HaptEx: Investigating Haptic Notification Channels for Exoskeletons Across Different Levels of Actuation

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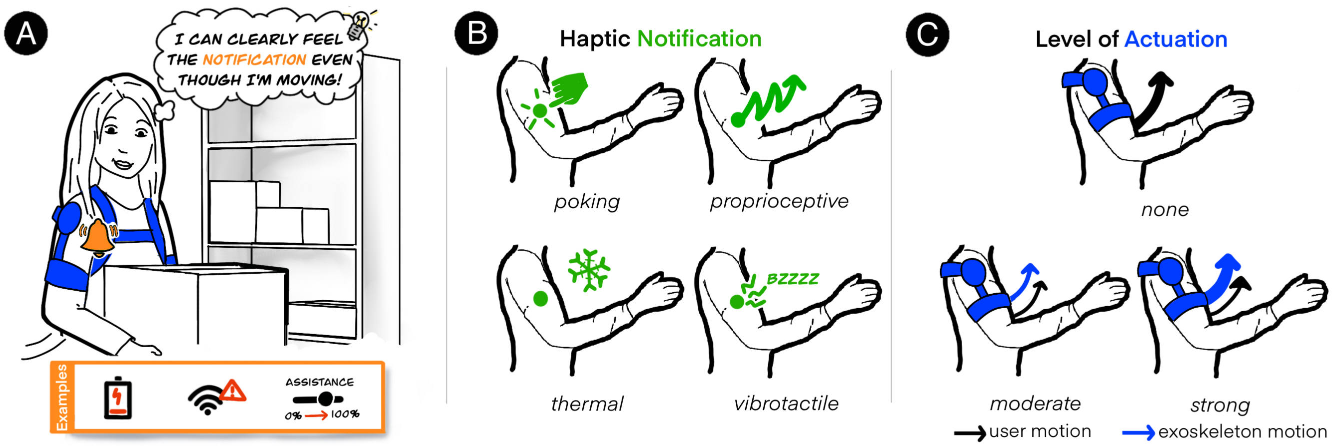

Figure 1: Exoskeletons require effective methods to inform users about (critical) system states and events during active actuation (A). This paper explores the noticeability of four haptic notification channels (B) under ongoing user movement across three distinct levels of exoskeleton actuation (C).

Abstract

Exoskeletons are increasingly deployed in real-world contexts, where communicating critical system states or unexpected events is important for effective interaction. Haptic feedback offers a direct communication channel, integrating naturally with the actuated body region. Yet, it remains unclear how well haptic feedback is perceived while the body is being actuated. In a controlled study (N=24) with a shoulder exoskeleton, we compare four common haptic notification channels (poking, proprioceptive, thermal, vibrotactile) under different levels of actuation. Results show that poking was detected fastest, while thermal and proprioceptive notifications were most accurate and noticeable. Actuation levels affected error rates and noticeability, but not response times. Participants reported that thermal notifications aligned best with the actuation levels, producing a distinct sensation that blended naturally with movement. In contrast, proprioceptive notifications conveyed the strongest sense of urgency. We discuss design implications for leveraging haptic notifications to support embodied communication with exoskeletons.

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CCS Concepts

• **Human-centered computing** → **User studies**; Haptic devices.

Keywords

Notification, wearable output, haptics, exoskeleton, actuation

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1 Introduction

Exoskeletons are emerging as assistive tools in industry [8], rehabilitation [42], healthcare and everyday life [48], thanks to their ability to actively aid movement or even fully actuate limbs. As exoskeletons act directly on the body, it is essential to keep users informed about (critical) system states and upcoming actions–such as an imminent transition in operational mode (e.g., from assistive to autonomous), battery status updates, or sensor malfunctions. Although exoskeletons are typically expected to handle safety-critical events automatically and align their actions with the user's intentions, abrupt system-initiated actions are possible and can themselves be hazardous. For example, if assistance must be disabled due to a malfunction while the system assists the user with holding a heavy object overhead or walking downstairs, informing the user about the imminent change allows them to react in time (e.g., by lowering the object or holding on to a railing). Beyond safety, there may be situations in which the system proactively detects need for assistance, such as to correct the user's posture. Informing the user in advance helps to build expectation for the shift in control. Yet, this raises an important question: *how* to communicate information in an exoskeleton while it actuates the human body?

Haptic feedback has emerged as a promising means to deliver notifications because it leaves vision and audition free for the primary task [45]. This makes haptic feedback an interesting option for active contexts – the contexts in which exoskeletons are typically used in. Prior work has considered a wide range of haptic notification channels for wearables at diverse body locations [6, 44, 49]. Yet, most studies have focused on low-movement contexts, such as sitting, standing or passive swinging of the arms while walking (e.g., [6, 22, 44]). Hence, it is unclear if common haptic notification channels remain similarly perceptible when the human body is being actuated by the exoskeleton, or if sensory conflicts and masking effects may emerge. This creates a novel perceptual context in which established assumptions about notification salience may no longer hold.

In this paper, we hence systematically investigate how reliably and quickly different haptic notification channels perform when the body is concurrently moved by an actuator. The study is guided by the following research questions (RQs):

RQ1: How does the haptic notification channel affect the response time, error rate, and user experience while the user's body is being actuated by the exoskeleton?

RQ2: How does the level of actuation affect the response time, error rate, and user experience of the haptic notification channels?

To this end, we compare the effectiveness of poking, proprioceptive, thermal and vibrotactile notifications across three different levels of actuation. The notification channels were selected from commonly chosen modalities for other wearables (e.g., [44, 49]) and integrated in a shoulder exoskeleton, a representative exoskeleton configuration commonly found in industrial contexts to support users during lifting tasks [34].

The results indicate that the actuation level did not influence response times. However, in the absence of actuation, error rates were significantly lower and the noticeability of haptic notifications significantly higher compared to conditions with actuation. Among the four haptic notification channels, poking consistently yielded the fastest response times, while proprioceptive and thermal notifications resulted in the lowest error rates overall. Both proprioceptive and thermal notifications were also rated highest in noticeability and required the least mental effort for detection across actuation levels. Due to its disruptiveness during ongoing user motion, proprioceptive feedback also conveyed the highest sense of urgency. Qualitative findings further reveal that actuation interfered with user perception, particularly for poking and vibrotactile notifications, due to the perceptual overlap with vibrations caused by the actuation itself and strain induced by the exoskeleton.

In summary, we contribute the results of a controlled experiment with 24 participants, which systematically examines the effects of varying actuation levels on the performance of different haptic notification channels. Based on the results of the experiment, we provide implications for designing haptic notifications for more effective human–exoskeleton communication.

2 Related Work

Our work contributes to the areas of human-exoskeleton interaction and wearable notifications in HCI.

2.1 Exoskeletons

Exoskeletons are gaining attention in the HCI community, with recent work exploring their potential to augment human capabilities across a wide range of application domains [35] and form factors, ranging from upper-limb exoskeletons to support motor learning [37] and rehabilitation [25, 42], enhance VR experiences [19, 55], or assist workers in industry [15], to exoskeletons supporting the back [2] or the lower limbs to assist gait [5]. Despite their diverse applications across domains, research on the design of effective human-exoskeleton interaction from an HCI perspective remains limited [35]. This gap is critical, as exoskeletons are tightly coupled to the human body and their actuation directly affects the user. Here, factors such as unexpected movements, sensor failures, and a lack of understanding of the device pose substantial safety risks [32]. Recent work highlighted the users' desire for feedback, for example, when a leg-based exoskeleton intends to initiate a step, and revealed preferences for discrete vibrotactile and auditory cues over visual, also noting that auditory feedback might not always apply in mobile contexts [36]. Given the embodied nature of exoskeletons, integrating notification channels in exoskeletons is an essential next step for enhancing safety and interaction with exoskeletons. Yet, which channels are suitable for exoskeletons, especially during actuation, remains largely unexplored. Hence, this work addresses this gap by investigating the performance and user experience of different notification channels in exoskeletons.

2.2 Wearable Notifications

Wearable notifications have been extensively explored across modalities, body locations, and form factors. Common notification channels include visual, auditory, and haptic feedback. Haptic feedback is emerging as a particularly promising modality for embodied interaction as it enables eyes- and ears-free communication and complements other channels when unavailable [45]. Prior work investigated several haptic notification channels in wearables, including vibrotactile [6, 44, 49], poking [6, 26, 44], thermal [6, 39, 44, 47], squeezing [20, 47], brushing [6, 50], dragging [22] or moisture [6]. In addition, a small body of work has investigated proprioceptive feedback as a channel for embodied notifications. This includes feedback induced via electrical muscle stimulation [18, 45], as well as mechanically actuated movement [9].

Several studies have systematically compared a subset of these modalities as notification channels across different usage contexts. For instance, Roumen et al. compared poking, thermal, vibrotactile, audio and visual notification channels on a smart ring under varying physical activity [44]. Stanke et al. contrasted private (poking, thermal, vibrotactile, electrotactile, sound) and public (display, light, sound) notification channels at the earlobe [49]. Bhatia et al. compared ten haptic notification channels across six body locations while the user was walking [6]. Other work has conducted studies to refine parameters for specific modalities. For instance, Shim et al. systematically explored optimal poking depth [46], while Wilson et al. examined relevant parameters for warm vs. cold thermal stimuli, such as the rate of change, across body locations and mobile conditions [56]. Similarly, Karuei et al. compared the effectiveness of vibrotactile feedback of several body sites and different mobile conditions and found reduced detection accuracy in mobile conditions across various body locations [28].

Given that exoskeletons are typically used in active contexts, in potentially visually and physically demanding environments, embodied haptic feedback offers a compelling channel for delivering notifications. However, most studies on haptic notification channels have focused on low-movement contexts, such as sitting, standing still or walking (e.g., [6, 22, 44, 56]). Therefore, it remains unclear how haptic perception is affected when the arm is actively moved by the user and externally actuated, respectively. Moreover, systematic comparisons between proprioceptive and other haptic notification channels are lacking to date. We address this gap by comparing three frequently considered haptic notification channels (poke, vibration, and thermal) to proprioceptive cues across varying levels of arm actuation.

3 Methodology

We conducted a controlled experiment to investigate the performance and user experience of distinct haptic notification channels during ongoing user movement and while the body is being actuated by an exoskeleton. For the experiment, we use a shoulder exoskeleton with the haptic actuators located on the lateral upper arm. The shoulder exoskeleton is chosen as a representative configuration commonly deployed in industrial settings to support lifting and overhead tasks [34]. Furthermore, the upper body, and particularly the shoulders and upper arms, is frequently considered in studies of haptic notifications (e.g., [6, 22, 28, 56]), providing a well-established basis for selecting promising channels and enabling meaningful comparisons to prior work. This choice thus allows us to situate our findings within both practical application domains and existing research on haptic perception.

3.1 Task

Our primary goal is to examine the noticeability of haptic notification channels for varying levels of actuation, providing fundamental insights that are independent of a specific task. To enable this, we opted for a simple box-lifting task that imposes controlled cognitive load and steady physical motion, making it suitable for providing varying levels of exoskeleton support. This task also reflects a common application of exoskeletons—offering physical assistance during manual activities involving repetitive lifting and lowering [40, 53].

As depicted in Figure 2, participants wore a shoulder-based exoskeleton and stood in front of a wall-projected virtual shelf with four color-coded compartments, embedded in a living room environment. Participants were instructed to lower their arm to pick up a colored box from the ground and then lift their arm to the appropriate height to place the box into the matching colored compartment. Once the box reached the correct height, it moved into the shelf and a new box appeared on the ground. These repetitive lifting and lowering movements were intentionally designed to require only flexion and extension of the shoulder (i.e., no grasping, rotational or lateral movements or involvement of other joints were necessary). This ensured that the single active DoF of the exoskeleton was sufficient to support the task.

Depending on the experimental condition, the shoulder exoskeleton provided varying levels of physical assistance to guide the user's arm toward the correct compartment, thereby easing the lifting and lowering. Participants were instructed to lift as many boxes as possible into the correct shelf compartment. At a randomized time interval (between 5-15 seconds after task onset), a haptic notification was provided and participants were asked to press a button as soon as they perceived the notification. As the lifting task served only as an exemplary usage context and our focus was on understanding how noticeable the haptic notifications were at different levels of actuation, the haptic notifications carried no specific meaning and were not intended to provide any feedback on task performance.

3.2 Experimental Design

Independent Variables. We systematically vary the haptic notification channels and levels of actuation as two independent variables (IV) with the following levels:

Haptic notification We selected four haptic notification channels (see Figure 1b) to represent the diversity of haptics: *poking*, *proprioceptive thermal*, and *vibrotactile*. *Poking*, *thermal*, and *vibrotactile* notifications are commonly used in prior work (e.g., [6, 44, 49]) and address distinct receptors in the skin: *Poking* is a typical way to draw attention in interpersonal interaction and has shown promise in prior studies for its good noticeability [6, 44, 46]. The mechanoreceptor most responsible for detecting the stimulus is the Merkel cell [46]. *Thermal* is received by the skin's thermoreceptors. As cold feedback has a sharper onset, is more attention grabbing [29], and preferred over warm stimuli [6, 56], we realize thermal notifications through a cooling sensation. *Vibrotactile* is widely used as a wearable notification channel (e.g. [6, 44, 49]), and thereby presents the users with a familiar notification channel. We additionally included *proprioceptive* notifications to complement the cutaneous modalities, as it naturally links to exoskeletons and is underexplored as a haptic notification. Inspired by the jerking function proposed in [35], we realize proprioceptive notifications through small,

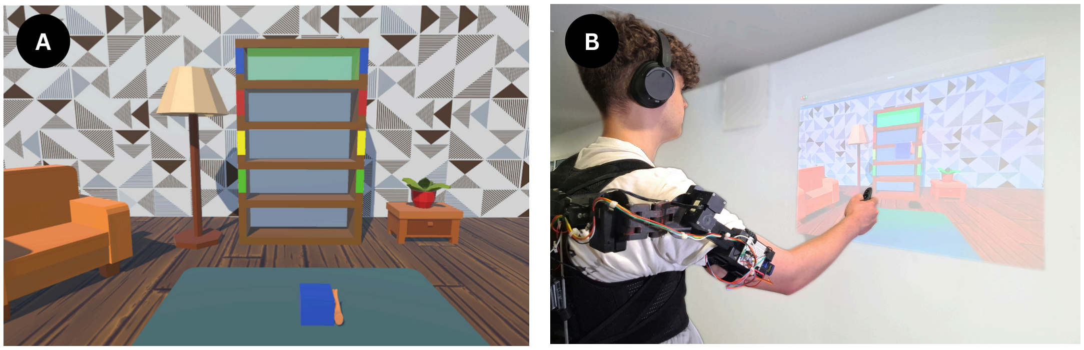

Figure 2: The study setup. Participants performed a lifting task with colored virtual boxes and a virtual shelf in a projected living room (A). They stood in front of the wall-projected shelf while the exoskeleton provided varying levels of physical assistance (B).

repetitive back-and-forth movements induced by the exoskeleton, resembling twitching muscles. As it creates a brief distortion in the movement path, it is perceptible both when the user is actively moving and when the exoskeleton is actuating the arm. The implementation of each stimulus is informed by prior work and detailed in Section 3.3.

Actuation level To assess the impact of exoskeleton actuation on haptic perception, we defined three levels of physical support (see Figure 1c): *none*, *moderate*, and *strong*. The three levels are defined through the magnitude of the applied torque guiding the user motion. The level *none* serves as a baseline, with participants actively moving their arms without any support from the exoskeleton (0 N.m). For *moderate*, the exoskeleton applies a guiding torque of 5 N.m (comparable to the effort required to lift a 1 kg weight at the end of a 0.5 m lever), requiring joint effort from the user and exoskeleton to reach the target position. For *strong*, the torque doubled to 10 N.m, which allows the exoskeleton to take the lead over the motion. The selected torques of up to 10 N.m lie within the typical range for shoulder exoskeletons (e.g., [1, 15, 43, 53]).

We employed a within-subjects design and counterbalanced all conditions with a balanced Latin square. Each participant repeated each condition three times, resulting in a total of $4 \times 3 \times 3 = 36$ trials per participant.

Dependent Variables. To assess the influence of Haptic notification and Actuation level, we measured the following dependent variables, commonly used in related work [6, 23, 24, 49]:

Response time The time from presenting the notification to the participant pressing the button, signaling that they perceived it.
Error rate Percentage of times a participant did not perceive notifications.
Custom questionnaire The questionnaire on a seven-point Likert scale consists of seven items: noticeability, urgency, comfort, and pleasantness of the notification. Also, we asked participants about the interference of the stimulus with the execution of the physical task, their mental demand and the match of the haptic feedback with the actuation level.

3.3 Apparatus

Hardware. Figure 3A depicts our exoskeleton prototype, which features one active degree-of-freedom (DoF) supporting flexion-and-extension movements of the shoulder joint. It was built with ExoKit [35]. A Dynamixel XM540-W270 motor provides up to 10 N.m of torque and is controlled via a Dynamixel Shield for Arduino. An Arduino Mega manages the communication with the motor and the haptic actuators. We embedded the haptic actuators on the lateral upper arm and inside the exoskeleton's arm cuff, to deliver notifications directly to the stimulated body part. We used Autodesk Fusion 360 to modify the 3D models of the arm cuffs, such that the haptic actuators could be embedded. We integrated all actuators into a single prototype (see Figure 3B), positioning them in close proximity, rather than creating separate prototypes for each method to avoid time-consuming switching and re-calibration of the exoskeleton during the study. In line with prior work (e.g., [6, 44]), all participants experienced the same stimulus intensity rather than a customized level to ensure a controlled study setup. Below, we provide details on the actuator types and stimulus design:

Poking notification We attach a SG90 Mini 9G Gear Micro Digital Servo Motor with a 3D-printed blunt poking tip to the outer side of the arm cuff (see Figure 3C), replicating the design of [6]. The tip consists of two links joined at a 45° angle, measuring $10mm \times 5mm \times 5mm$ and $15mm \times 5mm \times 5mm$, respectively. When the motor rotates, the tip gently pokes to the upper arm. The motor's torque (1.5 kg·cm) and poking depth (~3 mm) are comparable to prior work [6, 46].

Proprioceptive notification Inspired by the exoskeleton's ability to alter the characteristics of the user motion [35], the Dynamixel motor attached to the shoulder joint executed small and repetitive flexion-extension movements, designed to be clearly distinguishable from any ongoing user motion and exoskeleton support. Here, the motor applies maximum torque to lift the shoulder by 8°, then pauses by disabling torque for 200 ms, allowing the user to freely continue their motion. It then lowers

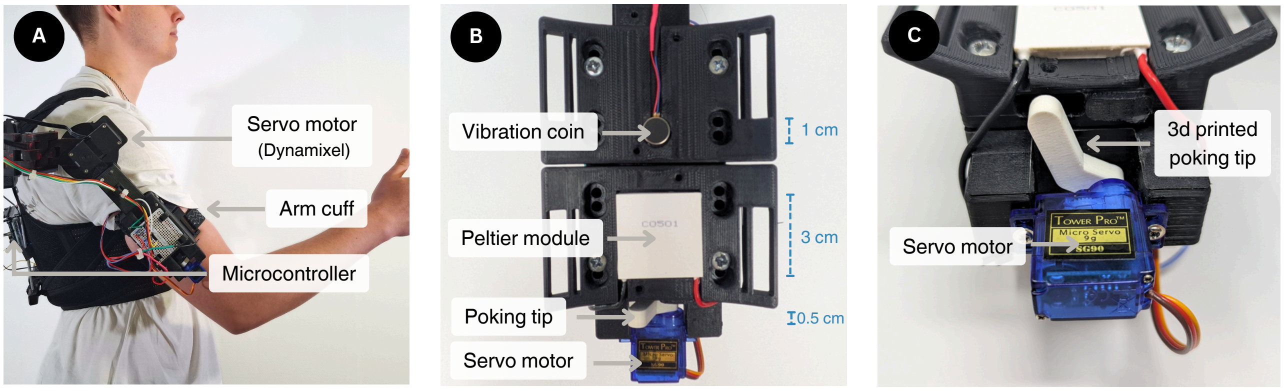

Figure 3: In the study, we used a shoulder exoskeleton (A). We integrated the haptic actuators for poking, thermal and vibrotactile notifications into the exoskeleton's arm cuff (B). To realize poking, a motor rotates a 3d printed blunt tip into the arm (C).

the shoulder again by 8° from the user's current shoulder angle, followed by another 200 ms pause. The angular displacement of 8° was selected to be above the shoulder joint's detection threshold for externally induced motions [3, 7] and fine-tuned for the experimental task.

Thermal notification A Peltier module ($30 \times 30 \times 5.3mm$) cooled the skin by ~6°C within 4 seconds (see Figure 3B). This temperature change is consistent with prior work [6] and remains within safe limits, above thermal pain thresholds (~11–15°C) [27, 56]. The module is embedded in the cuff to make direct contact with the skin.

Vibrotactile notification We used a coin-like vibration motor ($10 \times 10 \times 2.7mm$, 1.0G amplitude), vibrating at a frequency of ~240 Hz near the peak sensitivity of Pacinian corpuscles [31] frequently targeted in vibrotactile feedback (e.g., [12, 38]). Like the Peltier module, the motor is embedded in the arm cuff (see Figure 3B).

In line with prior work [6], each stimulus was presented for two seconds except for the thermal stimulus, which was presented for four seconds due to the actuator's longer onset time. Furthermore, all haptic actuators directly were in contact with the skin, i.e., not separated by any additional fabric or cushioning for enhanced noticeability.

Software. The experimental environment was implemented in Unity (version 2022.3.28f1) and the exoskeleton motion control using the Arduino IDE. The Unity application rendered a virtual living room, and handled the task logic (spawning boxes and assigning random target compartments), communication with the exoskeleton, and data logging. During the task execution, participants controlled a virtual hand by raising and lowering their upper arm. When the position of the virtual hand and box aligned, the box attached to the hand and could be lifted to the target compartment. Upon reaching the height of the target compartment, the box moved into the shelf and a new box spawned at the bottom. To control the virtual hand, the exoskeleton continuously streamed the Dynamixel's motor position to Unity, enabling real-time motion tracking of the shoulder joint angle. Simultaneously, Unity sent commands to the exoskeleton to activate haptic feedback and adjust physical support levels according to the experimental condition. For moderate and strong actuation levels, the exoskeleton applied a directional torque to guide the user's arm toward the correct shelf compartment. When reaching the goal position, the system guided the arm back to the starting point to reach for the next box.

3.4 Procedure

The study was conducted in single-user sessions in a quiet environment. Participants wore short sleeves to ensure direct skin contact with the haptic actuators. At the beginning of the session, the experimenter measured room and skin temperature, following best practices for studies involving thermal feedback [56]. After obtaining informed consent and collecting demographic information, the exoskeleton was attached and calibrated to operate within each participant's comfortable range of motion. Participants were informed that they could request breaks or leave the experiment at any time if they felt uncomfortable. During the experiment, participants stood in front of the wall-projected virtual shelf and wore noise-canceling headphones (see Figure 2b). The session began with a learning phase, allowing participants to familiarize themselves with the lifting task and the actuation levels. For each actuation level, we then introduced participants to the haptic notification channels, which they could practice until they felt confident in detecting them.

In the main phase of the experiment, each of the 12 experimental conditions was introduced individually. For each condition, consisting of three consecutive trials, participants were informed about the actuation level and the haptic notification to detect. At the beginning of each trial, they were asked to lift as many boxes as possible into the correct shelf compartment and press a button as soon as they perceived the haptic notification, which occurred at a randomized point in time (see Section 3.1). After completing the three trials, participants filled out the custom questionnaire. The study concluded with a semi-structured interview to collect qualitative insights on user preferences, perceived noticeability, suitability, and urgency of the haptic notifications. Sessions were

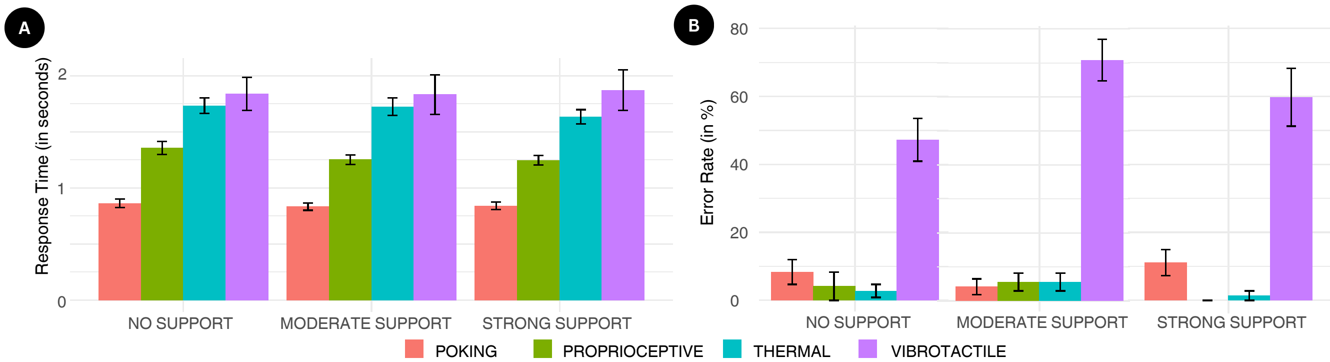

Figure 4: The mean response times (A) and error rates (B) across all haptic notification channels and levels of actuation. The error bars depict the standard error.

audio-recorded, transcribed, and lasted approximately one hour per participant. The study was approved by the university's ethical review board (no. 25-07-9).

3.5 Participants

We recruited 24 participants (17 m; 7 f; 0 d) with a mean age of 26.3 years (SD = 9.6). None reported any prior experience with exoskeletons nor any physical or neurological condition that would have affected their arm's motion or haptic perception.

3.6 Data Analysis

For error rates and response time, we first assessed the assumption of normality using Shapiro-Wilk. As the assumption of normality was violated for both dependent variables, we performed the Aligned Rank Transformation (ART) ANOVA as proposed by Wobbrock et al. [57] to analyze error rates, response times and the ordinal Likert items. For significant results, we followed up with the ART-C procedure as suggested by Elkin et al. [17]. We report on partial eta-square η_p^2 as the measure of effect size and classify it as small (> .01), medium (> .06), or large (> .14) [14].

We analyzed the interview transcripts with a collaborative, qualitative content analysis (QCA) [33] to explore usability-related aspects of the notification channels and perceived effects of varying exoskeleton actuation levels and to complement the quantitative findings. First, one author reviewed the transcripts and proposed an initial codebook with three categories and several subcategories. Two coders among the authors then independently applied this scheme to 25% of the data and inductively added additional (sub)categories as needed. We achieved an initial inter-coder reliability of Fleiss' $\kappa = 0.69$. After resolving ambiguities and refining the codebook through discussion, κ improved to 0.92[1]. The coders then used the final codebook to independently code each 9 of the remaining transcripts.

[1] Landis & Koch classify $0.6 < \kappa <= 0.8$ as substantial agreement, and $\kappa > 0.8$ as almost perfect [30].

4 Results

In this section, we present the study's quantitative and qualitative results[2]. To enhance readability and focus on the most relevant findings, we report only statistically significant effects.

4.1 Response Times

Response times (see Figure 4A) ranged from 0.83 seconds (SD = 0.26) for POKING when MODERATE actuation was provided to 1.87 seconds (SD = 0.96) for VIBROTACTILE notifications during the STRONG level of actuation.

We found a significant ($F_{3,617} = 169.81$, $p < .001$) main effect for the HAPTIC NOTIFICATION with a large ($\eta_p^2 = 0.45$) effect size. Post-hoc tests reveal significantly faster response times for POKING compared to VIBROTACTILE, THERMAL, and PROPRIOCEPTIVE (all $p < .001$), as well as significantly faster response times for PROPRIOCEPTIVE compared to VIBROTACTILE and THERMAL (both $p < .001$).

4.2 Error Rates

Error rates (see Figure 4B) varied largely and ranged from 0% (SD = 0) for PROPRIOCEPTIVE notifications during STRONG actuation, indicating that all trials have been detected, to 71% (SD = 30) for VIBROTACTILE during MODERATE actuation.

We found a significant ($F_{3,253} = 100.34$, $p < .0001$) main effect for the HAPTIC NOTIFICATION with a large ($\eta_p^2 = 0.54$) effect size. Post-hoc tests reveal significantly higher error rates for VIBROTACTILE compared to POKING, PROPRIOCEPTIVE and THERMAL (all $p < .0001$). We also found significantly lower error rates for PROPRIOCEPTIVE compared to POKING ($p < 0.05$).

We further found a significant ($F_{2,253} = 20.11$, $p < .0001$) main effect for the ACTUATION LEVEL on the error rates with a medium ($\eta_p^2 = 0.14$) effect size. Post-hoc tests reveal significantly lower error rates for NONE compared to MODERATE and STRONG (both $p < .0001$).

We also found a significant ($F_{6,253} = 5.04$, $p < .0001$) interaction effect between HAPTIC NOTIFICATION and ACTUATION LEVEL

[2] Participants' skin temperature showed low variability, sitting at a neutral level of 33.0°C (SD = 0.8) at an average room temperature of 25.5°C (SD = 1.2).

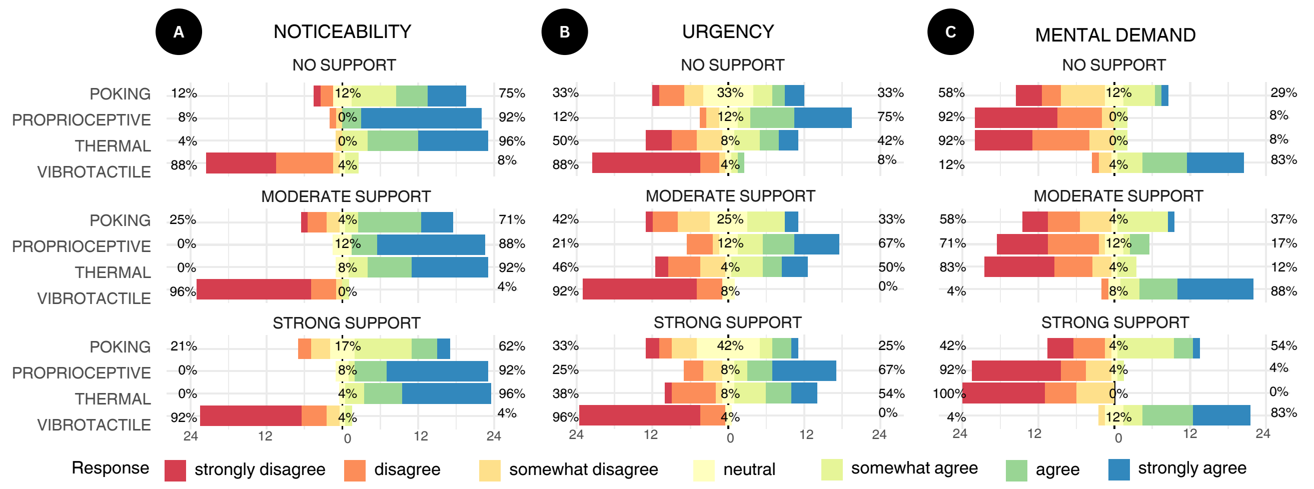

Figure 5: Participants' responses regarding (A) noticeability (*"The haptic feedback was clearly noticeable"*), (B) sense of urgency (*"The haptic feedback conveyed a high sense of urgency"*), and (C) mental demand (*"Detecting the haptic feedback was mentally demanding"*). Graphs are centered around the neutral response. The proportion of positive and negative responses are displayed on the right and left side, respectively.

with a medium ($\eta_p^2 = 0.11$) effect size. Post-hoc tests reveal significantly higher error rates for VIBROTACTILE compared to all levels of HAPTIC NOTIFICATION across all levels of ACTUATION LEVEL (all $p < .0001$).

4.3 Custom Questionnaire

After each condition, participants rated the seven items of the custom questionnaire on a 7-point Likert scale. We analyze the results for each statement:

4.3.1 The haptic feedback was clearly noticeable. As depicted in Figure 5A, VIBROTACTILE notifications at MODERATE and STRONG levels of actuation were rated as the least noticeable, both with a median of $\tilde{x} = 1$ and a median absolute deviation (MAD) of 0. The highest median ratings were achieved for PROPRIOCEPTIVE feedback across all ACTUATION LEVELS and for THERMAL at a STRONG level of actuation (all $\tilde{x} = 7$, MAD = 0).

We found a significant ($F_{3,253} = 198.54$, $p < .001$) main effect for HAPTIC NOTIFICATION on noticeability with a large ($\eta_p^2 = 0.70$) effect size. Post-hoc tests reveal significantly lower noticeability for VIBROTACTILE compared to POKING, PROPRIOCEPTIVE, and THERMAL (all $p < .0001$). Furthermore, users rated the noticeability of POKING significantly lower than PROPRIOCEPTIVE and THERMAL (both $p < .0001$).

We further found a significant ($F_{2,253} = 3.21$, $p < .05$) main effect for the ACTUATION LEVEL with a small ($\eta_p^2 = 0.02$) effect size. Post-hoc tests reveal significantly higher noticeability for NONE compared to STRONG actuation ($p < .05$).

4.3.2 The haptic feedback conveyed a high sense of urgency. As depicted in Figure 5B, participants rated VIBROTACTILE notifications across all three ACTUATION LEVELS as least urgent (all $\tilde{x} = 1$, MAD = 0), while PROPRIOCEPTIVE notifications received highest urgency ratings amongst all experimental conditions for NONE and STRONG levels of actuation ($\tilde{x} = 6$, MAD = 1.5).

We found a significant ($F_{3,253} = 104.61$, $p < .001$) main effect for the HAPTIC NOTIFICATION on the sense of urgency with a large ($\eta_p^2 = 0.55$) effect size. Post-hoc tests reveal significantly higher perceived urgency for PROPRIOCEPTIVE compared to POKING, THERMAL, and VIBROTACTILE (all $p < .0001$). Furthermore, users rated the perceived urgency of VIBROTACTILE significantly lower than POKING and THERMAL (both $p < .0001$).

4.3.3 Detecting the haptic feedback was mentally demanding. As depicted in Figure 5C, participants rated detecting VIBROTACTILE notifications at a MODERATE level of actuation as the most mentally demanding ($\tilde{x} = 6.5$, MAD = 0.7), while the least mentally demanding were PROPRIOCEPTIVE notifications for NONE and STRONG as well as THERMAL for STRONG levels of actuation (all $\tilde{x} = 1$, MAD = 0).

We found a significant ($F_{3,253} = 115.26$, $p < .001$) main effect for the HAPTIC NOTIFICATION on the mental demand with a large ($\eta_p^2 = 0.58$) effect size. Post-hoc tests reveal significantly higher demand for VIBROTACTILE compared to POKING ($p < .0001$), THERMAL ($p < .0001$) and PROPRIOCEPTIVE ($p < .0001$). Furthermore, users rated the mental demand of detecting POKING significantly higher than PROPRIOCEPTIVE ($p < .0001$) and THERMAL ($p < .0001$).

4.3.4 The haptic feedback physically interfered with my ability to successfully perform the task. As depicted in Figure 6A, participants rated PROPRIOCEPTIVE notifications as most interfering with their ability to perform their task across all ACTUATION LEVELS (all $\tilde{x} = 6$, MAD = 1.5), while all other conditions were consistently rated as not interfering (all $\tilde{x} = 1$, MAD = 0).

We found a significant ($F_{3,253} = 122.12$, $p < .001$) main effect for the HAPTIC NOTIFICATION on the interference with a large

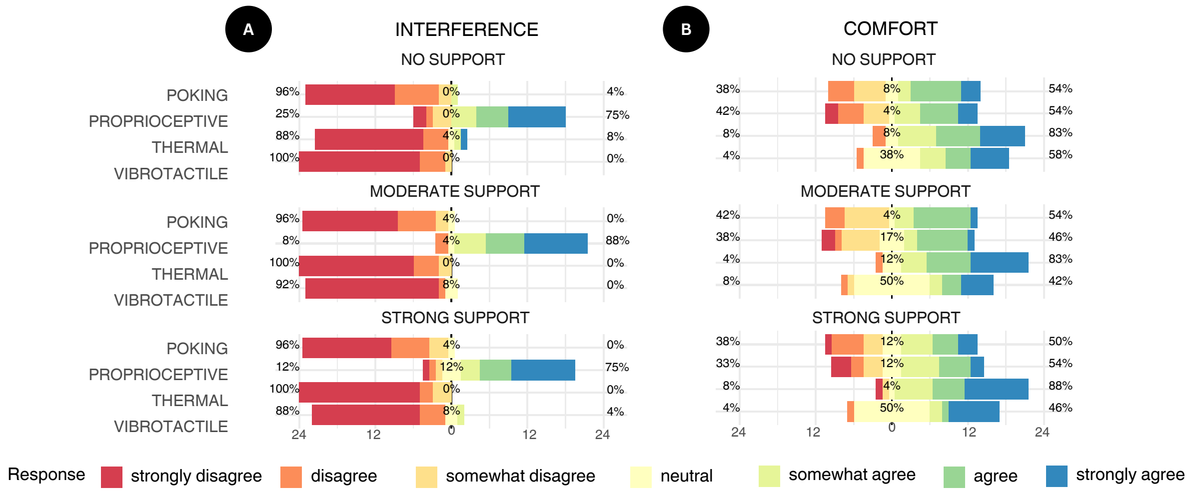

Figure 6: Participants' responses regarding (A) physical interference (*"The haptic feedback physically interfered with my ability to successfully perform the task"*) and (B) comfort (*"The haptic feedback was physically comfortable"*).

($\eta_p^2 = 0.59$) effect size. Post-hoc tests reveal that PROPRIOCEPTIVE interfered significantly more with the user's motion than POKING, THERMAL, and VIBROTACTILE (all $p < .0001$).

4.3.5 The haptic feedback was physically comfortable. As depicted in Figure 6B, THERMAL notifications were consistently rated as the most comfortable across all ACTUATION LEVELS ($\tilde{x} = 6$, MAD = 1.5). In contrast, the lowest comfort ratings with a neutral median rating of $\tilde{x} = 4$ were reported for PROPRIOCEPTIVE notifications at MODERATE (MAD = 2.2) and for VIBROTACTILE notifications at MODERATE and STRONG levels of actuation (both MAD = 0.7).

We found a significant ($F_{3,253} = 11.92$, $p < .001$) main effect for the HAPTIC NOTIFICATION on the comfort with a medium ($\eta_p^2 = 0.12$) effect size. Post-hoc tests reveal significantly higher comfort for THERMAL compared to POKING and PROPRIOCEPTIVE (both $p < .0001$).

4.3.6 I found the haptic feedback pleasant. While physical comfort is important to prevent painful or harmful interactions, pleasantness reflects the affective dimension, including enjoyment or likeability of the stimulus. As depicted in Figure 7A, THERMAL notifications were consistently rated as the most pleasant across all ACTUATION LEVELS ($\tilde{x} = 6$, MAD = 0.7). In contrast, least pleasant ($\tilde{x} = 3$) were PROPRIOCEPTIVE notifications at MODERATE and STRONG levels of actuation (both MAD = 1.5), and POKING at STRONG actuation (MAD = 2.2).

We found a significant ($F_{3,253} = 26.96$, $p < .001$) main effect for the HAPTIC NOTIFICATION on the pleasantness with a large ($\eta_p^2 = 0.24$) effect size. Post-hoc tests reveal significantly higher pleasantness for THERMAL compared to POKING, VIBROTACTILE, and PROPRIOCEPTIVE (all $p < .0001$). Furthermore, we found a significantly higher pleasantness for VIBROTACTILE compared to PROPRIOCEPTIVE ($p < .01$).

4.3.7 The haptic feedback was well-matched to the exoskeleton's actuation level. Beyond assessing the general qualities of each notification channel, we also examined which channels participants perceived as most appropriate for different actuation levels. As depicted in Figure 7B, the lowest perceived matches were VIBROTACTILE for NONE and STRONG levels of actuation (both $\tilde{x} = 2$, MAD = 1.5), while the best match was THERMAL for actuation level NONE ($\tilde{x} = 6$, MAD = 1.5).

We found a significant ($F_{3,253} = 50.11$, $p < .001$) main effect for the HAPTIC NOTIFICATION on the match with the exoskeleton actuation with a large ($\eta_p^2 = 0.37$) effect size. Post-hoc tests reveal that THERMAL matched significantly better with the different levels of exoskeleton actuation than POKING ($p < .001$), VIBROTACTILE ($p < .0001$) and PROPRIOCEPTIVE ($p < .0001$). Furthermore, POKING matched significantly better than PROPRIOCEPTIVE ($p < .05$) and VIBROTACTILE ($p < .0001$), and PROPRIOCEPTIVE significantly better than VIBROTACTILE ($p < .0001$).

4.4 Subjective Feedback

We conducted a QCA to analyze the 24 interview transcripts. We report on practical and usability related aspects by denoting categories mentioned per participant as n:

4.4.1 Noticeability & sources of confusion. Most participants reported that the actuation level generally influenced the perceived noticeability of the haptic notifications ($n = 21$). Eight participants found notifications more recognizable without actuation, attributing this to the absence of mechanical noise: *"[With no actuation] it is easier [to notice] because the internal motors are just working much less"* (P16). This noise from the motor was also noted as a source of confusion ($n = 2$); for instance P06 *"mistook the vibration [notification] and the general vibration of the exoskeleton itself."*

Furthermore, a few participants perceived notifications as more noticeable during strong actuation due to reduced cognitive load: *"because I didn't need to focus on the task itself anymore"* (P06). Several participants also noted factors inherent to the exoskeleton design ($n = 7$) that affect the noticeability. These include sensations such as scratching, friction, and pressure arising from the cuffs

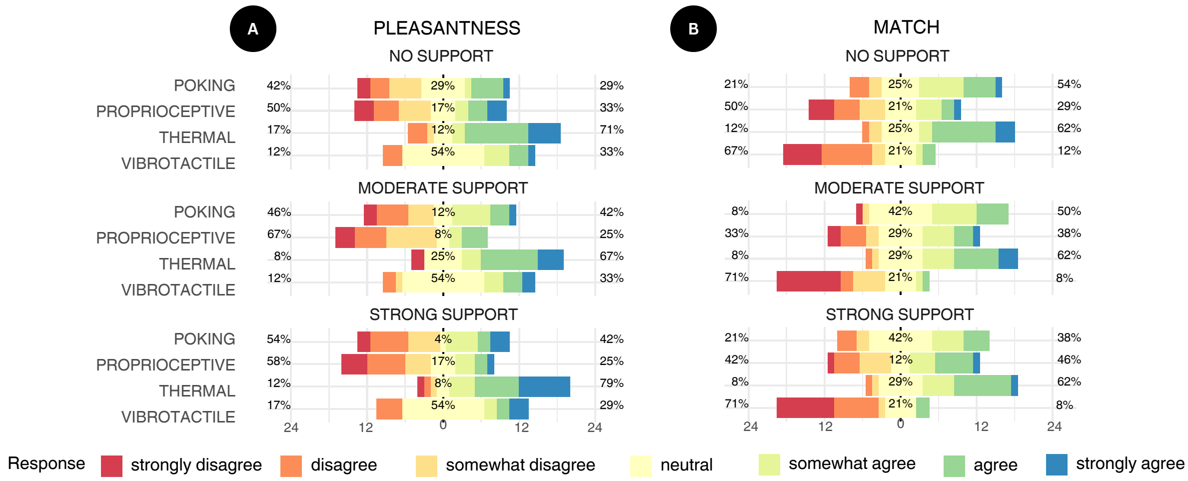

Figure 7: Participants' responses regarding (A) the pleasantness (*"I found the haptic feedback pleasant"*) and (B) match (*"The haptic feedback was well-matched to the exoskeleton's actuation level"*).

attached to the upper arm (n = 4): *"because the arm is also moving and then like the straps are kind of also moving and stretching and pushing a bit"* (P05).

However, the notification channels were affected differently by these factors. Thermal notifications were mostly described as highly noticeable (n = 22), due to their distinctiveness from the sensation of actuation and mechanical noise. Proprioceptive notifications were also frequently rated as highly noticeable (n = 14), although a few participants noted confusion with the actual exoskeleton actuation (n = 3). Opinions were more mixed for poking. Almost half of the participants emphasized that poking was clearly noticeable (n = 11), but also indicated that the actuation of the exoskeleton interfered with detecting the poking sensation (n = 11). Vibrotactile notifications were consistently rated to have low noticeability (n = 21). One influencing factor was the actuation level (n = 10). Most participants explained that the moderate and full actuation conditions resembled the stimulus (n = 8): *"if there's support, it's kind of hard to tell the difference between the vibration and the movement."* (P04). Two participants contrasted that the vibrotactile noticeability was higher for full actuation *"because I didn't have to pay so much attention to the task"* (P23), reflecting the slightly lower error rates for the full actuation compared to the moderate actuation condition.

4.4.2 User experience & preferences. Nearly all participants attributed the likeability of a notification channel to high noticeability (n = 23) with a good balance between comfort and intensity (n = 22). Another influential factor was the perceived fit between a haptic notification channel and the level of actuation. Participants expressed stronger preference when the notification channel aligned well with the actuation level (n = 9), while mismatching channels led to lower preference (n = 7).

Unsurprisingly, many participants generally were less in favor of notifications that hindered task completion (n = 17) and were not seamlessly integrated with their ongoing motion (n = 9); conversely, notifications that integrate smoothly with their motion were received positively (n = 7). In line with these considerations, thermal notifications were liked by most participants (n = 22) for their high noticeability (n = 14), comfort (n = 10), and seamless integration in the user's primary task and ongoing motion (n = 9). Furthermore, *"you don't mismatch [the cooling sensation] with a malfunction where [the exoskeleton] would heat up"*, making this haptic notification channel a particularly distinct sensation.

Poking and proprioceptive notifications were received positively by nearly half of the participants (n = 11 each). Poking was appreciated for its noticeability (n = 5), comfort (n = 3), non-intrusiveness (n = 2), and naturalness (n = 2) as it is *"a natural 'I want to get your attention'-gesture"* (P03). However, few participants found it less favorable as they associated it with negative sensations, such as *"a sting"* (P12). For proprioceptive notifications, a primary reason for the diverging preferences was their interference with the user's arm movement and task (n = 11). However, this perception varied with the actuation level: *"[When fully actuated,] jerks were fine because my arm was moving on its own anyway"* (P07), reducing perceived disruptiveness.

Finally, a few participants also indicated that they *"like the idea of vibration"* (P11) if its intensity was increased (n = 5), because it does not interfere (n = 3) and *"because that's also something I'm used to from like my phone"* (P08).

4.4.3 Perceptions of urgency. Most participants commonly associated a high noticeability and strong intensity with a heightened sense of urgency (n = 21); several also linked greater discomfort to increased urgency (n = 8). Reflecting this, proprioceptive notifications were most frequently described as conveying a high sense of urgency (n = 17), as it is rather disruptive (n = 5), intense (n = 5), and has a pronounced impact on the user's ongoing motion (n = 5). However, views diverged on whether notifications conveying urgent notifications should interrupt the user's primary activity (n = 8) or integrate with it (n = 3). For instance, P10 emphasized that *"your body is moving in a direction you did not expect and this is urgent"*, whereas P12 contrasted that *"[proprioceptive* *notifications] prevented me from moving. So in a way that took away urgency again. Because I wasn't really able to act when I felt them."*

Thermal notifications were perceived as urgent by half of the participants, due to their high noticeability (n = 3) and intensity (n = 3). Yet, urgency was diminished for some because *"the change in temperature was so gradual"* (P08). Consequently, P05 argued: *"I enjoyed [thermal] quite a lot, so that's why I didn't feel it to be too urgent."* Similarly, vibration was largely considered non-urgent (n = 19) *"because it's very soft"* (P16).

Poking elicited the most divergent responses: Eight participants perceived it as urgent as it would be rather uncomfortable (n = 5) and evoked associations with unpleasant experiences: *"I thought it was a bee"* (P06).

While perceived urgency consistently was influenced by the haptic notification channels, no participant considered the actuation level to be an influential factor fo urgency, which aligns with the quantitative findings.

5 Discussion & Implications

In the following, we discuss our findings and derive implications for designing haptic notifications for varying levels of exoskeleton actuation.

5.1 Choose Haptic Notification Channels Distinct from Sensory Pathways Affected by Actuation

Our results show that the noticeability of haptic notification channels was significantly higher when the body was not actuated. Interview data further supported this finding and revealed several reasons for the reduced noticeability: While few participants explained that channels like the proprioceptive one can be prone to being confused with the exoskeleton actuation itself, others pointed to mechanical or design-related influences. For example, poking was perceived close to the pressure applied to the cuffs when being actuated, and vibrotactile feedback was sometimes mistaken for motor vibrations. While improved control strategies and designs may reduce motor-induced vibrations and strain, they remain a potential confounder in current exoskeletons [32] and must be considered when choosing a notification channel.

The reported perceptual interferences were also reflected in significantly lower error rates when no actuation was present despite the user's ongoing own motion. These findings align with prior work showing that perceptual interference between different haptic cues can reduce the effectiveness and require higher amplitudes to ensure salience [52, 59]. However, increasing the stimulus amplitude is also limited by pain thresholds. Among the tested notification channels, thermal feedback emerged as the most distinct channel, as it does not overlap with haptic sensations produced by the exoskeleton and is generally less likely to be masked or confused with actuation. Consequently, to reduce error rates and enhance noticeability, we recommend selecting haptic notification channels that engage sensory pathways unaffected by actuation or exoskeleton-induced strain. Notably, this choice does not compromise response time, which remained stable for all haptic notification channels across the varying actuation levels.

5.2 Choose Thermal and Vibrotactile Feedback for Non-urgent Haptic Notifications

For notifications which do not impact user safety or require immediate attention (e.g., updates on battery status or a slight adjustment in the provided actuation level), there is no need to employ disruptive or intrusive feedback. Instead, notification channels that prioritize comfort and pleasantness while maintaining sufficient noticeability are preferable to support an unobtrusive and user-friendly interaction. For instance, thermal notifications were rated highest in comfort and pleasantness, and showed significantly better noticeability and lower mental demand than vibrotactile and poking feedback. However, its significantly slower response times compared to poking and proprioceptive feedback limit its suitability for time-critical alerts. Thermal notifications are thus well-suited for non-urgent notifications, such as status updates or low-priority alerts. However, the perceptibility of thermal feedback may vary with ambient temperature [21, 51], which in turn can negatively impact comfort and detection.

Alternatively, literature suggests vibrotactile feedback as an unobtrusive notification channel [10, 13]. Our participants rated it neutral to rather pleasant, and significantly more pleasant than proprioceptive notifications. However, it also suffered from higher error rates and stronger perceptual interferences when the exoskeleton actuated the body. We acknowledge that its noticeability may be improved with different actuators and stimulus design and assume that its familiarity and pleasantness may turn it into a viable alternative to thermal feedback for non-urgent notifications.

When selecting a haptic notification channel, we suggest to select the channel that best balances comfort and noticeability based on the present actuation level and context of use, or even defer notification delivery until actuation ceases to enhance noticeability.

5.3 Choose Poking and Proprioceptive Feedback for Time-critical Haptic Notifications

Certain system states (e.g., sensor failure, overloaded motors, or a detected joint misalignment) might require immediate user attention to prevent safety hazards. For such time-critical notifications, designers must select notification channels that can be quickly, correctly and confidently detected, and also convey a high sense of urgency.

Poking and proprioceptive notifications emerge as two promising options which offer distinct advantages: Proprioceptive notifications consistently conveyed the highest sense of urgency across all actuation levels due to its disruptive nature and pronounced effect on user's motion. It yielded fast response times, low error rates, and low mental demand, but also interfered most with the user's primary task. Poking notifications demonstrated the fastest response times and did not disrupt ongoing motion as proprioceptive notifications, making it suitable for rapid alerts. However, poking yielded significantly higher error rates compared to proprioceptive notifications as it suffered from occasional perceptual confusion with exoskeleton-induced strain. In addition, both were rated lower in comfort and pleasantness compared to thermal notifications, which contributed to the heightened sense of urgency. This aligns with prior work (e.g., [4, 16]), which argues that higher-intensity stimuli increase perceived urgency, albeit potentially compromising comfort.

Based on these considerations, we recommend to choose proprioceptive notifications when task interruption is acceptable or even necessary and the detection of the notification is crucial, while poking may be favored when rapid responses are critical and occasional misses are tolerable. In addition, the actuation level influenced noticeability and error rates, albeit not perceived urgency. This further suggests two principled design strategies: (1) temporarily alter the actuation before delivering important notifications to enhance noticeability if the task allows, or (2) dynamically select the most effective notification channel based on the current actuation level and user context.

5.4 Comparison to Prior Work

Inspired by [6], we contextualize error rates and response times by comparing them to prior haptic research, noting that direct comparisons are limited due to differing study setups. Yet, the comparison situates our work within the broader related literature, contributes a rough understanding of fundamental similarities and differences, and facilitates a discussion of potential influencing and limiting factors contributing to performance differences.

Consistent with prior work [6], poking at the upper arm was the fastest channel (0.8 seconds) among the haptic modalities, reinforcing the suggestion to use it for time-critical notifications. While Bhatia et al. reported slower response times of 2.0 seconds during walking for the upper arm, other studies reported comparable detection times for other body parts, ranging from 0.5–1.9 seconds at the finger across varying activity levels [26, 44]. However, our findings showed higher error rates compared to prior work (HaptEx: 8%; Soma-noti: 0% [6]; Notiring: 1.9% [6]). These differences may stem from variations in poking depth and strength, but might also be the result of perceptual interference between the exoskeleton and the notification channel.

Comparing proprioceptive notifications is challenging due to limited data in prior work. Closest is Faltaous et al. who reported response times of 1.9 seconds when the user was sitting and experiencing a higher cognitive load, which may be the reason for the slightly higher response times compared to our study (1.3 seconds).

Thermal notifications showed improved performance over prior work, even when the body was actuated. Our response times (1.7 seconds) and error rates (3%) were lower than those of Soma-noti (3.5 s, 7%) [6] and those reported by Wilson et al. [56]. The latter reported response times of ∼2.5 seconds in still conditions with increased times during movement. Their mobile detection rate of 12% was notably higher than ours. Some discrepancy may be attributed to technical differences in the thermal modules and how closely the actuators were attached to the skin.

Vibrotactile notifications yielded an average response time of 1.9 seconds and an average error rate of 59%. Bhatia et al reported higher response times of 2.2 seconds at the upper arm, but substantially lower error rates (4%) [6]. Karuei et al. [28] further revealed that movement negatively impacts vibration detection across the body, increasing both response time and error rate. They reported upper-arm response times of approximately 1.4 seconds when seated and 1.8 seconds when walking, placing our response times within a comparable range. Their error rate of ∼35% while walking was lower than the 47% observed in our study under no actuation. However, it is important to note that our experimental task involved active limb movement, as opposed to the passive arm swinging in their setup. Prior research suggests that active movement can raise detection thresholds [11, 41], which may explain this discrepancy. While response times are comparable to those reported in prior work, we acknowledge that increasing the stimulus intensity could help mitigate this effect and further improve detection accuracy [28].

6 Limitations and Future Directions

This study offers insights into the integration of haptic notifications within an active shoulder-based exoskeleton. Nonetheless, several limitations should be acknowledged, which also point to directions for future research.

Broadening the exploration of notification channels. Beyond the four notification channels studied in this work, additional notification channels warrant exploration. These include, but are not limited to techniques using electrotactile, squeezing or dragging feedback as well as visual and auditory cues. Combining channels across different sensory modalities, such as thermal and auditory, may further increase robustness against masking effects and environmental factors constraining the effectiveness of individual channels, such as ambient noise affecting the perceptability of audio feedback. In addition, while vibrotactile notifications yielded fast response times comparable to prior work, error rates suggest that noticeability can be further improved. Future work should explore stronger motors, varied frequencies and rhythmic patterns to enhance perception and distinctiveness from motor vibrations. In this study, we further used the same standard stimulus intensities for each participant. Investigating customized levels of haptic feedback represents another important opportunity for future work. Finally, we only conveyed a binary signal (presence or absence of the notification). Investigating how the proposed notification channels can encode richer information suited for the different actuation levels presents an interesting direction for future work.

Exploring other body locations and exoskeleton designs. We intentionally focused on shoulder exoskeletons due to their relevance in various work contexts. Literature suggests that the observed trends may generalize beyond the upper arm to other locations of the upper body: Compared to the upper arm, the lower arm shows comparable thermal detection accuracy and response times [56]; the collarbone and shoulder exhibit similarly low error rates, fast response times, and high comfort ratings across diverse haptic notification channels [6], and the wrist and spine demonstrated slightly higher, yet comparable sensitivity to vibrotactile feedback [28]. Beyond the upper body, it will be an interesting next step to investigate how these notification channels integrate, e.g., into exoskeletons actuating the legs for gait assistance or exoskeletons supporting the lower back. Moreover, the prototype employed a motor-based actuation. Alternative actuation strategies exists, such as hydraulic-, pneumatic- or SMA-based actuation [54]. These may introduce sensory artifacts different from motor vibrations, which should be explored in future work. Similarly, some exoskeletons are capable of providing higher torques. Therefore, future work should investigate potential masking effects and perceptual interferences of haptic stimuli across more diverse exoskeleton designs, stronger actuation levels and actuation methods to further increase external validity.

Investigating the applicability in diverse contexts. While our study was conducted in a controlled lab setting, real-world applicability of haptic notifications may be constrained by environmental factors. For example, thermal feedback perception is influenced by ambient temperature [51], and clothing layers in outdoor settings can attenuate thermal, poking, and vibrotactile feedback. Integrating haptic actuators directly into textiles or under-clothing wearables (e.g., [6, 58]) presents a promising direction for future work. In this context, our findings suggest that proprioceptive notifications can be a reliable alternative when direct skin contact is impractical or additional wearables to deliver notifications are undesirable. However, in tasks requiring fine motor control, disruptive notifications may hinder performance depending on the user activity. Hence, future studies should evaluate the effectiveness of these haptic notification channels under varying tasks with different physical and cognitive load (e.g., when lifting different weights or performing static overhead work). Furthermore, while the sample size fulfills established CHI standards (e.g., [6, 28, 44], future studies should also consider larger sample sizes and more diverse user demographics (e.g., industrial workers or elderly people). Finally, while we suggest to select the haptic notification channel based on user context, the effects of alternating feedback on physical and cognitive performance and user experience were not tested in this experiment, which presents an interesting opportunity for future work.

7 Conclusion

As exoskeletons act directly on the human body, it is essential to inform users about (critical) system states. Haptic feedback offers a promising communication channel that integrates naturally with the actuated body region. Hence, this paper investigated the performance of four haptic notification channels (poking, proprioceptive, thermal, and vibrotactile) across three levels of exoskeleton actuation. Our findings reveal that actuation significantly affected error rates and noticeability, but not response times. Poking consistently yielded the fastest response times, while proprioceptive and thermal notifications were rated highest in noticeability. Proprioceptive notifications further conveyed the strongest sense of urgency but also interfered most with the user's primary task. Thermal and vibrotactile feedback were considered most comfortable and pleasant; however, the error rates of vibrotactile feedback increased significantly when the body was actuated. These results highlight the importance of selecting haptic notification channels that are distinct from the sensory pathways affected by the actuation and exoskeleton-induced strain. We recommend thermal and vibrotactile feedback for non-urgent alerts due to their comfort and integration in user's activities, and proprioceptive and poking feedback for notifications where rapid detection, low error, and a heightened sense of urgency are essential. In urgent situations, we further suggest either to temporarily alter actuation before delivering those notifications or select the most effective channel for the current actuation level; for non-urgent notifications, designers might defer the notification until actuation ceases. We hope that these findings serve as a valuable foundation for follow-up work, supporting the design of more effective human–exoskeleton interaction.

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