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Research paper

Investigating sensitivity to vibrotactile stimulation in isometric and dynamic work for effective ergonomic intervention

Mahdis Tajdari [a], Xiang Yang [a], Md Shafiqul Islam [b], Sol Lim [a,*]

[a] Department of Industrial and Systems Engineering, Virginia Tech, 1145 Perry Street, Blacksburg, 24061, VA, USA
[b] College of Applied Health Sciences, University of Illinois, Urbana-Champaign, 75 Bailey Dr, Champaign, 61820, IL, USA

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ABSTRACT

This study examined how isometric force exertion (Study 1) and dynamic work tasks (Study 2) influence vibrotactile sensitivity and spatial acuity across body regions. In Study 1, eighteen participants exerted isometric force at 30% of maximum voluntary contraction, with perception tested at the upper arm, thigh, and lower back. In Study 2, another eighteen participants performed shoveling, lifting, and standing tasks, with assessments at the upper arm, upper back, and lower back. Results showed that isometric force exertion reduced sensitivity and spatial acuity. The upper arm was more sensitive than the thigh and lower back, while the thigh exhibited better spatial acuity than the upper arm and lower back. Shoveling reduced spatial acuity compared to standing, and the upper arm had the highest spatial acuity among sites. These findings suggest that force exertion and task type significantly influence tactile perception, with implications for designing vibrotactile feedback in ergonomics applications.

1. Introduction

Wearable vibrotactile devices have gained popularity in occupational settings, delivering real-time warnings (Pundlik et al., 2021; Yang and Roofigari-Esfahan, 2023) and supporting postural intervention in ergonomic applications (Kim et al., 2021; Lim and Yang, 2023; Lind et al., 2023; Choi et al., 2025). This trend is driven by the urgent need to reduce work-related musculoskeletal disorders (MSDs), a leading cause of nonfatal occupational injuries. In construction alone, MSDs account for substantial lost work time, with 33,200 missing days of work between 2021 and 2022 due to these injuries (Harris et al., 2025). The risk is further amplified by the projected 11% increase in construction labor employment from 2018 to 2028 (Bureau of Labor Statistics, 2021).

While visual and auditory feedback systems have been explored for ergonomic interventions (Breen et al., 2009; Vignais et al., 2013), their utility is often limited in construction environments, where visual obstruction (Li et al., 2015) and high noise levels (Jones and Sarter, 2008) degrade signal clarity. Vibrotactile feedback, by contrast, leverages a separate sensory channel, which – according to Multiple Resource Theory (Wickens, 2002) – remains available when visual and auditory modalities are overloaded or unavailable (Jones and Sarter, 2008). Reflecting these advantages, more than two dozen commercial systems (e.g., Soter Analytics, GoX Labs) now use wearable sensors to monitor worker postures and deliver vibrotactile feedback when high-risk postures are detected. However, despite these advantages and increasing real-world adoption, a critical gap remains: the influence of task-related factors – such as physical exertion and dynamic movement – on vibrotactile perception and effectiveness is not well understood in occupational settings. Addressing this gap is essential for ensuring the reliability and design of such systems.

The effectiveness of these systems depends on perceptible and well-designed cues, which in turn require a clear understanding of two perceptual factors: vibrotactile sensitivity thresholds and spatial acuity. Sensitivity thresholds define the minimum vibration intensity detectable, ensuring that cues are noticeable without being uncomfortable during prolonged use. Spatial acuity refers to the ability to distinguish between multiple vibration sources on the body, which is critical when multiple tactors are used to convey directional information (Kim et al., 2021). If tactors are too close together, users may struggle to localize the vibration source, reducing clarity and effectiveness. However, while these perceptual factors are well established under controlled conditions, their behavior under varying levels of physical exertion and during realistic work activities remains poorly understood, which limits our ability to design reliable vibrotactile systems for real-world contexts. Understanding these limits is essential for optimizing tactor placement in applications ranging from communication (Carrera et al., 2017) and navigation (Filgueiras et al., 2016; Tajdari et al., 2025a) to

* Corresponding author.
E-mail address: sol@vt.edu (S. Lim).

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ergonomic interventions in physically demanding work (Lim and Yang, 2023).

Research to date has mapped vibrotactile thresholds and spatial acuity across several body regions [e.g., head (de Jesus Oliveira et al., 2016), torso (Jóhannesson et al., 2017), forearm (Cholewiak and Collins, 2003), and thighs (Wentink et al., 2011)], but mainly under static conditions. Some studies have extended this to movement—examining the upper arm (Sanderson et al., 2022; Karuei et al., 2010; Gomes et al., 2020), forearm (Schönauer et al., 2015; Chen et al., 2018), wrist (Karuei et al., 2010; Pakkanen et al., 2008; Tajdari et al., 2025b), dorsal hand (Tajdari et al., 2025b), and thigh (Karuei et al., 2010). These investigations have predominantly been conducted under static conditions or during light, repetitive movements, which do not reflect the forceful exertions and complex, whole-body dynamics characteristic of manual material handling tasks in occupational settings. Consequently, it remains unclear how higher levels of force exertion and realistic task demands influence vibrotactile sensitivity and spatial acuity across commonly used body sites. Although posture-intervention studies have reported challenges in perceiving vibrotactile cues on the upper arm and trunk (Langenskiöld et al., 2023; Choi et al., 2025), the underlying role of force intensity and task dynamics in shaping these perceptual limitations has not been systematically investigated.

Several additional factors also influence vibrotactile perception. Sensitivity and spatial acuity vary with body region due to differences in mechanoreceptor density (Cholewiak and Collins, 2013). The fingers exhibit the highest sensitivity, while regions such as the back are far less responsive (Johansson and Vallbo, 1979; Weinstein, 1968). Spatial acuity in the upper extremities declines from distal to proximal regions, with the fingertips offering finer discrimination than, for example, the dorsum of the hand (Shibin and Samuel, 2013). Despite these limitations, many commercial systems place tactors on the back or upper arm, often to co-locate them with posture monitoring sensors such as inertial measurement units (IMUs).

Frequency is another key determinant of perception. Sinusoidal vibrations in the 200–400 Hz range can enhance tactile sensitivity more effectively than band-limited white noise vibrations ($\leq$ 500 Hz) (Suzuki, 2024), and optimal frequencies differ across body sites: 200 Hz on the lower wrist, 125 Hz on the upper wrist (Ævarsson et al., 2022), and 55 Hz at joints such as the elbow, knee, and ankle (Quick et al., 2022). Despite these established frequency-dependent effects, it remains unclear how they are influenced by different body sites under force exertion. In particular, the interaction between vibration frequency, anatomical location, and physical effort has not been systematically examined, leaving an important gap in understanding how to optimize vibrotactile feedback in realistic task conditions.

Finally, individual differences contribute to variability in perception. Some studies report greater sensitivity in females than males (Gescheider et al., 1994), potentially due to differences in mechanoreceptor density, skin structure (Venkatesan et al., 2015), and hormonal influences (Alves et al., 2017), though others have found no significant sex-based differences in specific regions such as the dorsal hand, wrist (Tajdari et al., 2025b), or upper arm (Bikah et al., 2008). Such variations highlight the importance of designing cues that remain perceptible and comfortable across diverse worker populations.

We address these gaps in understanding vibrotactile perception under force exertion and task-driven conditions through two complementary experimental investigations. **Study 1** examines how isometric force exertion influences vibrotactile sensitivity and spatial acuity, with vibration frequency as an additional factor. We hypothesize that force exertion will reduce both sensitivity and spatial acuity, with effects varying by body sites and frequency. **Study 2** extends this to dynamic, construction-related tasks, testing whether realistic exertions similarly impair perception. Together, these studies clarify how physical exertion shapes tactile perception under both controlled and task-driven conditions, providing a foundation for designing vibrotactile systems that remain effective in real-world occupational settings and support applications such as hazard awareness and collision avoidance. Importantly, to our knowledge, this study is among the first to systematically examine vibrotactile perception under both controlled force exertion and realistic task conditions, thereby bridging controlled laboratory findings with real-world occupational applications.

2. Methods

We performed two studies to examine vibrotactile sensitivity thresholds and spatial acuity under static and dynamic force exertion conditions, with spatial acuity assessed using the two-point discrimination threshold method. In each study, an array of eight piezoelectric vibration tactors (Engineering Acoustic, FL, USA) was attached to specific body regions (see Fig. 1). The tactors were driven by sinusoidal signals within their operating frequency range (180–300 Hz). Because the device does not provide a calibrated mapping between input signal and the physical vibration delivered at the skin surface, stimulus intensity is reported in device-specific (relative) units rather than absolute measures (e.g., acceleration or velocity).

Selection of body sites in both experiments was informed by prior studies on vibrotactile feedback for ergonomic interventions, particularly those addressing unsafe postures (Cerqueira et al., 2020; Lim and Yang, 2023; Lins et al., 2018; Langenskiöld et al., 2023; Yang and Roofigari-Esfahan, 2023; Lind et al., 2020a,b; Salzer et al., 2011; Tuken et al., 2025). Previous work has applied vibrotactile feedback to regions such as the upper arm, trunk, back, wrist, and thighs to support posture correction in occupational settings. These locations have been incorporated into systems for industrial workwear (Lins et al., 2018), simulated manual handling tasks (Langenskiöld et al., 2023), reducing ergonomic risks in surgical tasks (Kelly et al., 2023; Bonin et al., 2026), and real-time construction applications (Lim and Yang, 2023). Building on these studies, we selected the tactor sites in the present study. To eliminate potential auditory cues from the tactors that could influence perception, participants wore headphones playing rain sound throughout the trials.

2.1. Participants

We recruited eighteen participants (9 female and 9 male) for each study, forming two distinct, non-overlapping groups. The mean age of participants was 27.3 years (SD = 5.0) in Study 1 and 23.5 years (SD = 4.7) in Study 2. All participants provided written informed consent prior to participation, and the study protocol was approved by the Institutional Review Board (IRB# 21-1022).

2.2. Study 1 (Isometric force exertion)

We examined vibrotactile sensitivity thresholds and spatial acuity at three body sites – the upper right arm, lower back (L4), and right thigh (see Fig. 1) – under two conditions: (1) static force exertion at 30% of the participant's maximum voluntary isometric contraction (MVIC); and (2) a no-force baseline condition. The 30% MVIC level was selected through pilot testing as a moderate and sustainable exertion level that participants with diverse physical characteristics could reliably maintain throughout the experimental tasks, while introducing meaningful muscular effort relevant to occupational contexts. Before the main trials, participants' MVICs were measured at the elbow, trunk, and knee joints using the HUMAC NORM Extremity System (CSMI, Stoughton, MA, USA) (Fig. 2).

Sensitivity and spatial acuity were assessed at three vibration frequencies – 200, 250, and 300 Hz – selected based on prior research indicating that the 200–300 Hz range elicits peak sensitivity in Pacinian corpuscles (Verrillo, 1966; Bolanowski, Jr. and Zwislocki, 1984). Tactor arrays were positioned transversely over the corresponding muscle groups: the biceps (upper arm), quadratus lumborum (lower back),

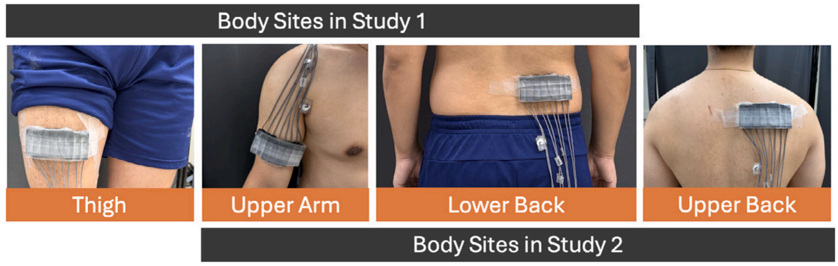

Fig. 1. Body sites examined in Study 1 and Study 2, along with the corresponding tactor placements.

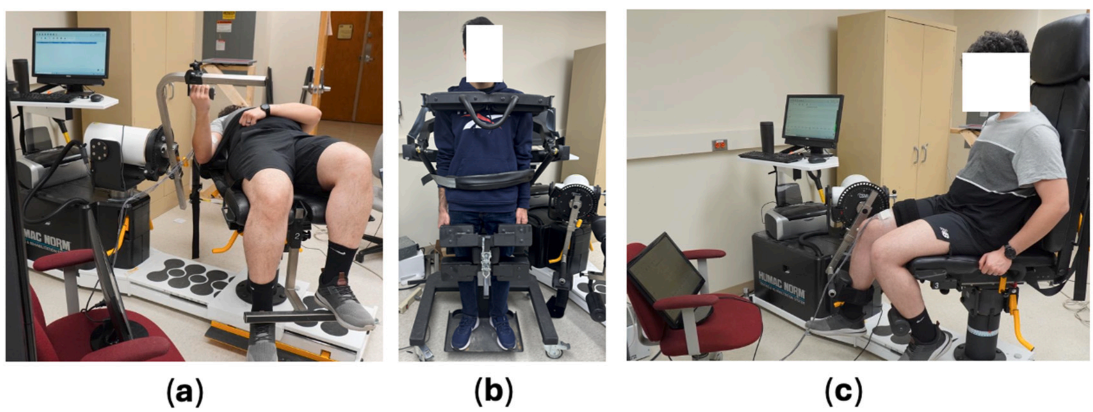

Fig. 2. Isometric force exertion tasks performed using the HUMAC NORM system: (a) elbow flexion, (b) trunk extension, and (c) knee extension.

and quadriceps (thigh) (see Fig. 1). Tactors were secured to the skin to ensure consistent and stable contact across participants and body locations. For all regions, double-sided adhesive was used to maintain skin contact, and the entire tactor array was further secured with medical tape to ensure firm attachment. We did not apply specific skin preparation procedures beyond standard cleaning, as the focus was on maintaining consistent attachment conditions rather than altering skin properties. We acknowledge that variations in contact pressure across body locations and individuals are inherent in wearable haptic studies and may influence perception; however, attachment procedures were standardized across all participants as much as possible.

The experimental design followed a 2 (force conditions) × 3 (frequencies) × 3 (body sites) structure, resulting in 18 trials per participant for each sensitivity threshold and spatial acuity test. To minimize fatigue effects, the order of body sites was counterbalanced across participants. Tactors were attached to only one body site at a time. Within each body site, six trials (2 force conditions ×3 frequencies) were randomized separately for the sensitivity threshold and spatial acuity tests. The sensitivity threshold assessment was always conducted first, followed by the spatial acuity assessment. After completing both tests for a given body site, the tactors were removed and reattached to the next site. Sufficient rest breaks (at least 1 min) were provided between trials. The experimenter adjusted the vibration intensity or frequency using a single keystroke.

For the sensitivity threshold assessment, a 3-down-1-up adaptive staircase method (Hatzfeld et al., 2016) was used. In this procedure, the stimulus intensity decreased after three consecutive correct responses and increased after one incorrect response (see Fig. 3). Participants verbally responded ‘yes’ when they detected a vibration during the trials. If they did not perceive the vibrations, the intensity was increased by 10 units, and if they did, it was decreased by 10 units. Trials continued until three reversal points were recorded, and the final sensitivity threshold was calculated as the mean vibration intensity at these reversal points. The initial vibration intensity was set to 5 on a 0–255 scale.

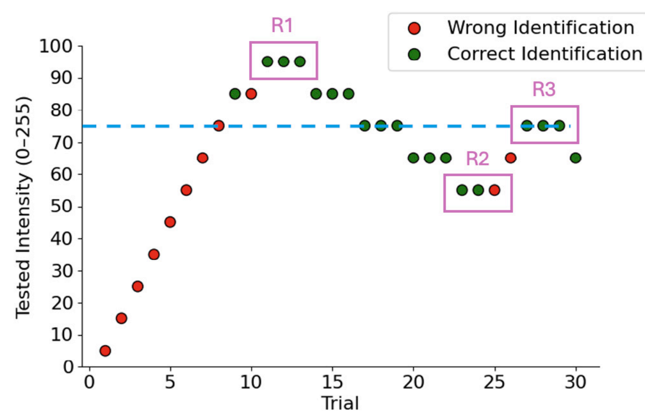

Fig. 3. Illustration of the 3-down-1-up staircase procedure for estimating vibrotactile sensitivity threshold. Pink boxes indicate reversal points, and the dashed blue line represents the final sensitivity threshold, calculated as the mean of three reversals.

Spatial acuity was similarly measured with a 3-down-1-up adaptive staircase method (Elsayed et al., 2020), where each trial consisted of two tactors delivering sequential 250 ms vibrations at maximum intensity, separated by a 100 ms interval. The initial distance between the tactors was set at 70 mm. Participants were instructed to respond verbally with ‘same’ if the two vibrations were perceived at the same location and ‘different’ if they were felt at different locations, as quickly as possible while performing the tasks. To familiarize them with the task, three demonstration trials of each pattern (using random tactors) were provided. Following three consecutive correct identifications of distinct vibration locations, the separation distance was reduced by 14 mm; after an incorrect response, the distance was increased by the same amount. Trials continued until three reversal points were recorded, and the spatial acuity threshold was calculated as the mean separation distance at these reversal points.

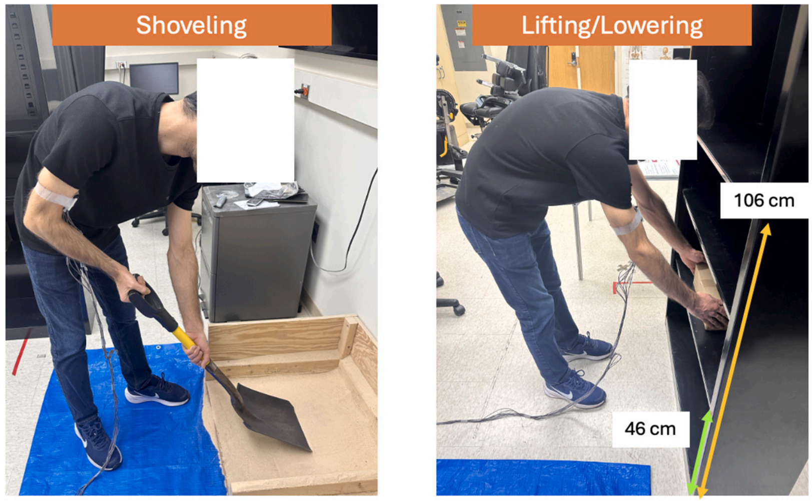

Fig. 4. Shoveling and lifting/lowering tasks performed in Study 2. In this example, the vibrotactile tactors are placed on the participant's upper arm.

2.3. Study 2 (Dynamic work task)

We examined vibrotactile sensitivity thresholds and spatial acuity during three construction-related manual tasks: shoveling, lifting/lowering, with the standing posture serving as a non-force-exerting reference condition (Fig. 4). Importantly, unlike Study 1, task demands were not normalized across participants in Study 2. This decision was made to better reflect realistic occupational variability and to capture natural differences in task execution and exertion.

Sensitivity threshold and spatial acuity assessments were conducted while participants maintained the corresponding task posture, with stimuli delivered during periods of active force exertion. In the shoveling task, participants scooped sand from the right side of a compartment to the left, simulating realistic construction shoveling conditions. Participants performed the task at a self-selected pace and quantities of sand. Vibration was initiated after the completion of one full scoop-and-dump cycle and continued during the exertion phase of each subsequent repetition—specifically while the participant was filling the shovel with sand, representing maximal force exertion. For each trial, the shoveling task was restarted. In the lifting/lowering task, participants lifted and lowered a 5-pound box between two shelves set at different heights (lower shelf = 46 cm; upper shelf = 106 cm) at a self-selected pace. A relatively light load was used to ensure that both male and female participants could complete the trials without excessive fatigue. Vibrations were delivered during the active lifting/lowering phase—that is, while the participant was lifting the box, moving it between shelves, or lowering it. Each trial in both the shoveling and lifting/lowering tasks lasted approximately 1–2 min. The standing posture served as the reference condition. In this condition, participants stood upright in a relaxed posture with their arms at their sides. To minimize fatigue, rest breaks of at least one minute were provided between trials across all conditions.

Based on the results from Study 1, a vibration frequency of 300 Hz (identified as eliciting the highest sensitivity) was used in Study 2. This decision was made to maintain consistency across studies and to avoid introducing vibration frequency as an additional experimental factor, allowing us to isolate the effects of task type and body location on vibrotactile perception. Notably, frequency showed relatively limited influence on the statistical outcomes in Study 1 compared to force and body site effects, further supporting the selection of a single representative frequency. All stimuli were therefore delivered at this constant frequency, and assessments were conducted on the upper arm, upper back, and lower back across all task conditions (see Fig. 1). The thigh, included in Study 1, was excluded in Study 2, and the upper back was added instead, as this site is more commonly targeted in ergonomic intervention systems.

The experimental design followed a 3 (task conditions) ×3 (body sites) structure, resulting in 9 trials per participant for each sensitivity threshold and spatial acuity test. Consistent with Study 1, sensitivity thresholds were measured first, followed by spatial acuity testing. A nested randomization procedure was applied in which the order of body sites tested was randomized, and within each body site, the sequence of tasks was also randomized. The experimental setup and procedures were consistent with those in Study 1, with some key modifications: a 1-down-1-up adaptive staircase method was used to reduce cumulative fatigue from repeated work tasks and to limit the overall duration of data collection, as using a 3-down-1-up procedure would have substantially increased the total study duration. Similarly, the vibration intensity was increased by 20 units (rather than 10 units) to further balance task duration and participant fatigue while maintaining effective threshold estimation. As in Study 1, the vibration intensity was decreased by 10 units when the stimulus was detected. For the spatial acuity testing, the vibrations were delivered at maximum intensities.

2.4. Data analysis

Mixed effects models with restricted maximum likelihood (REML) were used to analyze factor effects on dependent measures, treating participants as a random effect and biological sex as a block. Frequency was treated as a continuous variable. To quantify the magnitude of observed effects, partial eta squared (η_p^2) was calculated for all fixed effects and interpreted following Richardson (2011), with values of 0.01, 0.06, and 0.14 indicating small, medium, and large effects, respectively. Tukey–HSD and Student's t tests identified significant pairwise differences for interaction effects. All analyses were conducted in JMP Pro (v18.0.0, SAS, NC, USA) at $\alpha = .05$.

3. Results

3.1. Study 1 (Isometric force exertion)

Statistical results for sensitivity thresholds and spatial acuity, along with significant pairwise comparisons, are shown in Table 1.

Sensitivity Thresholds: Sensitivity thresholds varied significantly by body site ($F = 150.11$, $\eta_p^2 = 0.21$, $p < .001$) (see Fig. 5). The upper arm was more sensitive than the thigh (mean difference = 27.03, $p < .001$) and the lower back (mean difference = 32.74, $p < .001$). Additionally, the thigh was significantly more sensitive than the lower back (mean difference = 5.71, $p = .01$). Across all body sites, exerting force at

Table 1
Summary of mixed-effects model results for sensitivity threshold and spatial acuity in Study 1. Significant effects are highlighted using bold font. ($p < 0.05$).

Effect	Sensitivity Threshold	Spatial Acuity
Force	F(1, 297) = 23.87, η_p^2 = 0.03, ***p* <.001**	F(1, 297) = 4.58, η_p^2 = 0.008, ***p* = .03**
	30% MVIC > No Force	30% MVIC > No Force
Body Site	F(2, 297) = 150.11, η_p^2 = 0.21, ***p* <.001**	F(2, 297) = 22.23,η_p^2 = 0.07, ***p* <.001**
	Lower Back > Thigh > Upper Arm	Lower Back > Upper Arm > Thigh
Frequency	F(1, 297) = 0.28, η_p^2 = 0.001, *p* = .60	F(1, 297) = 4.53, η_p^2 = 0.008, ***p* < .03**
Force × Body Site	F(2, 297) = 12.77, η_p^2 = 0.06, ***p* <.001**	F(2, 297) = 1.77, η_p^2 = 0.006, *p* = .17
	Thigh: 30% MVIC > No Force	
Force × Frequency	F(1, 297) = 0.83, η_p^2 = 0.002, *p* = .36	F(1, 297) = 0.72, η_p^2 = 0.001, *p* = .40
Body Site × Frequency	F(2, 297) = 0.08, η_p^2 = 0.001, *p* = .93	F(2, 297) = 0.22, η_p^2 = 0.001, *p* = .80
Biological Sex	F (1, 16) = 3.46, η_p^2 = 0.06, *p* = .08	F(1, 16) = 0.99, η_p^2 = 0.03, *p* = .33

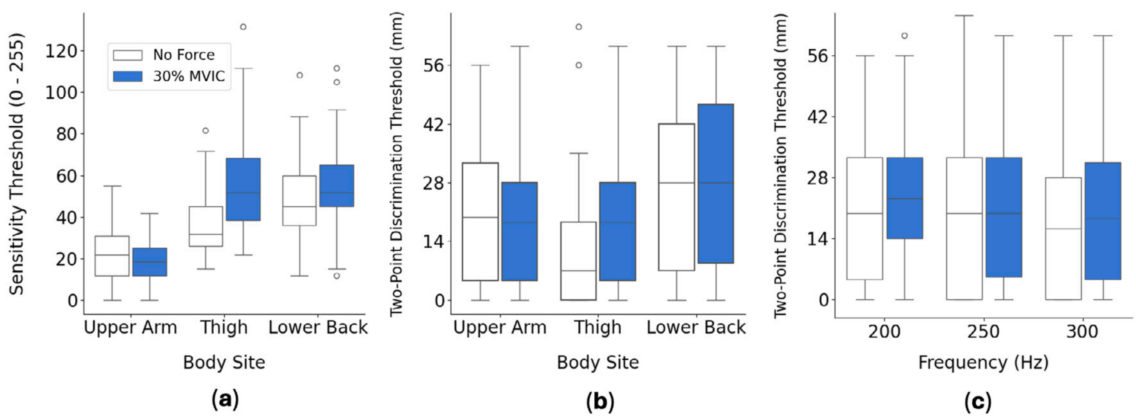

Fig. 5. (a) Sensitivity thresholds; (b) spatial acuity (mm) across examined body sites; and (c) spatial acuity (mm) across vibration frequency levels, all stratified by force condition.

30% MVIC significantly impaired vibration sensitivity compared to the no-force condition (F = 23.87, p = <.001). However, the effect size was small (η_p^2 = 0.03). The mean differences in sensitivity thresholds between force and no-force conditions for all body sites was 8.05.

A significant interaction between Body Site and Force was also observed for sensitivity thresholds ($p < .001$), with a moderate effect size ($\eta_p^2 = 0.06$). The thigh showed reduced vibration sensitivity (i.e., higher sensitivity threshold) during force exertion, with a mean difference of 18.64 ($p < .001$).

Spatial Acuity (Two-Point Discrimination Thresholds): There were significant main effects of force condition, body site, and frequency on spatial acuity. Discrimination thresholds were significantly higher (i.e., lower spatial acuity) during force exertion compared to the no-force condition (F = 4.58, p = .03) (see Fig. 5). However, the force condition had a small effect size (η_p^2 = 0.008). Body site also had a significant effect on spatial acuity (F = 22.23, p < .001), with a moderate effect size (η_p^2 = 0.07). Spatial acuity was poorer at the lower back compared to both the thigh (mean difference = 10.92 mm, p < .001) and the upper arm (mean difference = 6.58 mm, p < .001). Vibration frequency significantly influenced spatial acuity thresholds as well (F = 4.53, p = .03), with the highest sensitivity observed at 300 Hz, although the effect size was negligible (η_p^2 = 0.008). No significant differences in sensitivity threshold or spatial acuity were found based on biological sex.

3.2. Study 2 (Dynamic work tasks)

Construction-related work tasks did not significantly affect vibrotactile sensitivity thresholds (see Table 2). However, significant main effects were found for both task and body site in the two-point discrimination test for determining spatial acuity. Task condition significantly influenced spatial acuity (F = 4.65, p = .01), with the shoveling task resulting in higher thresholds (i.e., lower spatial acuity) compared to standing (mean difference = 14.7 mm, p = .01). The effect size was small to moderate (η_p^2 = 0.04) (see Fig. 6). Body site also had a significant effect on spatial acuity (F = 11.58, η_p^2 = 0.09, p < .001). The upper arm showed significantly lower thresholds (indicating better spatial acuity) than both the upper back (mean difference = 14.28 mm, p < .001) and the lower back (mean difference = 12.18 mm, p < .001) (see Table 2).

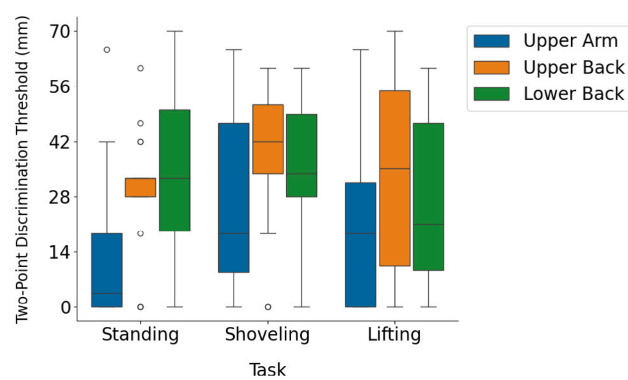

Fig. 6. Spatial acuity (mm) across construction tasks, stratified by body sites.

4. Discussion

In this study, we investigated the effects of static and dynamic force exertion on vibrotactile sensitivity thresholds and spatial acuity across multiple body sites, using tasks involving sustained isometric force or dynamic construction activities such as shoveling and lifting/lowering. By combining controlled experimental conditions with realistic work tasks, this study provides a more comprehensive understanding of

Table 2
Summary of mixed-effects model results for sensitivity threshold and spatial acuity in Study 2. Significant effects are highlighted using bold font ($p < 0.05$).

Effect	Sensitivity Threshold	Spatial Acuity
Task	$F(2, 136) = 2.26$, $\eta_p^2 = 0.02$, $p = .11$	$F(2, 136) = 4.65$, $\eta_p^2 = 0.04$, $\boldsymbol{p = .01}$ Shoveling > Standing
Body Site	$F(2, 136) = 2.53$, $\eta_p^2 = 0.02$, $p = .08$	$F(2, 136) = 11.58$, $\eta_p^2 = 0.09$, $\boldsymbol{p < .001}$ Upper Back, Lower Back > Upper Arm
Task × Body Site	$F(4, 136) = 0.56$, $\eta_p^2 = 0.008$, $p = .69$	$F(4, 136) = 0.77$, $\eta_p^2 = 0.01$, $p = .55$
Biological Sex	$F(1, 16) = 1.35$, $\eta_p^2 = 0.04$, $p = .26$	$F(1, 16) = 1.83$, $\eta_p^2 = 0.04$, $p = .19$

vibrotactile perception in practical settings. Our results demonstrate that both vibrotactile sensitivity and spatial acuity are reduced during isometric force exertion, although these effects were relatively small in magnitude, with the thigh showing particularly pronounced decreases. This finding is consistent with previous work reporting that walking reduces vibrotactile stimuli detection rates and increases response times, especially at lower body sites such as the thighs and feet (Karuei et al., 2010). These results are also supported by research showing that voluntary muscle contractions, such as isometric pinching, can suppress subjective peripheral sensation and attenuate somatosensory processing at the cortical level, likely through sensory gating mechanisms (Takahara et al., 2020). Moreover, even low-intensity aerobic exercise involving muscle contraction can induce hypoalgesia, reducing pain sensitivity across body areas including the thigh (quadriceps) and upper arm (biceps) (Niwa et al., 2022).

While dynamic work task did not significantly affect vibrotactile sensitivity thresholds, spatial acuity was notably reduced during the shoveling task compared to the standing (baseline) condition. This aligns with findings by Bouffard et al. (2020), who reported that biceps contraction during repetitive pointing reduced spatial acuity for both light touch and pain perception. Although different mechanoreceptors are involved – Meissner's corpuscles for light touch in the referenced paper and Pacinian corpuscles for pressure and high-frequency vibrations in our study – similar neuromuscular mechanisms likely contributed to the observed decline in spatial acuity in our study. Collectively, these results suggest that reductions in tactile sensitivity during force exertion may reflect broader effects of muscle activation on sensory processing. This has important implications for the design of wearable vibrotactile feedback systems, particularly in occupational settings involving physical exertion. Designers should account for the influence of muscle engagement on tactile perception to ensure that vibrotactile feedback remains effective and perceptible during physically demanding tasks.

We did not observe any significant sex differences in either sensitivity thresholds or spatial acuity across body sites in both studies. This is consistent with some of previous reports, primarily focused on the hand and upper arm, showing no measurable sex-based differences in vibrotactile perception at regions such as the dorsal hand and wrist (Tajdari et al., 2025b) and the upper arm (Bikah et al., 2008). Similarly, Seah and Griffin (2008) found no significant sex effects on vibrotactile thresholds at 31.5 Hz and 125 Hz on the middle finger (Seah and Griffin, 2008). In general, these findings suggest that while sex may influence vibrotactile perception under specific conditions, its impact appears limited in the thigh, upper arm, and lower and upper back under the static and dynamic work tasks examined in the present study.

4.1. Design guidelines for vibrotactile feedback in work context

Our findings offer practical guidance for designing vibrotactile feedback systems used in physically demanding work environments. Effective design requires a nuanced understanding of how force, location, and movement interact to influence tactile perception.

Feedback Location: The lower back consistently emerged as the least effective location for tactor placement, showing low perceptual sensitivity and spatial acuity across both static and dynamic conditions. Although one prior study identified the lower back as a favorable site for postural correction feedback (Visser, 2018), and it is widely used in wearable safety systems such as hazard communication (Sakhakarmi et al., 2021; Cho and Park, 2018) and ergonomic posture interventions (Ferrone et al., 2021), our findings suggest its effectiveness may be limited under force exertion and should be carefully considered when selecting feedback locations. The thigh also showed reduced sensitivity during isometric force exertion, suggesting that stronger or more salient cues may be necessary for reliable perception. By contrast, the upper arm and upper back proved more effective, with the upper arm demonstrating the highest perceptibility under static force exertion condition. Commercial systems such as SoterCoach (Soter, Delaware, USA) or Boost Plus (GoX Labs, Arizona, USA), which deliver cues to the upper arm or wrist, are well-positioned to take advantage of these perceptual benefits. Similarly, SafeWork (Strongarm Tech, Colorado, USA) may benefit from upper-back placement, though spatial resolution may be limited during force exertion. These examples are intended to provide contextual illustrations of current design practices; however, differences in actuator characteristics (e.g., frequency, amplitude, and contact conditions) across systems may influence vibrotactile perception, and thus these implications should be interpreted with caution unless the physical characteristics of the tactors and signals are comparable.

Feedback Frequency: A vibrotactile frequency of 300 Hz yielded higher spatial acuity in Study 1, suggesting its potential utility for applications requiring precise spatial discrimination, although it did not significantly affect sensitivity.

Tactor Spacing: Based on Studies 1 and 2, we recommend the following minimum tactor spacing to ensure cues remain perceptible during force exertion. For body sites tested in both studies, we used the highest mean threshold across task conditions as the basis for our recommendations: upper arm, 26.5 mm; lower back, 35.4 mm; upper back, 39.2 mm; and thigh, 18.8 mm (noting that the thigh value was obtained only during the isometric force exertion condition, so the actual threshold in work contexts is likely to be higher). These guidelines are intended to inform the design of systems that convey directional information through multi-tactor arrays (e.g., hazard direction notification), where sequential activation of tactors requires sufficient spatial separation for users to reliably distinguish stimulation locations; however, these applications were not directly evaluated in this study.

4.2. Limitations

This study has several limitations. First, although the n-down-1-up method is a well-established approach for estimating sensory thresholds, its application to spatial acuity in vibrotactile feedback remains untested. Alternative methods, such as randomly varying the distances between vibration sources across trials, may improve reliability by reducing participants' ability to anticipate patterns. Second, the weight lifted by participants was relatively low compared to typical workplace loads. Using heavier loads may yield findings that better reflect real-world exertions. Third, while tactors in this study were placed directly on muscle groups, most commercial systems attach them to garments, which may further reduce cue perception and result in lower perceptibility under real-world conditions. Fourth, vibration intensity was defined using device-specific units rather than calibrated physical measures. Future work may incorporate external measurement tools to report absolute vibration characteristics. Additionally, external factors such as temperature (Green, 1977; Klinenberg et al., 1996) and individual differences in body composition (e.g., body fat variability) (Bikah et al., 2006) may influence tactile sensitivity and cue recognition. Long-term use of such systems may also lead to sensory adaptation and reduced perceptual sensitivity over time (Klöcker et al., 2016). Despite these limitations, this work establishes a critical foundation for the design of vibrotactile feedback systems aimed at enhancing safety and usability in physically demanding environments.

5. Conclusion

This study examined how isometric force exertion (Study 1) and dynamic work tasks (Study 2) influence vibrotactile sensitivity and spatial acuity across multiple body sites. In Study 1, we found that exerting force significantly impaired both sensitivity thresholds and spatial acuity, with the lower back exhibiting the highest thresholds. The thigh also demonstrated a notable decline in sensitivity during force exertion. In Study 2, the shoveling task led to a significant increase in spatial acuity thresholds, suggesting reduced discriminability under physically demanding conditions. Across all tasks, the upper arm consistently exhibited better spatial acuity than both the upper and lower back, reinforcing its potential as a favorable location for delivering vibrotactile feedback in ergonomic and safety applications. By showing how vibrotactile perception changes with physical activity and body location, this study offers practical guidance for designing ergonomic feedback systems that are both effective and comfortable to use. Future research should consider exploring real-world conditions and extended usage to improve the performance and usability of these systems in demanding work environments.

CRediT authorship contribution statement

Mahdis Tajdari: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Xiang Yang:** Writing – review & editing, Software, Data curation, Conceptualization. **Md Shafiqul Islam:** Writing – review & editing, Writing – original draft, Conceptualization. **Sol Lim:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Ethical statement

The study procedures were approved by the Institutional Review Board (IRB) of Virginia Tech (IRB-21-1022), and conducted in compliance with the ethical principles for research involving human subjects expressed in the Declaration of Helsinki.

Declaration of generative AI in scientific writing

The manuscript text was refined with the assistance of ChatGPT, primarily to enhance clarity, grammar, and overall readability. All content was reviewed and edited by the authors to ensure accuracy and alignment with scientific standards. No content was generated without direct author oversight.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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