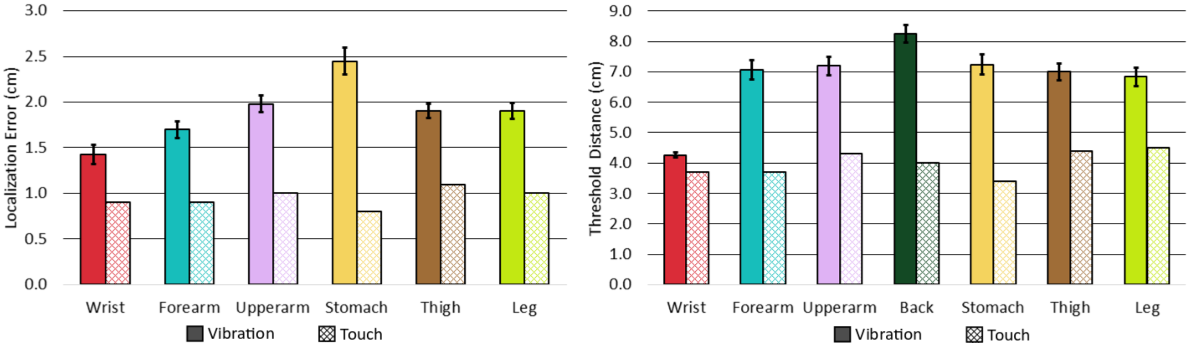


Fig. 7. Comparison of localization and two-point distance thresholds for vibrations and touch as reported by [65]. Error bars are the standard errors.

In experiment 1, thresholds for phantom sensations were consistently larger than reported values for two-point discrimination of touch stimulation [39]. For instance, two-point thresholds for simultaneous touch stimulation on the forearm and thigh are ≈ 2 cm in comparison to 7 cm for simultaneous vibrotactile stimulation.

Additionally, the localization error was always larger for vibrations than touch stimulation across all tested body locations [65]. For example, a touch has a localization error of 1 cm on the forearm and thigh in comparison to ≈ 2 cm for vibrotactile stimulation. Figure 7 compares two-point thresholds and localization for touch and vibrations.

These findings necessitate that designers abstain from using values on the human body's spatial acuity to touch stimulation when designing vibrotactile interfaces. Relying on information on touch acuity results in degraded recognition rates for spatial patterns due to a denser than required placement of vibrotactile actuators. Instead designers should base their decisions regarding spacing of vibrotactile actuators on information obtained specifically for vibrotactile stimulation.

7 LIMITATIONS AND FUTURE WORK

In this section, we mention limitations relating to our approach for deriving VibroMap and outline directions for future work.

Although we systematically investigated the perception of vibrations on major parts of the human body, a few locations such as the hand, head and shoulder were excluded. We excluded these body locations, as due to their complex geometries and properties such as hair on the head, they required significant changes to our experimental setup. These locations are promising for vibrotactile interfaces and should be systematically evaluated in future work. Moreover, we also investigated a single intensity level, varying intensity can lead to changes in threshold distances.

A second limitation that has to be mentioned is the granularity of VibroMap. We used a coarse-grained representation of the human body that assumes no variance in vibrotactile perception within body parts. Although this is in line with related work on spatial acuity of the human body [39], we plan to investigate in future work how vibrotactile perception varies on the human body in a more fine-grained manner.

Lastly, there are many different vibrotactile actuators available. In our experiments, we chose to use eccentric rotating mass (ERM) vibrotactile actuators as they are most commonly used in HCI research (e.g., [3, 68]). They are also cheap and widely accessible due to their use in phones. However, ERM actuators are controlled only by varying input voltage with no precise control over the frequency of the vibration. Future work should investigate the effect of using other types of vibrotactile actuators (e.g. LRA and piezos), the influence of the vibration frequency and important factors beside frequency, e.g rythm [6] on the spacing of vibrotactile actuators.

8 CONCLUSION

A systematic exploration of the spacing required for vibrotactile interfaces on the body is required in the HCI community given the amount of research using vibrations as a modality for interaction. We conducted two controlled experiments in which we explored the minimum and maximum spacing necessary for correctly discriminating between vibrotactile actuators and ensuring the ability to generate phantom sensations. Based on the results, we discussed implications for the design of vibrotactile interfaces to be worn on the body.

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