Investigating Osseoperception in Distal Regions of the Upper Limb for Augmented Sensory Feedback

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***Abstract*— The somatosensory function is crucial for motor control, but is often deemed secondary in the design of assistive technologies for individuals with neuromotor impairments. This study investigates osseoperception—auditory and vibrotactile sensations evoked through bone stimulation—at the wrist pisiform bone (PB) and metacarpal head (MCH) of the index finger in 12 participants. Vibratory stimuli (100–6000 Hz) were applied during four psychophysical experiments: sensation discrimination, perception thresholds, sensory mapping, and loudness evaluation. Tactile sensations occurred below 940 Hz at the PB and 1000 Hz at the MCH, while auditory sensations predominated above these thresholds. Stimulation at 400 Hz expanded tactile zones, with PB sensations extending to the forearm and MCH sensations to carpal and interphalangeal joints. MCH stimulation had lower perception thresholds (0.14 N), while PB stimulation exhibited frequency-dependent loudness variations. These findings suggest the MCH and wrist as promising sites to elicit osseoperception, paving the way for the development of sensory feedback strategies to complement the effect of assistive technologies, especially those interfaced through osseointegration.**

I. Introduction

The loss of sensory feedback, resulting from neurological disorders, peripheral nerve damage, amputation, trauma, and degenerative diseases, may significantly impair the ability to perform fundamental movements for the activities of daily living (ADLs), such as grasping [1]. This because sensory information plays a crucial role in motor control, enabling precise adjustments through feedback and feedforward mechanisms [2]. The central nervous system (CNS) achieves this through internal models in the cerebellum: the inverse model predicts movements, while the forward model anticipates their sensory outcomes based on an efferent copy of the motor command [3]. Discrepancies between predicted and actual sensory feedback, known as sensory prediction errors, initiate corrective actions to reduce the error during motor performance, closing the control loop [4], [5].

Sensory information originates from mechanoreceptors embedded in the skin of the hand. These specialized sensory neurons detect and process tactile stimuli and are characterized by different properties such as spatial and temporal resolutions, and adaptability [5]. Superficial receptors, i.e., Merkel cells and Meissner corpuscles, enable fine-texture and shape detection, while deeper receptors, such as Pacinian corpuscles and Ruffini endings, detect vibrations and stretch. Loss of tactile, visual, or proprioceptive sensitivity disrupts fine motor control, grasp force, and prehension patterns, leading to significant functional impairments [6].

Sensory feedback can be intrinsic - arising naturally from sensory receptors in skin, muscles, tendons, and joints —, or extrinsic, artificially provided through external devices [6]. Extrinsic feedback, also referred as augmented feedback, is generally provided in the form of visual (through display monitors), auditory (through speakers, headphones), haptic cues (through robots, vibrotactile actuators), or a combination of them [7], [8]. Despite its importance, many assistive and rehabilitation technologies, such as robotic exoskeletons, focus primarily on motor assistance and overlook sensory feedback, possibly hindering their potential to restore natural and intuitive movements [9]. A reason could be the lack of optimal sensory modalities for providing effective augmented feedback, particularly with lightweight, fast-response, noninvasive devices.

Bone conduction has emerged as a promising approach for delivering augmented sensory feedback [10], [11]. By applying vibrational cues to the bones, it is possible to selectively elicit local vibrotactile sensations, stimulating the mechanoreceptors in the periosteum, or auditory sensations, when the vibrations reach the skull and stimulate the cochlea, i.e., osseoperception. This offers the advantage of conveying rich sensory information, using a single, lightweight, low-power transducer [10]. Previous studies have explored invasive applications, where bone transducers were attached to osseointegrated abutments in transhumeral amputees [10], and non-invasive applications, where the transducers were applied on the bone prominence of the elbow in healthy and amputee participants [11]. However, osseoperception in more distal upper-limb segments, such as the wrist or metacarpal bones, remains unexplored. Our preliminary explorations have focused on estimating the minimum perceivable stimulus on the wrist, limited to small sample sizes [12].

In this study, we investigated osseoperception by applying vibratory stimuli to the pisiform bone (PB) of the wrist and the Metacarpal Head (MCH) bone of the index finger. We conducted four psychometric tests to assess tactile, auditory, and combined sensory responses across different stimulation frequencies and forces. We used sensory mapping techniques

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to delineate the vibration perception zones across the upper-limb and quantified auditory sensation loudness using a categorical scaling procedure. To the best of our knowledge, this approach has not been previously applied to the distal regions of the upper limb. By exploring osseoperception at these underexplored sites, our study contributes new insights into its potential application for restoring sensory feedback in individuals with neuromotor impairments. Furthermore, we believe that osseoperception as supplementary sensory feedback modality could be leveraged to facilitate controlling assistive technologies, such as osseointegrated prostheses (e.g., prosthetic hands or fingers), offering a promising avenue for enhancing prosthetic functionality.

II. Material and Methods

A. Participants

Twelve healthy participants (age between 24 and 35 yrs, equal number of male and female volunteers) were recruited for this study. Experiments were conducted under the Declaration of Helsinki and the guidelines of the Ethics Committee of the Scuola Superiore Sant'Anna (Approval No.10/2023). Participants were seated in front of a computer and given detailed instructions before the beginning of each experiment. Subsequently, they wore earplugs (35.5 dB, Tokelu, GE) and noise-canceling headphones (Peltor X5A, 3M, US), as recommended in prior studies [10], [11], [13]. These measures minimized external auditory interference, creating an isolated environment for our sensory assessments.

B. Experimental setup

The experimental setup, shown in Fig.1, included a Personal Computer (PC), a function generator, an audio amplifier, and a bone conduction transducer, detailed hereinafter. This design was inspired by previous studies in the literature [10], [11], [13]. A Graphical User Interface (GUI) was developed in MATLAB® (2021b, Mathworks, US) to adaptively set stimulation amplitudes and frequencies and record user responses. A multifunction DAQ module (PCI 6259, National Instruments, US) served as the function generator for sinusoidal signals with a 44.1 kHz sampling frequency. These signals were subsequently amplified and filtered (AK-170 Audio Amplifier, Hi-fi, CN) before being delivered to the bone transducer (B-81, Radioear, US). The bone transducer was positioned on the PB of the participant's wrist using a 3D-printed support, secured with adjustable elastic bands and Velcro straps to ensure stability [12]. The flat surface of the bone transducer was placed in direct contact with the target boney prominence, ensuring minimized contact with adjacent bones and hence unwanted vibrational effects, and a static force of 3-5 N was applied. This force range, determined based on prior studies, was sufficient to elicit bone conduction [10], [14]. The same experimental procedure was repeated with the transducer positioned on the metacarpal head (MCH) of the index finger (Fig. 1A). Prior to testing, the bone transducer was calibrated to ensure correct amplitude and frequency vibration using an artificial mastoid (4930, Bruel &Kjaer, DK).

C. Psycophysical experiments

1) Sensation Discrimination

This experiment aimed to evaluate what sensation was elicited by varying the parameters of the stimuli, i.e., frequency and amplitude. A single stimulus (1 s) was delivered to the participant, who was asked to report the elicited sensation among four options: tactile (T), auditory (A), both at the same time (T+A), or no perceived stimulus, by clicking on the corresponding button on the GUI (Fig. 1B). The stimulation frequency was randomly picked among seven values: 100, 200, 400, 750, 1500, 3000, 6000 Hz, based on values used in previous studies [10], [13]. Nine values of stimulation amplitude were randomly presented across the whole output range of the transducer (0-1 N of vibrational force). Each pair of parameters was presented to the participant twice, giving a total of 126 stimulations.

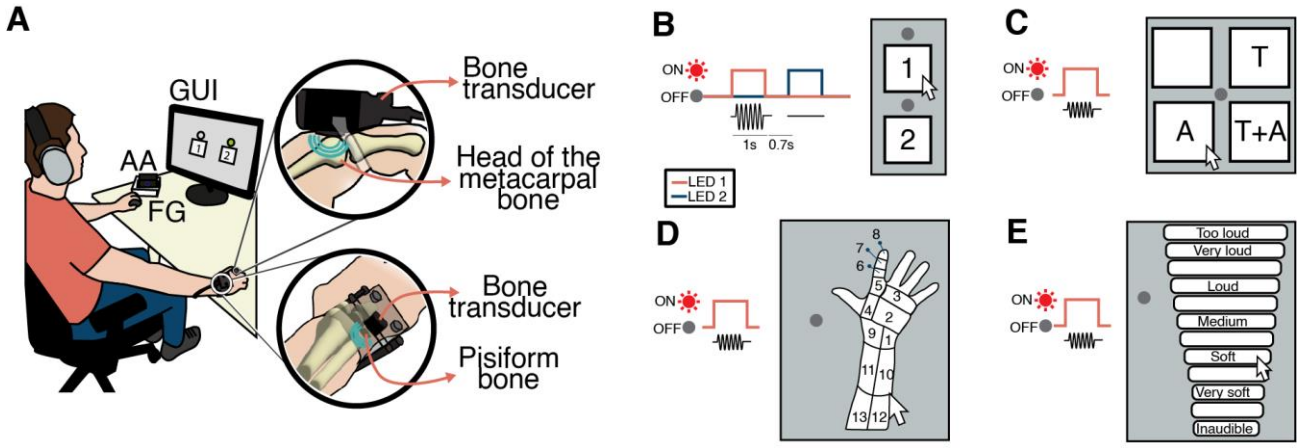

Fig. 1. (A) Experimental setup showing the PC running the GUI, connected to a Function Generator (FG), an Audio Amplifier (AA), and a bone transducer. The bone transducer was placed onto either the Pisiform Bone (PB) or the Metacarpal Head (MCH) of the index finger using two custom 3D-printed supports. A static force of 3–5 N was applied to ensure stable contact and effective vibration transmission. Timing of stimulation and user interface (gray background) for the four psychological experiments performed by the individuals: (B) Sensation discrimination, where the participants were asked to report which sensation (not perceived, tactile – T, auditory – A, or both – T+A); (C) Perception threshold, where the participants were asked to detect when a stimulus was delivered, discriminating against the null stimulus; (D) sensation zone, where the participants were asked to indicate the approximate zone were a tactile stimulus was elicited among 13 zones; (E) loudness evaluation, where the participants were asked to rate the auditory stimulus among 11 levels of loudness scaling.

For each participant, data were grouped by frequency. A logistic psychometric function was then fitted to each group of sensory responses, allowing to estimate the amplitude value corresponding to a 50% detection threshold (D50) for each sensation type. The D50 value indicates the sensitivity threshold for detecting each sensation, with lower D50 values signifying a higher sensitivity. The sensation with the lowest D50 at each frequency was classified as the predominant sensation. This methodology was based on the experimental procedures described in [10].

2) Perception threshold

The amplitude perception threshold (i.e., the minimum perceivable amplitude stimulus each participant could detect) was assessed upon stimulation at various frequencies. A single trial was administered, composed of a standard two-interval forced choice threshold procedure, in which participants discriminated between a target and a null stimulus (both 1 s in duration) in random order, separated by a retention interval of 0.7 s (Fig. 1C). The amplitude of the target stimulus was adjusted using a stochastic approximation staircase (SAS) method. If the participant's response to the previous trial was incorrect, the amplitude was increased; if correct, it was decreased. The step size of the SAS was calculated according to previous studies [10], [12]. Each SAS was stopped after 50 trials per frequency, and the value of the stimulus that would have been presented as the 51st trial was considered as the perception threshold. We selected 100, 400, and 750 Hz, since previous studies identified them to predominantly evoke tactile, combined tactile-auditory, and auditory responses, respectively [10], [11]. This methodology was based on the experimental procedures described in [10].

3) Sensory map

To assess the spatial distribution of tactile sensation, we conducted a test where a single vibrational stimulus (1 s) was delivered to the participant, who was asked to identify the approximate region where the tactile sensation was perceived. Then, the participant was asked to select one or more of 13 predefined regions displayed in the GUI (Fig. 1D). Since no prior studies have mapped the regions of tactile sensations elicited by bone-conducted vibrations on the upper-limb, we based the region layout on previous studies examining haptic points distribution [15], [16]. Stimulation frequencies were randomly selected between 100 and 400 Hz, known to elicit tactile sensations [10]. Nine stimulation amplitude levels were randomly presented across the whole output range of the transducer (0-1 N of vibrational force). Each frequency-amplitude combination was presented to the participant twice, for a total of 36 stimulations.

For each participant, responses were grouped by frequency and amplitude. The probability of stimulus perception in each zone was calculated as follows: 100% for consistent reports across the two stimuli, 50% for one report, and 0% for no reports.

4) Loudness evaluation

This experiment aimed to evaluate the loudness of sounds perceived by the participants, conveyed through bone conduction when their upper limb was stimulated. To achieve this, we used the categorical loudness scaling method following the recommendations of ISO:16832, similarly to [17]. The scaling procedure was presented through the GUI with 11 response options (Fig. 1E), each representing a 5-unit categorical increase in loudness, from 0-50 categorical units (cu).

The procedure consisted of delivering a single vibrational stimulus (1 s) to each participant at two frequencies, 1500 and 3000 Hz, chosen because they are known to convey auditory sensations only [9], [10]. The amplitude levels were calibrated using categorical loudness scaling with “Inaudible” (0 cu) and “Too loud” (50 cu) as reference points. We determined these levels with a staircase method, initially setting the bone transducer’s vibrational force to 0.6 N and incrementally increasing it by 0.05 N until the sound was rated as “Too loud”. Then, the amplitude was reduced by 0.10 N until the sound was rated “Inaudible”. If participants did not select the “Too loud” or “Inaudible” options, the vibrational force was limited between 0.2- 1 N to operate within the optimal range of the bone transducer (Fig. 1E). To obtain the loudness function for each participant, the following iterative procedure was employed.

i) **Initial Function Generation:** Using the stimulation forces at 0 and 50 cu, a linear interpolation function $F(L)$ was created to associate vibrational force L with the categorical loudness levels: “Very soft” (5 cu), “Soft” (15 cu), “Medium” (25 cu), “Loud” (35 cu), and “Very loud” (45 cu) (Fig. 1E). Variables k_{lo}, k_{hi}, and L_{cut} were initialized, with k_{lo} and k_{hi} representing the gradients of the interpolation (in cu/N), and L_{cut} representing the force associated with F(L)= 25.

ii) **Participant Ratings:** Five stimulation levels, corresponding to each loudness category (Fig.1E), were presented, and participants rated their perceived loudness using the GUI.

iii) **Updating the Function:** For each stimulation level, the perceived loudness c might differ from the function $F(L)$ prediction. Thus, the actual function $F_p(L)$ was computed using a piecewise approach:

   a) $Fp(L)=k_{lo}(L-L_{cut})+25$ for $c\leq 15$ cu
   b) $Fp(L)=k_{hi}(L-L_{cut})+25$ for $c\geq 35$ cu
   c) $Fp(L)=bezier(L,k_{lo},k_{hi},L_{cut})$ for 15 cu $< c <$35 cu

iv) **Function Refinement:** The variables k_{lo}, k_{hi}, and L_{cut} were iteratively updated by minimizing the mean squared error between the initial function F(L) and the estimated function Fp(L).

v) **Recalculation of Forces:** New stimulation forces L were calculated using the inverse function $F^{-1}(L)$ and the updated parameters, corresponding to the five intermediate loudness levels: 5, 15, 25, 35, and 45 cu.

vi) **Iteration:** Steps **ii** through **v** were repeated three times

The final function F(L), derived after three iterations, provided the best-fit loudness function for each participant. This methodology was based on the experimental procedures described in [17].

D. Statistical Analysis

For the sensation discrimination test, D50 values were grouped by sensation type and frequency across all participants. The normality and homogeneity of variances were assessed using the Kolmogorov-Smirnov and Levene tests, respectively. A one-way ANOVA was conducted to evaluate whether the D50 for one sensation was significantly lower than for the other two sensations at each frequency (α=0.05). Subsequently, post hoc comparisons were applied using the Tukey-Kramer method. The null hypothesis posited no significant differences among the sensations, while the alternative hypothesis suggested that one sensation was better perceived (lower D50) than the others [10].

For threshold perception, data from all participants were grouped by frequency (100, 400 and 750 Hz) and stimulation zone (i.e., PB and MCH). Normality and variance uniformity were confirmed using the same methodology as in the sensation discrimination test. A paired t-test was then employed to compare the minimum thresholds between the PB and MCH zones for each frequency. The null hypothesis stated no significant differences between zones, while the alternative hypothesis suggested statistically different thresholds (α=0.05).

For the loudness experiment, data were grouped by frequency (1500 Hz and 3000 Hz) and stimulation zone (PB and MCH). Normality and homogeneity of variances were assessed as before, and a paired t-test was applied to determine whether perceived loudness significantly differed by frequency or stimulation zone. The null hypothesis suggested no significant differences, while the alternative hypothesis posited that perceived loudness varied significantly. Results are presented as [mean ± standard deviation].

III. Results

A. Sensation Discrimination

Tactile D50 values were significantly lower than auditory D50 values at 100 Hz ($p<0.05$), 200 Hz ($p<0.05$), and 400 Hz for both wrist and MCH stimulation (Fig. 2). In contrast, auditory D50 values were significantly lower than tactile D50 values at 750 Hz and above, including 1500 Hz ($p<0.05$), 3000 Hz ($p<0.05$), and 6000 Hz ($p<0.05$). However, participants P01 and P12 did not perceive stimuli at 6000 Hz during wrist stimulation, and participants P02 and P12 failed to perceive stimuli at this frequency during MCH stimulation.

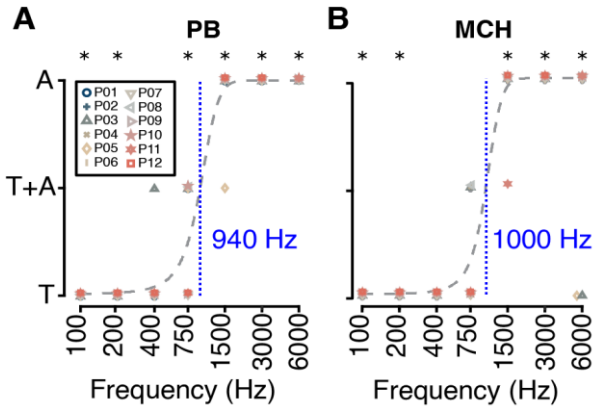

Fig. 2. Comparison of 50% of detection level (D50) for tactile (T), auditory (A), and combined tactile-auditory (T+A) sensations, measured across all participants. A) D50 values during stimulation of the PB of the wrist and (B) D50 values during stimulation of the MCH bone of the index finger. (*) Indicates statistically significant difference ($p<0.05$)

Some participants experienced combined tactile and auditory sensations. For instance, at 400 Hz, participant P03 reported both sensations during wrist stimulation, while at 750 Hz, this combined sensation was reported by participants P01, P02, P01, P02, P03, P05, P08, and P10. During MCH stimulation, combined sensations were reported by participants P01, P03, P04, and P08 at 750 Hz, and by participant P11 at 1500 Hz. Psychometric logistic functions revealed that the frequency threshold separating tactile and auditory sensations was approximately 940 Hz for wrist stimulation and 1000 Hz for MCH stimulation.

B. Perception threshold

On average, across all evaluated frequencies, the perception threshold was lower during MCH stimulation compared to wrist stimulation, although the difference is not statistically significant ($p>0.05$). The lowest average threshold was observed at 400 Hz during MCH stimulation (0.14±0.15 N), while the highest average threshold was recorded at 100 Hz during wrist stimulation (0.35±0.08 N) (see Fig. 3). At 400 Hz, the lowest perception thresholds were observed for the wrist (0.06 N, participant P08) and MCH (0.06 N, participant P06). In contrast, the highest perception thresholds were observed during wrist stimulation at 750 Hz (0.50 N, participant P05) and MCH stimulation at 100 Hz (0.51 N, participant P01).

C. Sensory map

Across all participants, the probability of detecting tactile sensations was higher during MCH stimulation than wrist stimulation (Fig. 4). At 100 Hz, the highest detection probabilities for wrist stimulation were in zones 1 (62% at 0.8 N) and 2 (38% at 0.9 N), while for MCH stimulation, zones 5 (77% at 0.4 N) and 6 (54% at 0.6 N) showed the highest probabilities (Figs. 4B, 4D). At 400 Hz, tactile sensations were perceived across additional zones compared to 100 Hz. For wrist stimulation, these included zones 3, 9, and 10, while for MCH stimulation, they expanded to zones 3, 4, 7, and 8. Furthermore, the probability of detecting tactile stimuli at lower vibration force amplitudes increased with frequency (e.g., from 100 Hz to 400 Hz), aligning with the trends observed in perception thresholds (Figs. 4C, 4E).

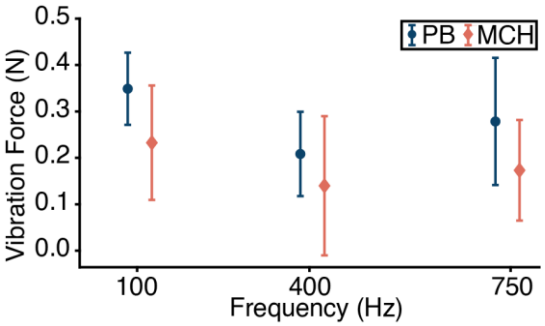

Fig. 3. Averaged perception thresholds across all participants per frequency using SAS technique. Error bars represent standard deviations.

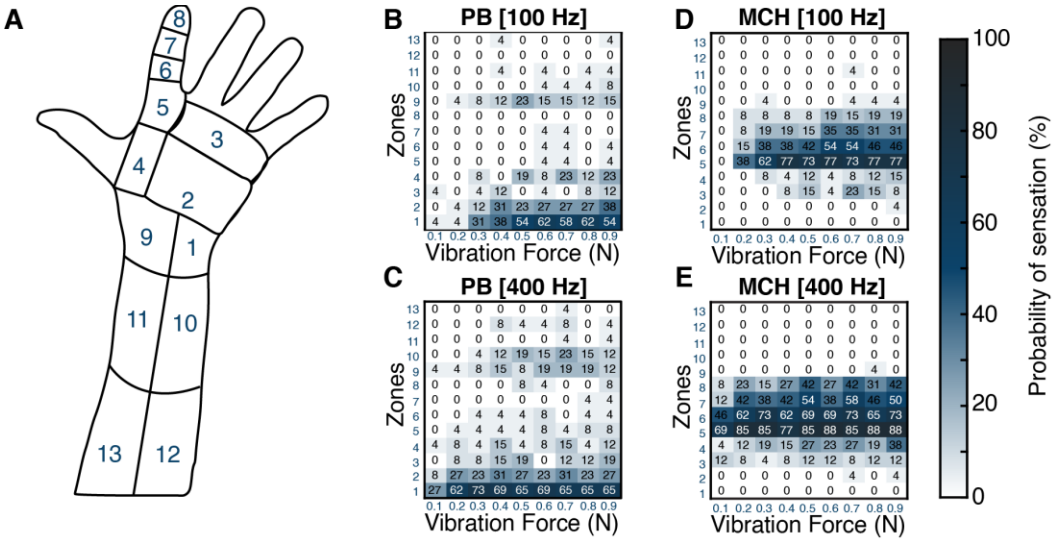

Fig. 4. (A) Reference image displayed in the GUI, showing the 13 perceptual zones that can be selected after stimulation. (B, C) Average probability of tactile perception across all participants in each zone during PB of the wrist (B) and MCH bone of the index finger (C) stimulation at 100 Hz. (D, E) Average probability of tactile perception during PB of the wrist (D) and MCH bone of the index finger (E) stimulation at 400 Hz. Results are shown for all vibration force amplitudes.

D. Loudness evaluation

The estimated loudness functions for 3000 Hz and 6000 Hz showed an approximately linear relationship between perceived loudness and stimulation force (Fig. 5). In general, higher vibration forces were required to achieve the same loudness perception at the wrist compared to the MCH. Additionally, a significant variation in vibration force (Δ) was observed between the two frequencies (3000 Hz and 6000 Hz) during wrist stimulation, indicating a frequency-dependent effect on loudness perception ($p<0.05$). However, this variation was almost null during MCH stimulation.

IV. Discussion and Conclusion

This study investigated evoking osseoperception in humans by stimulating with vibrotactile transducers two anatomical sites, i.e., the PB of the wrist and the MCH of the index finger. Four psychophysical experiments were carried out with healthy participants to assess their sensations.

All participants perceived vibrotactile sensations between 100 and 750 Hz and auditory sensations between 1500 and 3000 Hz for both PB and MCH stimulation, which is consistent with prior findings [10], [13]. However, the stimulation site influenced the threshold frequency distinguishing tactile and auditory sensations. Psychometric analysis suggested that this threshold frequency was approximately 940 Hz for PB stimulation and 1000 Hz for MCH stimulation. Previous studies reported different thresholds depending on the stimulation site: Clemente *et al.*[10] found a threshold near 309 Hz using an invasive interface on transhumeral amputees, while Mayer *et al.* reported thresholds between 400 and 750 Hz when stimulating the elbow of healthy participants [13]. These results suggest that the frequency required to evoke tactile, auditory, or combined sensations depends on the stimulation site. Furthermore, there may be a proportional relationship between the distance of the stimulation site from the mastoid bone and the required frequency, indicating that more distal sites require higher frequencies to convey auditory sensations [10]. However, further investigation is required to confirm this trend and identify its underlying mechanisms.

Our study found that the minimum perception thresholds occur during the stimulation of MCH at 400 Hz with a force of approximately 0.14 N. While Clemente *et al.* [10] reported the lowest thresholds at 100 Hz, our findings align more closely with Mayer *et al.*[13], who observed no consistent pattern in thresholds at frequencies above 200 Hz. This variability may be influenced by factors such as population sensitivity or the invasiveness of stimulation. Furthermore, the difference between the minimum thresholds during MCH and PB stimulation was not significant. This can be associated with the limited statistical power due to the sample size in this study.

Vibration strength and frequency significantly influenced the zones where tactile sensations are perceived. For instance, stimulating the pisiform bone elicited sensations around the wrist and forearm, particularly towards the ulnar side. In contrast, stimulation of the MCH produced sensations

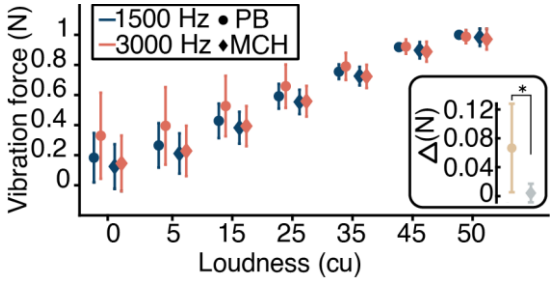

Fig. 5. Averaged loudness functions derived from the categorical loudness scaling procedure across all participants, plotted against varying vibration force and frequency for PB of the wrist and MCH bone of the index finger. (Δ) represents the difference in vibration force between frequencies, highlighting variations in categorical loudness scaling at each stimulation site. (*) indicates statistically significant differences ($p<0.05$). Error bars represent standard deviations.

extending to the carpal bones and the interphalangeal joints. These effects were intensified when the stimulation frequency was 400 Hz. Due to the rigid nature of the bone, mechanical waves, i.e., vibrations, can travel across it [18]. Consequently, these waves can stimulate the mechanoreceptors in the periosteum [9] and, possibly, the nearby innervated areas, potentially leading to sensations perceived in different regions in proximity of the bone [2], [10], [14].

The iterative scaling procedure provided accurate measures of loudness perception for each frequency. Our results suggest that higher loudness is perceived when vibration force increases, consistent with findings by Stenfelt *et al.* [17]. They found a proportional relationship between loudness and vibration force using bone transducers placed on the mastoid. However, the loudness ranges found when the transducer was placed on the mastoid were higher than those observed in this study. This can be associated with the attenuation of mechanical waves caused by the distance between the transducer and the cochlea [9]. Additionally, we observed that when the stimulation point was the PB, perceived loudness varied significantly with frequency (e.g., between 1500 Hz and 3000 Hz), which was not observed when stimulating the MCH.

To conclude, this study investigated psychophysical responses to vibrational stimuli applied to distal upper-limb bones for the first time [10], [11], [13], expanding the current understanding of osseoperception. However, it is important to note that our knowledge of osseoperception is still limited and further research is required before its clinical application. A potential limitation may be the perceivable sound generated by the mechanical waves applied by the transducers during auditory tests, particularly pronounced at high stimulation forces. Although measures were taken to minimize this effect—such as verifying the transducer's range and equipping participants with earplugs and noise-canceling headphones—sounds exceeding 35 dB are sometimes generated, possibly influencing psychophysical responses [10], [11], [13]. Future studies should implement stricter noise isolation measures or alternative calibration methods to enhance reliability of auditory perception data. Additionally, the relatively small sample size and the limited age range of participants may restrict the generalizability of our findings. Future approaches should include a more diverse sample to better understand individual differences and their impact on osseoperception.

The findings of this work indicate that the MCH region is more effective for eliciting tactile sensations, as evidenced by lower perception thresholds and more distinct sensory maps. In contrast, the wrist showed greater efficacy for auditory sensations, as shown by results from the sensation discrimination experiment and loudness scaling. These differences may be attributed to anatomical and physiological factors: the high density of mechanoreceptors in the hand likely contributes to the superior tactile sensitivity in the MCH [2], [10], [14], while the wrist's proximity to the cochlea may justify enhanced auditory perception [10], [18]. These findings emphasize the importance of both the stimulation site and frequency on the phenomenon of osseoperception. We aim at conducting other studies involving both healthy individuals and people with neuromotor impairments, focusing on functional tasks and possibly exploring its application to deliver augmented sensory feedback in assistive devices. This will allow us to explore the potential of osseoperception for enhancing tactile and auditory perception, and eventually extending the reach of assistive technologies.

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