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Walking Does Not Diminish Localizability of Vibrotactile Feedback on the Waist

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***Abstract*—Individuals who lack tactile and/or proprioceptive sensations in their lower limbs commonly report postural and locomotive imbalance. To mitigate imbalance, haptic feedback has been implemented using devices that employ external sensors and waist-worn actuators for sensory augmentation. Analyses of the effectiveness of these devices have primarily focused on balance outcomes and generally disregard the potential effect of the user's varying activities or anthropometric data on their perception of the haptic feedback. Since motor activity can influence haptic perception, we investigate vibrotactile cue localizability in a waist-worn haptic device for two conditions, standing and walking on a treadmill at a self-selected speed. In this preliminary study, ten participants without sensorimotor deficits wore a waistband equipped with seven vibrotactile actuators. Vibrotactile cues were played at randomized locations during standing and walking, and participants reported the perceived stimulation location. In addition, we recorded relevant anthropometric data for each participant. In both standing and walking conditions, participants correctly localized 51% of the vibrotactile cues on average. When considering zonal accuracy, or localization within one vibrotactor position, participants, on average, achieved an accuracy of 91% in standing and 90% in walking.**

***Index Terms*—vibrotactile feedback, wearable devices, sensory substitution, balance assistance, sensory augmentation**

I. Introduction

Postural and locomotive imbalances are commonly reported in those with sensory deficits arising from conditions such as lower limb loss [1], [2], stroke [3], spinal cord injury [4], Parkinson's disease [5], peripheral neuropathy [6], vestibular disorders [7]–[9] and multiple sclerosis [10]. Disruption of sensory information in the lower limbs limits the perception of the base of support and whole-body balance information, such as center of pressure (COP) and center of mass, which are vital to maintaining balance [11].

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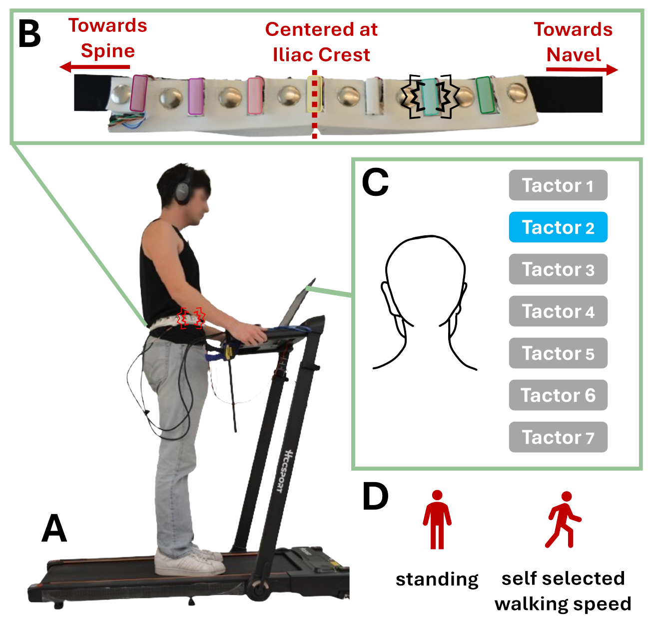

Fig. 1. Overview of study and device. A) Study Setup: Participants stood on a treadmill and interacted with a laptop computer while wearing the haptic waistband (depicted over the shirt for visualization but worn underneath for the study). B) The haptic waistband is comprised of seven independently actuated vibrotactors. C) Graphical User Interface (GUI): User's view of GUI, where the highlighted vibrotactor is the participant's response. D) Participants stood or walked on a treadmill while receiving the vibrotactile cues.

Recent studies have investigated how sensory augmentation via haptic feedback integrates with human neural control to improve lower limb coordination and balance control [12], [13]. Haptic devices for balance often provide feedback at the waist [14]–[19] or on the lower limb [20]–[27], given the proximity to the missing sensory information. The waist is commonly used (as shown in Fig. 1) due to anatomical limitations of specific pathologies, such as tactile sensory loss in the lower limb or distal limb obstruction due to prosthetic sockets. Additionally, the waist has distinct benefits as a site for haptic feedback due to ample space for devices, the hands-free nature of the feedback, and the potential for integration into existing waist-worn garments such as belts. The advantages of the waist make it a prime candidate for different applications of haptic feedback, including human-agent communication tasks such as navigation, or for balance and spatial awareness training through sensory augmentation.

Studies using such devices have investigated balance task performance across several common activities, including quiet standing [17], walking [16], [28], sitting [19], and stair ambulation [16], [21], [23]. These efforts have found improvements in user control of weight shifting [15], [22], foot placement awareness [21], [23], and gait symmetry [28]. While promising, these studies have primarily focused on evaluating devices for balance-related outcomes, focusing less on psychophysical perceptual and user anthropometric aspects of cue identification and usability.

Prior studies have investigated how different haptic cue location parameters affect the perceptibility of haptic feedback at the waist in an application-agnostic manner [29]–[31]. These studies assessed the impact of factors including vibrotactor location, vibrotactor quantity, and cue frequency on the localizability of the haptic cues at the waist. The outcomes of these psychophysical studies highlight the effectiveness of certain vibrotactor arrangements at the waist for high localizability, which can be applied to the design of application-focused wearable haptic devices. However, these studies do not examine how individual anthropometric differences or activity variations could further affect localizability.

Another study investigated vibrotactile cue localization and reaction times for different stimulus intensities and locations around the waist [27]. They found that stimulus intensity affected reaction time, and that stimulus localization performance was superior at the navel and spine, aligned with prior haptic perception studies conducted while standing [29]. They also found that varying gait events during haptic cue display did not significantly affect stimulus localization performance [27]. However, the study did not directly investigate the difference in cue localization performance between standing and walking conditions. Understanding perception accuracy during both activities is vital for refining waist-based haptics, as perception during gait may be influenced by skin movement along the waist or fluctuating focus caused by the cognitive load of walking and neural integration.

In this preliminary study, we examine the impact of activity, haptic feedback location, and anthropometric variation on user localization of vibrotactile stimuli. We asked participants without sensorimotor deficits to perform a cue identification task during two activities: standing and walking at a self-selected walking speed. Participants wore a waistband with seven integrated vibrotactors and reported the perceived location of the stimulus for both activities. We analyzed accuracy, information transfer, and perceptual distance. In addition, we examined the relationship between haptic perceptual performance in the task and the participant's anthropometric parameters of age, sex, height, weight, waist circumference, suprailiac skinfold thickness, and estimated body fat percentage.

II. Methods

In this study, participants were asked to identify the location of vibrotactile cues played at seven different locations on a haptic waistband (Fig. 1A). Ten participants without sensorimotor deficits completed the study (4 female, 6 male; age $\mu = 31$, $\sigma = 10.2$). All participants provided informed consent (IRB-FY2019-49). The study consisted of three phases: familiarization, training, and testing. Participants performed the study on a treadmill, standing still and walking at a self-selected walking speed (Fig. 1D). Experimental conditions were counterbalanced to ensure equal groups started with each activity to avoid learning bias. Our outcome measures included information transfer (IT) to quantify the effectiveness of incorporating haptic information, perceptual distance to assess the distinctiveness of vibrotactor pairs, overall localization accuracy, and zonal accuracy.

A. Haptic Waistband

We developed a haptic waistband (Fig. 1B) with seven equally-spaced eccentric rotating mass (ERM) vibrotactors (Vybronics VZ6DL2B0055211) integrated into a flexible, thermoplastic polyurethane (TPU) band 30 cm in length with 40 mm between vibrotactors. The band length was selected to ensure it covered no more than one hemisphere of the waist, using the 1st percentile of American female waist circumference as a conservative threshold [32]. The band was fixed to an adjustable, elastic waistband using metallic snaps, allowing for easy donning, doffing, and waist size adjustment between participants. When donning the haptic waistband, the center (4th) vibrotactor was placed above the iliac crest (Fig. 1B), and the haptic waistband was worn underneath the shirt.

B. Vibrotactile Haptic Cue Design

Cue duration was selected for the intended use case of providing center of pressure information to users while walking. Assuming a constant foot COP velocity while walking at 1 Hz stride frequency, and given that stance constitutes 60% of the gait cycle, each vibrotactor plays a cue for approximately 86 ms.

The vibrotactors were actuated directly via a pulse-width modulation (PWM) command signal using an Arduino Mega 2560 Rev 3, with a maximum voltage of 5 V and an amperage of 20 mA. To ensure that cue intensities were perceivable, we determined each participant's detection threshold during walking by gradually increasing the PWM duty cycle while they walked at a self-selected speed on the treadmill. During this process, vibrotactors were actuated one at a time at each duty cycle threshold. The stimulus intensity was then set to a duty cycle nominally equivalent to 2 V above the highest detection threshold. If this value exceeded 5 V, the intensity was set at 5 V.

C. Study Design

Participants wore the haptic waistband and identified haptic cues played one at a time from the seven possible vibrotactor sites. The experiment had three phases: familiarization, training, and testing. During each phase, participants interacted with a GUI (Fig. 1C) to select and identify cue locations.

1) Familiarization: This phase allowed participants to select vibrotactor locations where the vibrotactile cue would be played on demand. This allowed participants to become acquainted with the range of possible locations used in the study. Participants were required to play each cue at least five times and could continue the activity for up to five minutes.

2) Training: Next, participants performed the vibrotactile cue localization task with correct-answer visual feedback. After the participant identified the location of a randomized cue, the GUI displayed the correct location of the stimulus vibrotactor. Participants were required to identify at least 70 cues during this phase, and could continue for up to 20 minutes if desired. The minimum set of 70 cues was presented randomly without replacement to ensure equal exposure to all cues while learning. During the optional additional learning period, cues were randomized with replacement, uniquely to each participant. Participants were given a 90-second standing break after this phase. They remained standing to avoid shifting the haptic waistband. During the break, the vibrotactor alignment was confirmed before proceeding to the next phase.

3) Testing: Finally, participants completed the cue localization task without correct-answer visual feedback. Similarly to the prior phase, participants were presented with randomized cues and used the GUI to identify the perceived stimulus location. Participants were presented with 245 cues that were randomized with replacement, uniquely to each participant. While randomizing with replacement does not ensure an equal number of cue presentations at each possible location, it avoids statistical bias in estimating information transfer [33]. The number of cues was selected based on previously reported methodologies for estimating information transfer, $5 \times \text{cues}^2 = 5 \times 7^2 = 245$ [33]. Participants took two 90-second standing breaks after 86 cues each, splitting the testing phase into thirds. The alignment of the vibrotactors on the waist was verified during each break.

All three phases of the study were completed for two activities, standing and walking, using a within-subjects design. Each activity was separated by 24 hours to avoid physical, mental, and sensory fatigue effects. We counterbalanced the activities across the participants to prevent potential learning effects. Both activities were completed on a treadmill (HCCSport SOUTIEN-1), shown in Fig. 1A. The treadmill was held static for the standing activity, while for the walking activity, participants were allowed to select their own comfortable walking speed (the same speed used for cue magnitude calibration). Walking speeds ranged from 1.5 to 2.2 mph. During walking, cues were played indiscriminately throughout the gait cycle, as the perception of haptic feedback on the waist during gait is not altered by gait event proximity [27].

After the first session, participants responded to a survey to collect anthropometric data, including height, age, and sex. Researchers then measured participant weight with a digital scale, waist circumference with a fabric measuring tape, and suprailiac skinfold thickness with calipers. Suprailiac skinfold thickness was measured three times and the average value was used along with age to estimate body fat percentage via a look-up table (AccuFitness Accu-Measure) [34].

D. Outcome Metrics

Throughout the training and testing phases of the study, we recorded both the participants' perceived stimulus location via the GUI and the actual location of the applied stimulus. We used these data to calculate information transfer (IT), overall localization accuracy, zonal accuracy, and perceptual distance.

Information transfer was calculated as

$$IT_{est} = \sum_{j=1}^{K}\sum_{i=1}^{K} \frac{n_{ij}}{n} log_2(\frac{n_{ij} \cdot n}{n_i \cdot n_j}) \qquad (1)$$

where K represents the number of vibrotactors, n is the total number of trials collected, n_{ij} represents independent stimulus-response combinations (row-column intersection on the confusion matrix in Fig. 2), and n_i and n_j are the totals for displayed vibrotactor (rows in Fig. 2) and user selected vibrotactor (columns in Fig. 2) in those trials [33], [35].

To represent how well people performed this task, we examine overall cue identification accuracy and recall. Overall accuracy (Eq. 2) is a measure of how often people correctly identify the vibrotactor when it is played, where T is the total number of trials, i is the vibrotactor number, $C_{i,i}$ are the diagonal entries of the confusion matrix. Recall, for a particular cue (Eq. 3), is the proportion of cases where the cue is correctly identified compared to the total number of times that cue was delivered.

$$Overall\ Accuracy = \frac{\sum_i^7 C_{i,i}}{T} \qquad (2)$$

$$Recall_{cue} = \frac{C_{cue,cue}}{\sum_i^7 C_{cue,i}} \qquad (3)$$

Additionally, we calculated the zonal accuracy based on the perception of vibrotactors directly adjacent to the stimulated vibrotactor. To calculate zonal accuracy, we considered if the response was ± 1 of the true value [36]. We modify Eq. 2 by adding $C_{i,i-1} + C_{i,i+1}$ to the numerator sum.

We calculated the perceptual distance, d', for pairs using Eq. 4, where H is the true positive rate, F is the false positive rate, and $z(.)$ is the inverse Gaussian distribution function.

$$d' = z(H) - z(F) \qquad (4)$$

This formulation requires calculating the quantile of the normal distribution. In cases where this value is $< 0.01^{\text{th}}$ or $> 99^{\text{th}}$ percentile, we offset the value by $\epsilon = 0.01$ away from those extremes to avoid an infinity result. Thus, d' is saturated at 4.65, corresponding to 99% true or false positive rates. Israr et al. [37] determined that a $d' \geq 3$ corresponds to two distinct vibrations, which we use to contextualize our results.

E. Statistical Analysis

We fit generalized linear mixed-effects models to the data using the *brms* package in R with the appropriate family and a probit link function (participants' response accuracy was binary – they either identified the correct vibrotactor or not). To determine which model best predicts participant accuracy, we used approximate leave-one-out cross-validation via the *loo* function. Additional contrasts, when necessary, were performed using the *emmeans* package. Our inference criterion was that the 95% credible interval (CrI) excludes zero.

For results of interest that did not exclude 0, we ran a test for Practical Equivalence to determine if the groups can practically be considered the same, using the *bayestestR* package The test requires a Region of Practical Equivalence (ROPE), wherein any difference can be considered negligible. We used a range of ± 0.18 in log odds, corresponding to a difference of $\pm 4.5\%$ probability, and is commonly used as a rule-of-thumb for a negligible effect.

The simplest model, M0, predicts the *accuracy* of a single trial with main effects of *phase*, *activity*, and a random effect of *subject*. M1 adds a main effect of *vibrotactor*. The most complicated model, M2, includes an interaction effect between *activity* and *vibrotactor*. The predictor *accuracy* refers to the single-trial accuracy of either localizing the vibrotactor correctly or incorrectly.

M0: accuracy $\sim 1 +$ phase $+$ activity $+ (1 \mid$ subject$)$
M1: accuracy $\sim 1+$phase$+$activity$+$vibrotactor$+(1 \mid$ subject$)$
M2: accuracy $\sim 1+$phase$+$activity$*$vibrotactor$+(1 \mid$ subject$)$

III. Results

Our primary dependent variable was overall localization accuracy across the seven vibrotactors. Two independent variables affected accuracy: activity (standing vs. walking) and study phase (training vs. testing). We also consider the effect of participants' self-reported and measured features on accuracy (sex, age, height, suprailiac skinfold thickness (referred to as 'caliper'), waist circumference, body fat, and weight).

A. IT, Accuracy, & Perceptual Distance

Across both activities and phases of the study, participants performed the localization task with similar amounts of information transfer and accuracy (Table I). The table reports IT, accuracy, and zonal accuracy across all participants for each activity and study phase. We report individual participants' values from highest to lowest overall IT; these are solely from the testing and are separated by activity. People can reasonably identify at least two of the vibrotactors (lowest IT: 1.1 bits, $2^{1.1} = 2.14$ vibrotactors) and are well above the accuracy of guessing alone (accuracy: 51%, random $\frac{1}{7}$ = 14%). When you consider zonal accuracy (within ± 1 vibrotactor location), this increased significantly (accuracy: 90%, random $\frac{3}{7}$ = 43% to $\frac{2}{7}$ = 29%). However, when you consider these values on an individual level, we see evidence that some individuals (P5, Walking) can learn four signals ($2^{1.93} = 3.8$) with higher accuracy (74% and 100% zonal)

TABLE I
INFORMATION TRANSFER, ACCURACY, & ZONAL ACCURACY

	Standing			**Walking**		
	IT (bits)	Accuracy *All*	*Zonal*	IT (bits)	Accuracy *All*	*Zonal*
Train	1.21	52%	93%	1.36	58%	96%
Test	1.10	51%	91%	1.14	51%	90%
P5	1.80	56%	100%	1.93	74%	100%
P2	1.62	65%	100%	1.70	62%	96%
P1	1.59	63%	99%	1.73	55%	97%
P4	1.61	60%	97%	1.52	60%	98%
P3	1.22	53%	91%	1.51	58%	91%
P6	1.34	56%	96%	1.30	44%	80%
P9	0.94	48%	83%	1.29	53%	92%
P7	1.18	48%	88%	1.01	39%	86%
P8	0.94	36%	84%	1.08	38%	89%
P10	0.72	28%	71%	0.69	31%	70%

For the remaining results, we focus on the testing phase of the study, where participants did not receive correct-answer visual feedback. The testing phase is similar to how people would use the belt, where only haptic feedback is provided.

To better understand how the different vibrotactors were perceived and localized by users, we present a matrix that shows both exact and zonal accuracy (Fig. 2). Adjacent vibrotactors were confused, particularly near the front of the belt. However, there is strong consistency between displayed and selected vibrotactors, especially towards the back of the body (vibrotactors 5-7). There is also a higher tendency for participants to choose certain vibrotactors more than others, with vibrotactor 1 selected least often (column sums in Fig. 2). There are similar trends across standing and walking.

To determine people's relative sensitivity between the seven vibrotactors, we computed the perceptual distance (d') across all participants for both activities (Fig. 3). We considered a $d' \geq 3$ to correspond to two distinct vibrations, per [37]. Similarly to the Confusion Matrices, there is more difference, or sensitivity, for vibrotactors closer to the back (5-7) than those on the front and midline of the body (1-4).

B. Accuracy

We compared M0, M1, and M2 to explore what factors affected accuracy. Upon comparison, M1 was determined to be the model that best fit the data, compared to M2 ($elpd_{loo} = -3.9$, $SE = 2.3$) and M0 ($elpd_{loo} = -193.9$, $SE = 19.6$). For the remaining sections, we use M1 unless otherwise noted.

As noted in *Study Design*, participants selected their own walking speed. To confirm that this did not affect the results, we found no correlation between walking speed and accuracy ($r^2 = 7.2e^{-4}$).

1) Location of Vibrotactors: Previous works found that vibrotactors located at the navel and the spine resulted in the highest accuracy regardless of belt position along the longitudinal axis [27], [29]. With M1, we find an effect of vibrotactor location and evaluate which pairs differed notably in participants' task accuracy. As the vibrotactor location number increased, so did the estimated probabilities of an accurate response. Specifically, vibrotactors 1 to 3 had a lower

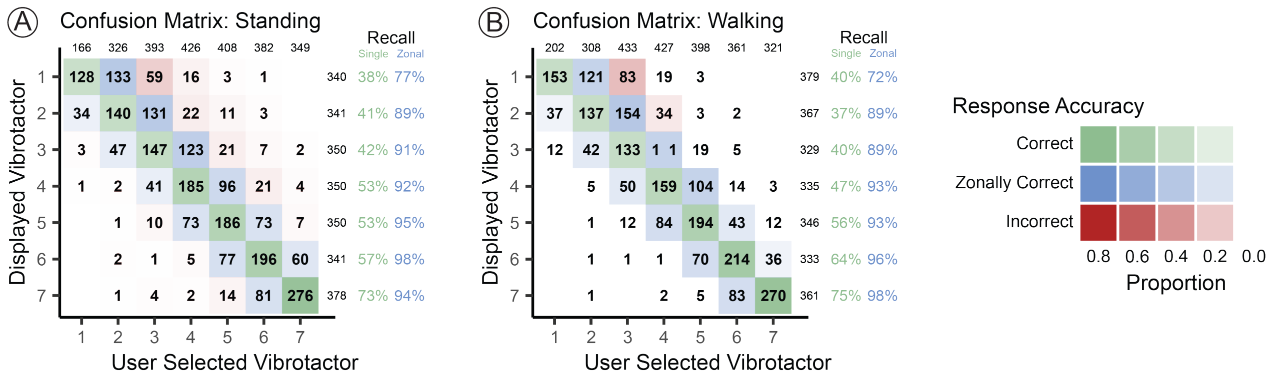

Fig. 2. Confusion Matrices for (A) Standing and (B) Walking for all participants combined. Colors show response accuracy across 3 levels: correct, zonally correct, and incorrect. Opacity demonstrates the proportion of responses in that square. Numbers are included for exact frequency counts. Additionally, numbers on the top and right sides of the graph indicate the sum for those rows and columns. The percentages show the single vibrotactor and zonal recall rates.

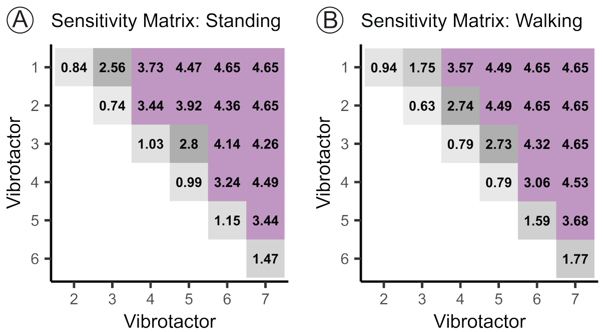

Fig. 3. Sensitivity Indices (d') for (A) Standing and (B) Walking for all participants combined, comparing each vibrotactor stimulus pair. Color shows highly distinct signals (purple) compared to others (gray). Opacity demonstrates how close a non-distinct pair came to being distinct (more opaque means closer to distinct). Exact values are written in the squares.

probability of correct responses $(0.40-0.43)$, 4 to 6 midrange $(0.53-0.62)$, and 7 was the highest (0.77).

Pairwise contrasts confirmed that the odds of an accurate response were lower for the front of the band than the back. Vibrotactor 7 had the highest accuracy, notably greater than all others (Table II). An odds ratio <1 means the first vibrotactor listed is less likely to result in an accurate response than the second vibrotactor. All notable differences are in white in the table, and we highlight those that do not meet our inference criteria in gray. Overall, there is a trend that consecutive vibrotactors (e.g., 1 vs. 2, 2 vs. 3, 4 vs. 5) sometimes have intervals crossing 0, indicating no reliable difference. While comparisons between vibrotactors far apart (e.g., 1 vs. 7, 2 vs. 6), typically show a strong difference. These results align with the sensitivity analysis from above. Adjacent vibrotactor confusion also skews heavier towards the front of the waistband, which is consistent with our earlier results.

2) Activity: Walking vs. Standing: From the previous section, IT and PC were similar between walking and standing. While we expected accuracy to decrease in the walking condition, we did not find any evidence to support that. Analysis of M1 demonstrated that there was no difference in accuracy between these two conditions (95% CrI $[-0.03, 0.17]$, 100% in ROPE).

3) Phase: Training vs. Testing: In the study, participants completed at least 70 trials while receiving corrective visual

TABLE II
PAIRWISE COMPARISONS OF VIBROTACTOR LOCATIONS ON ACCURACY

Vibrotactor	Odds Ratio	Log Odds	95% HPD
1 - 2	0.98	-0.020	[-0.20, 0.17]
1 - 3	0.87	-0.136	[-0.32, 0.06]
1 - 4	0.60	-0.512	[-0.70, -0.32]
1 - 5	0.51	-0.679	[-0.87, -0.49]
1 - 6	0.41	-0.891	[-1.09, -0.71]
1 - 7	0.20	-1.591	[-1.80, -1.39]
2 - 3	0.89	-0.115	[-0.32, 0.09]
2 - 4	0.61	-0.492	[-0.69, -0.30]
2 - 5	0.52	-0.660	[-0.84, -0.47]
2 - 6	0.42	-0.871	[-1.06, -0.68]
2 - 7	0.21	-1.569	[-1.78, -1.37]
3 - 4	0.69	-0.374	[-0.57, -0.19]
3 - 5	0.58	-0.543	[-0.72, -0.35]
3 - 6	0.47	-0.757	[-0.96, -0.56]
3 - 7	0.23	-1.454	[-1.66, -1.26]
4 - 5	0.85	-0.168	[-0.35, 0.03]
4 - 6	0.69	-0.379	[-0.58, -0.19]
4 - 7	0.34	-1.077	[-1.28, -0.86]
5 - 6	0.81	-0.212	[-0.42, -0.03]
5 - 7	0.40	-0.910	[-1.10, -0.70]
6 - 7	0.50	-0.699	[-0.91, -0.48]

feedback (training) before moving on to the testing phase. All participants completed at least one additional training trial. Most participants ($n = 7$) did no more than 7 additional trials, while the remaining three completed 10 to 19 additional trials. People performed slightly worse in the testing compared to the training phase, as demonstrated by analysis of M1 ($\beta = -0.15$, 95% CrI $[-0.28, -0.03]$) and the reduction in IT and PC. This result could indicate that more training was necessary.

C. Biological Features

In addition to the response data, we collected participants' sex, age, height, suprailiac skinfold thickness (*caliper*), waist circumference (*waist size*), body fat percentage (*body fat*), and weight. The goal is to explore which, if any, of these factors are essential for designers to account for when making vibrotactile belts. To address this, we considered several modifications to M1: first, all models with just one of these features added as a main effect, and second, a set of models that consider *age*, *sex*, and *height* in combination with *caliper*, *waist size*, and *weight*.

We only combined *body fat* with *height* because *age* and *sex* were already used in its calculation. We did not consider other combinations of *caliper*, *waist size*, and *weight* because we wanted to address which metric is the best predictor of accuracy without measuring all of these features.

In a comparison, B1 performed best compared to all others, including M1. This model had a notable effect of *weight*, although slight ($\beta = -0.007$, 95% CrI $[-0.012, -0.002]$), as this would not surpass our ROPE range. When weight increased, accuracy decreased. There was no difference in accuracy due to *height* (95% CrI $[-0.02, 0.11]$; 100% in ROPE).

$$\begin{aligned}\text{B1: accuracy} \sim\ & 1 + \text{activity} + \text{phase} + \text{vibrotactor} + \\ & \text{weight} + \text{height} + (1 \mid \text{subject})\end{aligned}$$

However, other metrics could also have a significant relationship with accuracy. Thus, we consider the best version of each model with the remaining metrics in order of relative performance. All models outperformed M1 and models of M1 that had additions for *height* and *sex*.

$$\begin{aligned}\text{B2: accuracy} \sim\ & 1 + \text{activity} + \text{phase} + \text{vibrotactor} + \\ & \text{caliper} + (1 \mid \text{subject}) \\ \text{B3: accuracy} \sim\ & 1 + \text{activity} + \text{phase} + \text{vibrotactor} + \\ & \text{waistSize} + \text{sex} + \text{height} + (1 \mid \text{subject}) \\ \text{B4: accuracy} \sim\ & 1 + \text{activity} + \text{phase} + \text{vibrotactor} + \\ & \text{bodyFat} + \text{height} + (1 \mid \text{subject})\end{aligned}$$

In B2, there was no main effect of *caliper*, but rather no difference (95% CrI $[-0.08, 0.01]$, 100% in ROPE).

In B3, there was a main effect of *waist size* – as waist size increased, accuracy decreased ($\beta = -0.062$, 95% CrI $[-0.11, -0.02]$). This difference is larger than that of *weight* but would not surpass our ROPE range. We find evidence for no differences between *heights* in this model (95% CrI $[-0.06, 0.09]$, 100% in ROPE). There is no effect of *sex*.

In B4, both *body fat* and *height* were no different (95% CrI $[-0.09, 0.11]$; 95% CrI $[-0.07, 0.05]$; 100% in ROPE).

IV. Discussion

We evaluated the effect of standing and walking activities on perceptual accuracy in a vibrotactile cue localization task and found no significant difference in localization accuracy between the two conditions. Without correct-answer feedback, participants were accurate, on average, 51% of the time for both activities. They were zonally accurate, on average, 91% and 90% of the time across standing and walking activities, respectively. The IT was also comparable (1.10 and 1.14 bits) as well as perceptual distance, where distinct signals were similar across activities. These results build on prior work that demonstrated no significant effect of gait events on stimulus localization accuracy [27]. High performance in identifying cues while walking further suggests that haptic feedback can be reliably perceived during dynamic activity, ensuring that feedback at the waist is well suited for balance augmentation.

Participants' accuracy increased from the front (adjacent to the navel) to the back (adjacent to the spine). As the stimulus moved farther back, adjacent vibrotactor pairs became more distinct, as indicated by our accuracy results. The pairwise comparison of vibrotactors also indicates that cues became increasingly identifiable as they moved backward (through the decreasing odds ratio). The front-to-back trend in accuracy is distinct from previous psychophysical studies of haptic feedback on the waist, which either reported higher accuracy at the extreme front (navel) and extreme back (spine) [27], [29] or relatively consistent high accuracy around the entire waist [30]. It is important to note that the type of vibrotactors used in our experiment differs from previous studies, and our experiment did not include vibrotactors exactly on the navel or spine. While further investigation is warranted to determine the repeatability of these effects, our results suggest that shifting the vibrotactors towards the back may improve the perception of cues for sensory augmentation devices for balance assistance.

We also investigated whether there was a relationship between anthropometric data and localization accuracy. Of all collected metrics, only weight and waist circumference notably affected accuracy. However, our limited sample size and range of body characteristics limit our ability to draw stronger conclusions. Further investigation is merited to determine the consistency and magnitude of these features' impact on cue localization to inform the personalization of balance feedback devices, such as an adjustable-sized haptic waistband.

While all vibrotactors were perceivable, confusion of adjacent vibrotactors during the localization task limited the overall IT (1.10 - 1.36 bits on average across activities and phases), indicating a small number of vibrotactors could be perceived (between 2 and 4, depending on the participant). Perceptual distance results suggest that vibrotactile cues were perceptually identifiable for vibrotactor pairs that were not immediately adjacent. The IT of our haptic device is lower than previously reported haptic devices applied to the waist (between 2.04 and 2.71) [29], which used sparser distributions of vibrotactors. These results indicate the need for further spatial separation in the vibrotactor distribution. Additionally, between training and testing phases, IT decreased in both activities (1.21 to 1.10 bits in standing, 1.36 to 1.14 in walking), indicating that further training could improve IT in the testing phase.

Low IT and low perceptual distance between adjacent vibrotactors indicate that our haptic device saturates the information a user can process, limiting their ability to perform conscious identification tasks. Due to limited long-term evaluation of haptic balance augmentation devices, it is unclear if such devices operate in the conscious or subconscious task space, such as with proposed sensory addition or sensory substitution modalities [13]. Further investigation is needed to understand how users process information from haptic balance augmentation devices over time and whether localizability is the most accurate predictor for maximizing device utility.

Our study results demonstrated consistent haptic perception for standing and walking, increased localization accuracy at the back compared to the front of the waist, and the impact of weight and waist circumference on localization accuracy. These results inform the design of balance augmentation haptic devices.

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