Perceived Midpoint of the Forearm

Ziyan Lu[1], Quan Liu[2], Roger Cholewiak[3], and Hong Z. Tan[1](✉)

[1] Purdue University, West Lafayette, IN 47907, USA
{lu396,hongtan}@purdue.edu
[2] Rime Downhole Technologies, LLC, Benbrook, TX 76126, USA
quan.liu@rimetools.com
[3] Princeton University, Princeton, NJ 08544, USA
rcholewi@gmail.com

Abstract. The present study estimates the perceived midpoint of the forearm by asking participants to judge whether a touched point is closer to the wrist or the elbow. Our results show a perceived midpoint at 51.4% of the forearm length from the wrist, which is slightly shifted towards the elbow (by about 3 mm) from the geometric midpoint. This trend is consistent with some past studies that demonstrate mislocalization of tactors towards the more distal and mobile joints, but not consistent with others that show the opposite trend. For the design of an arm-worn tactor array where the tactor location is used to encode information, the shift in perceived midpoint is too small to warrant any adjustment in tactor spacing in order to ensure accurate tactor localization.

Keywords: Midpoint perception · Forearm midpoint · Haptic perception

1 Introduction

In our everyday life, localization of touches on the skin usually is important when a raindrop, insect, or a loved one comes close to us. In such cases, we are often relatively accurate in identifying "where" the contact happened. When homing in on, and swatting a mosquito away, the hand is usually large enough to make up for this "relative" error. However, the development of tactile communication systems that are intended to present language, location, or spatial orientation to augment or replace sensory input from the eyes, ears, or orienting systems, often require more precise localization of stimuli on the skin, in particular, the ability to locate the relative location of numerous sites through which information such as spatial orientation or speech might be presented (e.g., [1, 2]).

The accuracy of tactile localization and the influences of factors including body site, stimulus frequency, duration, force, and size of the contactor, have a long history of exploration in the psychological and physiological literature. Even the position of the body site in space relative to the body core can influence the perception of tactile stimuli (e.g., [3, 4]). One of Boring's histories of psychology [5] (p. 475) describes numerous early attempts to study many of these parameters and how they influence the

R. Cholewiak—Princeton University (Retired).

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accuracy of tactile localization, especially the detailed work of Weber [6]. From the literature on the physiology of the skin and psychophysical modeling, we also know that the underlying receptor populations at a particular location can affect tactile localization as well. More recent reviews (e.g., [7, 8]) underscore the facts that both stimulus parameters as well as intrinsic factors such as body/limb orientation or proximity to certain "anchor" points can affect judgments of location. For example, Cholewiak, Brill, and Schwab [9] showed that certain body landmarks (such as the midline of the abdomen or the spine) could serve as anchor points. In a more common test of tactile mislocalization, Cholewiak and Collins [10] demonstrated the influences of both the elbow and wrist joints on the localization of seven stimuli on the forearm and upper arm – the closer a stimulus was to the joint, the better the touched site was localized. They also were able to mimic this so-called "perceptual anchor" effect by introducing a change in the stimulus frequency at the more uncertain locations on the arm, in the middle of their linear array. Vignemont, Majid, Jola, and Haggard [11] explored our knowledge of our body parts and their segmentation with reference to body landmarks – specifically the arm vs the hand as divided by the wrist, an acknowledged anchor point. Judgments of apparent distance between caliper touches were greatest when presented spanning the wrist, but this effect only occurred tactually, not visually, and was reduced with hand-arm motion (which, they argue, unifies the surface into a single less-segmented functional unit). So they argue that tactual appreciation of the body surface is mediated by a representation of the body linked to the perception of the touch, while visual appreciation is direct and unmediated. Medina, Tame, and Longo [12] reported evidence of gaze-direction modulation of tactile localization bias where participants performed a tactile localization task on their left hand while looking at the reflection of their right hand in a mirror, a box through the mirror, and the right hand directly. Their results show that body surface representation is modulated by high-level representations of frame of reference and better somatosensory localization can be achieved when gaze is directed towards the body site being simulated.

There are some trends that have been noted in the pattern of mislocalizations across these stimulus dimensions. One of the more interesting ones is the likelihood that stimuli will be localized in a direction towards so-called "anchor points," like the wrist and elbow (e.g., [10]). Historically, anchor points have been related to the joints, that correspond to Vierordt's "law of mobility" [13] (cited by [5]). That is, stimuli are localized towards more "mobile" geometric structures. So, for example, a touch on the arm might be mislocalized closer to the shoulder or the elbow, predictable from its actual position on the arm. Lewy [14] and Parrish [15] have argued that the direction of mislocalizations tend to occur more in the distal direction on a limb (towards more mobile structures). Sadibolova, Tamè, Walsh, and Longo [16] demonstrated that localization errors or biases to paired touches on the back of the hand were large and occurred in the distal direction (towards the fingertips), in agreement with the historic notions. However, Hölzl, Stolle, and Kleinböhl [17] showed mislocalizations of all of their eight tactors on the forearm tended to occur in the proximal direction, and a post-publication analysis of the data from Cholewiak and Collins [10] also showed that mid-array stimulus errors on their forearm array of tactors also occurred more frequently towards sites near the elbow than towards the wrist. More recently, Wang et al. [18]

placed bands with two tactors touching the dorsal and the volar sides of the upper and lower left and right arms (a total of eight sites) and studied vibrotactile localization for each of these sites as well as combinations of them when presented simultaneously (similar to Geldard and Sherrick's [19] exploration of multiple presentations on the arms and legs). Tactors were located close to the elbow for the forearms, and close to the shoulder for the upper arms, and identification rates for the individual sites (only one stimulus presented) ranged from 87% to 100% with no clear pattern of variation over sites. More common errors occurred in mislocalizing stimuli on a single band – Was it the volar or the dorsal site on that particular band that was activated? This was also one of the more common types of errors reported by Fontana et al. [20] – confusion among "adjacent" stimulus sites across the forearm or upper arm, despite earlier data arguing better resolution for localization for these transverse sites on the limb rather than for those along the length of the arm [21]. So we apparently do not know "exactly" where we are touched.

Given this history, one might ask the question, do these data then argue that perceived nominal positions along the arm, such as the apparent midpoint, are somehow skewed away from the veridical geometric locations? This is the question that is asked in this project. Our finding is expected to inform the design of wearable haptic communication systems that use the location of tactors on the forearm to encode information.

2 Methods

2.1 Participants

Twelve participants (P1 to P12; 6 females; age 21.8 ± 1.4 years old) took part in the present study. All participants were right handed and have normal haptic perception by self-report. They gave informed consent using a form approved by the IRB at Purdue University. They were compensated for their time.

2.2 Apparatus

The experimental apparatus was a custom-built device with one horizontal stage that moved beneath and along the length of the participant's arm, and two synchronized vertical stages mounted on the moving horizontal stage (see Fig. 1). The horizontal stage (V-Slot® Mini V Linear Actuator from OpenBuilds Part Store) moved along the x-axis with a 0.091 mm accuracy. The vertical stages (two L12-R Micro Linear Servos by Actuonix with a 50 mm actuator stroke and 100:1 gear ratio at 6 V DC; see #2 in Fig. 1) were securely mounted on two bases (#1 in Fig. 1) attached to the horizontal stage and moved up-and-down along the z-axis with a repeatability of ±0.3 mm. The stimulus probe (#4 in Fig. 1) was a 175-mm long cylindrical hollow polycarbonate clear tubing with a tapered tip of 1.28 mm in diameter. The tube was filled with kitchen salt so as to weigh a total of 27 g. Two parallel aluminum rods (3.18 mm in diameter) went through the probe and rested on the two 3-D printed alignment forks (#3 in Fig. 1). An arm rest made from high-density polyethylene synthetic wood (26"L × 2.125"W × 0.875"H; #6 in Fig. 1) supported the participant's forearm and was clear from all moving parts.

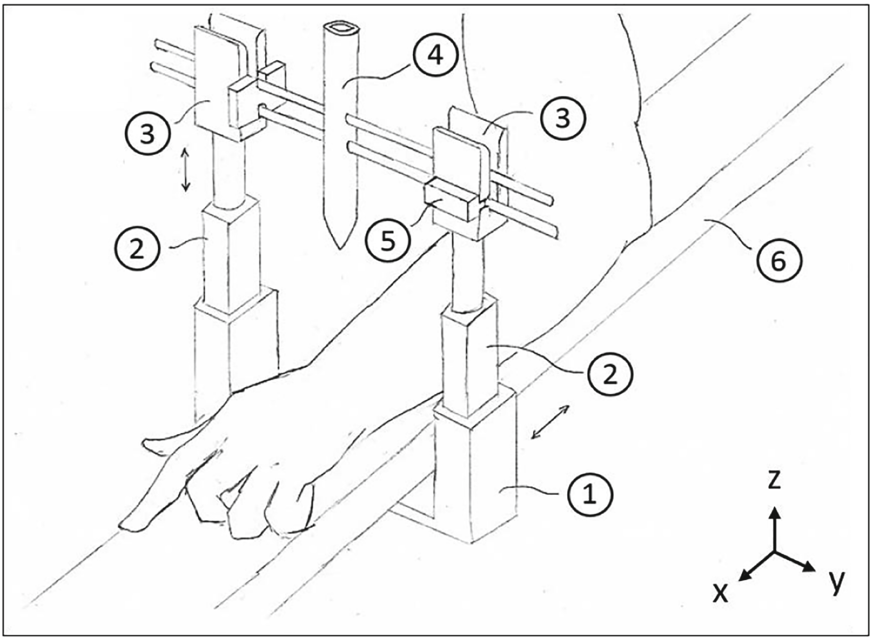

Fig. 1. Experimental apparatus: (1) vertical-stage base that is attached to the horizontal stage; (2) L12-R Micro Linear Servos; (3) alignment forks; (4) stimulus probe that is supported and kept vertical by the alignment forks; (5) infrared sensor; and (6) arm support. The V-Slot Mini V Linear Actuator for the horizontal stage is hidden by the arm support.

Past research has shown that force is the controlling factor in the perception of tactile intensity [22, 23], so our apparatus was designed to apply a consistent weight (27 g) to the skin. Since skin impedance differs over persons and locations, the resulting penetration depth varied, but was designed to be about 2 mm. LaMotte [24] used a 2-mm diameter probe that touched the finger pad for 900 ms to study magnitude estimation of skin indentation up to 1.6 mm. Our 2-mm indentation depth should therefore be clearly perceivable to all participants. To ensure sufficient contact time, the probe tip was allowed to press onto the skin for about 2 s [25, 26].

The horizontal stage served to position the stimulus probe on the desired skin location. The two vertical stages supported and lifted the probe off of the arm while the horizontal positioning stage moved. Once the probe reached its desired x position, the vertical stages lowered until the weight of the probe was fully supported by the skin on the arm. The vertical stage continued to move down for another 5 mm until the infra-red sensor (GP2Y0A41SK0F by Sharp; #5 in Fig. 1) no longer detected the bottom aluminum rod. At this point, the vertical stage was signaled to stop. The alignment forks supported the weight of the probe during the time it wasn't touching the skin. They also served to ensure that the probe remained vertical when the skin was supporting the probe's weight. At the end of the 2-s stimulus duration, the vertical stages lifted the probe off of the skin before the horizontal stage moved again. (Please see the supplemental video at https://youtu.be/RPhzymTr9jU that demonstrates the apparatus in action.)

The horizontal and vertical stages were controlled independently through an Arduino Uno R3 unit. A MATLAB program was developed to interface with the Arduino and to provide a GUI for the experiment.

2.3 Procedure

The participant sat next to a table and placed the non-dominant arm on the table, with either the dorsal or volar side facing up. We chose to test the non-dominant forearm because we envision most communication devices to be worn on the non-dominant forearm. The participant wore a noise-reduction earphone to block any possible auditory cues. An opaque screen blocked the participant's view of the forearm and the apparatus. Using a tape measure, the experimenter measured the length of the participant's forearm from the wrist (the crease at the volar base of the palm) to the elbow (the crease visible when the elbow is slightly bent), and the circumferences of the forearm at the elbow and the wrist. The experimenter then marked the wrist and elbow locations with ink. For bookkeeping, all positions were measured in mm from the wrist and then converted to percentage of total forearm length.

A one-interval forced-choice paradigm with a one-up one-down adaptive procedure was conducted. The thresholds obtained this way correspond to the 50 percentile point on the psychometric function (see [27], p. 470, left column, for a discussion of the pros and cons of the simple up-down procedure). Before each adaptive series, the probe touched the participant's wrist for 2 s, followed by a 2-s touch on the elbow, to ensure awareness of the exact positions of these two joints. On each trial, the stimulus probe contacted the skin at one point. The participant was asked to indicate whether the touched location felt closer to the "elbow" or the "wrist." If the participant responded "elbow" (or "wrist"), then the contact point was moved 10 mm away from the elbow (or wrist) on the next trial. After the first three reversals at the step size of 10 mm, the change in position was reduced to 5 mm. A reversal was defined as the contact location moving towards the elbow after having moved away from the elbow on the previous trial(s), or vice versa. The series ended after the participant had completed twelve (12) reversals at the smaller step size of 5 mm. If the participant's data did not converge by visual inspection of the stimulus vs. trial plot (e.g., see Fig. 2), the adaptive series was repeated. This happened to 4 participants (P3, P6, P9, P12).

Each participant completed four conditions: two starting positions (75% or 25% of the forearm length from the wrist) and two sides of the forearm (dorsal or volar). The order of the conditions was randomized over participants. The participant could take a break between the conditions. The entire experiment took two sessions, two conditions per session, for each participant and lasted a total of 1 to 2 h.

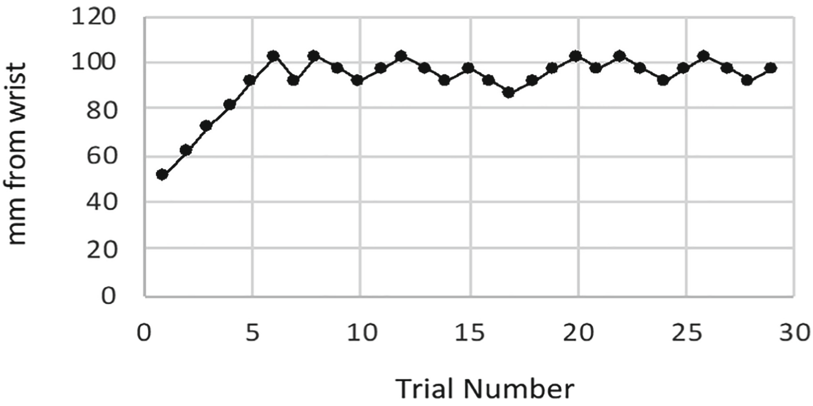

Fig. 2. One adaptive series for P10, with a starting point of 25% from the wrist, on the volar forearm. The measured forearm length is 210 mm. The estimated midpoint is 96.7 mm with a standard error of 0.3 mm, or 46.0% of forearm length from the wrist.

2.4 Data Analysis

The perceived midpoint on the forearm was estimated by averaging the peak and valley positions over the last 12 reversals. To determine the standard error of the perceived midpoint, six estimates were calculated from the six pairs of the peaks and valleys at the last 12 reversals. The average and standard error were then obtained from the six estimates (see [28] for a similar data processing method). Figure 2 shows a typical experimental series.

3 Results

The perceived midpoints in mm for each participant were first converted to percentage of forearm length for the participant. The measured forearm length varied from 180 to 225 mm for the twelve participants. Figure 3 is a scatter plot of perceived midpoints for all participants in percentage of forearm length from the wrist. For clarity, the data for the dorsal and volar sides of the forearm are slightly offset to the left and right, respectively, for each participant. It is evident that there are large differences in the data from the twelve participants. Three participants (P6, P7, P8) show a clear trend of having perceived midpoints at >50% over all conditions, which correspond to points closer to the elbow than to the wrist. Among the remaining participants, two (P1 and P12) exhibited different trends for dorsal (C1 and C2) vs. volar (C3 and C4) conditions. Yet others' data differed depending on the initial starting point at 75% from the wrist (C1 and C3) vs. 25% from the wrist (C2 and C4). These include P4, P5, P6, P7, P8, P10, and P11. Among the latter group whose data exhibited effect of starting point, some midpoint estimates hardly deviated from the starting points (e.g., C3 for P2, C2 for P11). Upon closer examination, the data that were most influenced by the starting position in these cases were from the randomly-selected first condition that the participants were tested on, reflecting a possible learning effect.

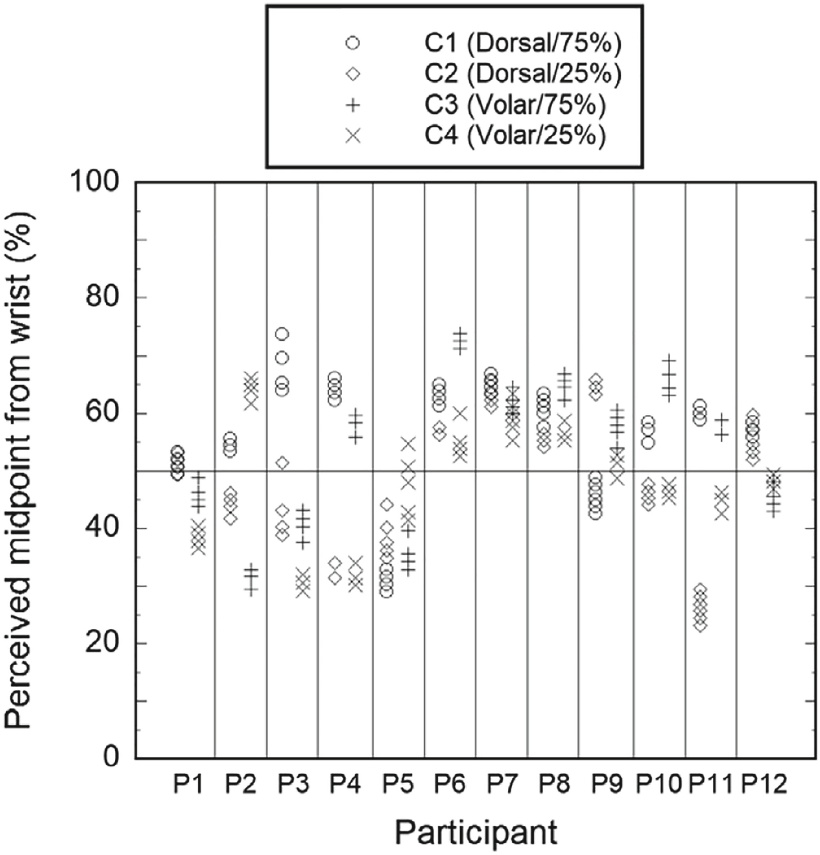

Fig. 3. Scatter plot of perceived midpoint estimates for each participant. The data for the dorsal side of the arm are slightly offset to the left of those for the volar side. There are six data points per condition, and some data points overlap.

The ranges of perceived midpoint were similar across the four experimental conditions, as shown in Table 1. The averages are above 50% for C1 and C3 (starting point at 75% from the wrist), and below 50% for C2 and C4 (starting point at 25% from the wrist). The standard errors are also similar across the four conditions. The average over all the participants and all the conditions shows a slight tendency (51.4%) toward the elbow.

Table 1. Perceived midpoint estimates for each experimental condition: Ranges, averages and standard errors over the twelve participants.

	Range	Ave ± std.err.
C1 (Dorsal, starting at 75% from wrist)	29.0–73.6%	56.4 ± 1.15%
C2 (Dorsal, starting at 25% from wrist)	23.1–65.8%	48.2 ± 1.38%
C3 (Volar, starting at 75% from wrist)	29.4–73.8%	53.2 ± 1.46%
C4 (Volar, starting at 25% from wrist)	29.2–66.1%	47.9 ± 1.20%

A repeated-measures analysis of variance (ANOVA) with the two factors starting point and side of forearm confirms significant inter-participant differences [$F(11,273) = 16.77$; $p < .0001$], a significant effect of starting point [$F(1,273) = 43.34$; $p < .0001$], but no significant effect of side of forearm [$F(1,273) = 2.99$; $p = 0.0847$]. A posthoc t-test comparing the perceived midpoints in percentage to 50% reveals a significant difference [$t(287) = 2.07$; $p = 0.0390$].

4 Discussions

The present study set out to ask the question of whether our perceived midpoint coincides with the geometric midpoint on the forearm. Past literature has shown tendency of mislocalization towards the more distal and mobile joint [5, 13–15]; in that a stimulated point at the geometric midpoint of the forearm is judged to be closer to the wrist. This suggests that in order for a point to be perceived as the midpoint, it needs to be located closer to the elbow, thereby suggesting a shift of perceived midpoint towards the proximal and less mobile joint (in our case the elbow). Other studies have shown the opposite trend [10] or no discernable pattern [18]. For example, a re-analysis of the localization errors for the mid-forearm tactor (#4) in the 7-tactor array from [10] showed that overall, there was a tendency for the tactile stimuli to be localized (incorrectly) in a direction closer to the elbow than to the wrist. That is, when Site 4 (at the physical midpoint of the arm) was stimulated, regardless of the magnitude of the error (1, 2, or 3 sites distant) it was more likely that the participant would respond that a site towards the elbow was stimulated than a site towards the wrist. This suggests a trend that the perceived midpoint was shifted towards the wrist.

While most past studies looked at tactor localization errors using one or more tactors placed on the skin, the present study directly asked the question of whether a touch that varied along the longitudinal direction (wrist to elbow) on the forearm felt closer to the wrist or the elbow. When the average was calculated over all the conditions and all the participants in the present study, we found a slight tendency for the perceived midpoint to be located in a direction towards the elbow; i.e., the average perceived midpoint was 51.4% of forearm length from the wrist. This finding was found to be significant in the post-hoc t-test analysis. Numerically, a 1.4% shift corresponded to a 3 mm displacement on the longest forearm (225 mm in length) among the participants tested. This slight shift of 3 mm is quite small, considering that most tactors have contact dimensions that are either similar to or larger than 3 mm. Therefore, for all practical purposes, we may conclude that the perceived midpoint and the geometric midpoint are quite close.

During the post-experiment debriefing, several participants commented that the tactile stimuli delivered by the weighted probe felt clearer on the volar side than on the dorsal side. This may be due to the slight differences in the detection thresholds at these two body sites. However our statistical analysis indicated that the side of forearm tested did not have a significant effect on the perceived midpoint estimates, presumably because the stimuli were well above thresholds on both sides of the forearm. Some participants were unsure about where the midpoint on the forearm was located. They pointed to a region rather than a point on the forearm as being in the "middle." Interestingly, when asked whether they could tell the location of a mosquito bite, more than half the participants (P1, P2, P3, P5, P6, P8, P12) said they couldn't.

5 Concluding Remarks

The results from the present study was useful to a tactile speech communication project where three locations on the forearm (near the wrist, middle of the forearm, and near the elbow) were used to encode phonemic information, in addition to other signal characteristics such as frequency and duration [29–31]. While it was clear that the tactors near the wrist and elbow could be easily localized, there was a question of whether the occasional mis-localization of the middle tactor could be attributed to a perceived midpoint that differed significantly from the geometric midpoint. Our finding is that the slight shift in perceived midpoint from the geometric midpoint (3 mm) is small compared to typical tactor sizes. Due to the variation among the participants and the different trends shown by individual participants (Fig. 3), it is conceivable that more data collected from additional participants may lead to a slightly different conclusion. However for the purpose of guiding the placement of tactors on an arm-worn array, there is sufficient evidence to determine that there is no need for adjusting the tactors placed in the middle of the forearm.

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