

> REPLACE THIS LINE WITH YOUR MANUSCRIPT ID NUMBER (DOUBLE-CLICK HERE TO EDIT) <

Psychophysical Characterization of Osseoperception Across Upper-Limb Bony Landmarks

Cristian Felipe Blanco-Diaz, *Graduate Student Member, IEEE*, Leonardo Cappello, *Senior Member, IEEE*, and Strahinja Dosen, *Member, IEEE*

Abstract— Somatosensory feedback is essential for fine motor control, yet it remains a challenge to restore it in assistive technologies such as prostheses or exoskeletons. This study investigates osseoperception—the perception of vibrotactile and auditory sensations through bone conduction—a feedback approach that has unique advantages but is rarely considered in literature. We have systematically assessed the psychometric properties of this method across four anatomical sites: the pisiform bone (PB) at the wrist, the olecranon (OL) at the elbow, the clavicle (CL) at the shoulder, and the mastoid process (MP) at the head. Twelve healthy participants underwent four psychophysical experiments to assess sensation discrimination, perception thresholds (PTs), and just-noticeable differences (JNDs) for amplitude and frequency. All tests have been performed at three frequencies (low, medium and high), except for JND, which was determined at two frequencies (low and high). Vibrotactile sensations predominated at low frequencies, whereas auditory sensations emerged at higher frequencies. PB and OL exhibited similar psychometric responses, mostly eliciting vibrations and mixed vibro-auditory sensations, while CL showed responses more comparable to MP, including a higher probability of occurrence of mixed and auditory sensations. PT showed significant differences, whereas JND did not differ significantly across the three upper limb landmarks (PB, OL and CL). Overall, these findings demonstrate that multiple upper-limb bony landmarks can reliably evoke osseoperceptive sensations, supporting their potential use as a single-channel multimodal feedback interface in assistive technologies, both wearable and implantable. The present study shows that there is flexibility in the placement of the bone transducer, which can be chosen based on the requirements of a specific application (e.g., OL for transradial amputation, and CL for transhumeral amputations)

Index Terms— Assistive technologies, Bones, Haptic interfaces, Osseoperception, Prosthetics, Vibrational Signal

This work was supported by INAIL (the Italian National Workers' Compensation) through projects HANDeVAL Project under Grant PR23-SV-P1 and DexterHand. The work of L. Cappello was co-funded by the European Union (ERC, MUSE, G.A. 101116249). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Council. Neither the European Union nor the granting authority can be held responsible for them. The work of S. Dosen was supported by the DexterHand project, funded by INAIL (L. Cappello and S. Dosen contributed equally to this work.) (Corresponding author C.F. Blanco-Diaz).

C.F. Blanco-Diaz and L. Cappello are with the BioRobotics Institute, Scuola Superiore Sant'Anna, Pisa, Italy, and with the Department of Excellence in Robotics and AI, The BioRobotics Institute, Scuola Superiore Sant'Anna, Pisa, Italy (e-mail: [cristianfelipe.blancodiaz; leonardo.cappello]@santannapisa.it). S. Dosen is with the Department of Health, Science, and Technology, Aalborg University, Aalborg, Denmark (e-mail: sdosen@hst.aau.dk)

I. INTRODUCTION

LOSS of sensorimotor function due to neurological disorders, nerve injury, or amputation severely affects daily motor activity [1]. Sensory feedback is essential for motor control, not only for implementing continuous adjustment in response to immediate errors, but also for facilitating the learning and maintenance of internal models, which are essential for state estimation and feedforward control within the central nervous system [2], [3]. In prosthetic and assistive devices, the absence of haptic feedback prevents users from closing the sensorimotor control loop, leading to degraded performance and reduced sense of embodiment [4].

To compensate for the loss of natural feedback, users of upper-limb prosthetic or assistive devices often rely on incidental cues such as visual observation or the sound of motors to estimate contact or applied force [4]. While these strategies can improve control, they are also cognitively demanding and unintuitive. Consequently, artificial or augmented sensory feedback systems have been developed to restore the missing sensory information and re-establish a functional sensorimotor loop [5]. These systems provide real-time feedback related to grip force, object contact, or joint angle, by stimulating the skin of the residual limb using vibrotactile, electrotactile, or mechanotactile stimulation [1], [6]. Feedback can also be provided using invasive approaches, in which electrical current is delivered directly to the peripheral nerve or brain using implanted electrodes [7], [8]. The latter approaches are rather promising, as they can elicit sensations that feel as if they come from the missing limb (somatotopic feedback); however, they require surgery and are, therefore, more challenging to translate clinically.

A persistent challenge in providing artificial sensory feedback is the limited amount of information that can be effectively conveyed through haptic stimulation. To enhance intuitiveness and encoding capacity, many systems employ arrays of vibrotactile actuators or electrotactile electrodes to convey richer or more spatially distributed information [9], [10]. Another approach to expand the sensory bandwidth is to implement multimodal feedback approaches by combining different stimulation methods, such as vibrotactile, electrotactile, mechanotactile or auditory cues, into one composite haptic interface capable of providing complementary information, sequentially and simultaneously [11], [12], [13], [14].

> REPLACE THIS LINE WITH YOUR MANUSCRIPT ID NUMBER (DOUBLE-CLICK HERE TO EDIT) <

Bone conduction offers a promising alternative for providing multimodal artificial sensory feedback in a more compact form (compared to the aforementioned multimodal and multichannel interfaces). When mechanical vibrations are transmitted through the bone, they can elicit vibrotactile sensations via the stimulation of mechanoreceptors, or auditory sensations, generated by vibrations propagating through the bones, eventually reaching and stimulating the cochlea [15]. This phenomenon, known as osseoperception, was originally observed in individuals with bone-anchored hearing aids, and was subsequently extended to amputees with osseointegrated implants [16], [17]. Importantly, osseoperception enables dual sensory pathways—tactile and auditory—to be activated using a single transducer, offering the potential for compact, lightweight, and multimodal feedback solutions.

Previous studies have explored osseoperception when bone transducers are placed in both invasive and non-invasive settings [17], [18], [19]. Invasive approaches typically involve bone transducers attached to osseointegrated abutments in transhumeral amputees, in which participants report sensations of sound, vibration, and mixed sensations in response to bone stimulation [17]. Non-invasive tests have placed transducers on bony prominences of the wrist, elbow, or fingers, demonstrating that both vibrotactile and auditory sensations can also be elicited in healthy participants [18], [19]. For instance, we demonstrated that osseoperceptive stimulation applied to the wrist can convey multimodal haptic feedback corresponding to the object contact and grip force of a robotic hand, thereby enhancing myoelectric control [20]. Similar findings were reported when stimulation was applied to the elbow to provide information in virtual tasks, showing that participants could discriminate the vibration intensity and frequency through the bone [18]. Recently, [21] characterized perception thresholds and discrimination of non-invasive bone-conduction feedback at multiple elbow landmarks in both able-bodied individuals and participants with transradial amputation provided further insight into the psychophysical characteristics of bone-conducted stimulation. However, these studies have typically focused on a single anatomical site and did not include systematic psychometric characterization across the same subject pool, limiting the understanding of how osseoperception varies across the upper limb.

A fundamental open question concerns how frequency, amplitude, and anatomical site interact to determine whether a stimulus is perceived as vibrotactile, auditory, or both, and how this affects the subject's ability to detect stimulation and discriminate changes in its parameters. Because bone geometry, thickness, and proximity to the cochlea differ substantially across upper-limb segments, it is plausible that the fundamental psychometric parameters that characterize the intrinsic capacity of the feedback can vary accordingly [15], [17], [19], [22]. Furthermore, it remains unclear whether specific bones are more suited to evoking one type of sensation over another, which is essential for designing feedback systems that leverage these properties effectively.

Therefore, in the present study, we investigated

osseoperception across four anatomical sites, from most distal to most proximal to the cochlea: the pisiform bone (PB) at the wrist, olecranon (OL) at the elbow, the clavicle (CL) at the shoulder, and mastoid process (MP) at the skull. The MP was included as a reference point, representing the canonical case of bone-conducted auditory perception [22]. Through four psychophysical experiments, we evaluated the type of sensation (vibrotactile, auditory, or mixed) elicited at different stimulation frequencies and amplitudes, and measured perception thresholds (PTs) and just-noticeable differences (JNDs) for both amplitude and frequency.

To the best of our knowledge, this is the first study to provide a systematic, multi-site comparison of osseoperception across the upper limb in non-disabled participants. By mapping perceptual sensitivity and sensation types across frequencies and anatomical locations, this work aims to expand our understanding of osseoperception and to inform the design of more intuitive, multimodal sensory feedback systems for upper-limb prosthetics and exoskeletons.

II. MATERIAL AND METHODS

A. Participants

Twelve healthy participants (aged between 22 and 32 years; 8 male and 4 female volunteers) were recruited for this study. The participants did not have any self-reported history of neurological disorders, upper-limb musculoskeletal or sensory impairments, or hearing impairments. All participants provided informed consent prior to enrollment. The experimental protocol was approved by the Ethics Committees of the Nordjylland region (Approval No. N-20250021) and Scuola Superiore Sant'Anna (Approval No. 10/2023) and conducted in accordance with the Declaration of Helsinki.

During testing, the participants were seated comfortably in front of a computer and received standardized instructions before each session. The participants wore earplugs (35.5 dB; Tokelu, GE) and active noise-cancelling headphones (WH-700N; Sony, USA) delivering a low-level white noise background. These measures were implemented to minimize external auditory interference, ensuring that osseoperceptive responses were not influenced by airborne sound cues [17], [18], [19]. The assumption is that such blocking will not be required in actual clinical applications, because the bone-conduction transducers will be integrated within the prosthesis socket and/or exoskeleton structure, which will effectively dampen airborne sound transmission. All 12 participants completed the full experimental protocol, which included all anatomical sites and stimulation conditions. No trials were excluded because of technical issues or incomplete data acquisition.

B. Experimental Setup

The experimental setup (Fig. 1A) included a Personal Computer (PC), function generator, audio amplifier and B-81 bone conduction transducer. This design was inspired by previous studies [17], [18], [19], [23]. A Graphical User Interface (GUI) was developed in MATLAB (2022b,

> REPLACE THIS LINE WITH YOUR MANUSCRIPT ID NUMBER (DOUBLE-CLICK HERE TO EDIT) <

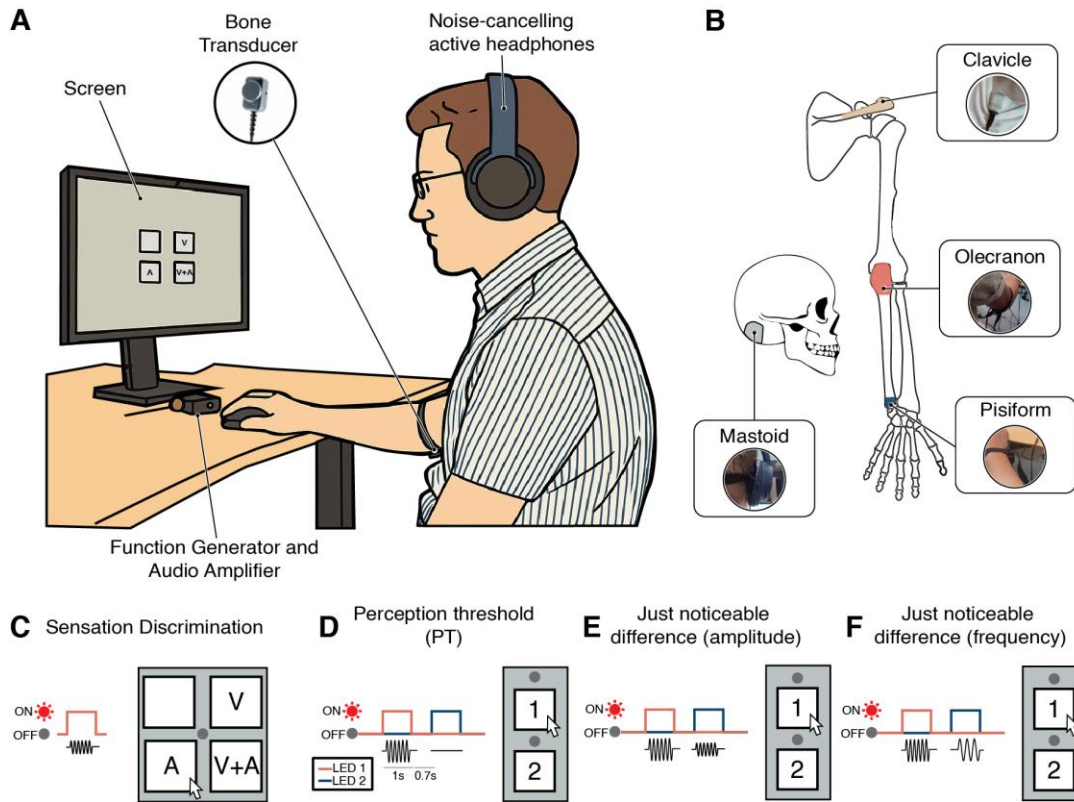


Fig. 1. (A) Setup showing the PC running the GUI connected to the function generator, audio amplifier, and bone transducer. (B) Placement of the bone transducer at four bony landmarks: Pisiform Bone (PB), Olecranon (OL), Clavicle (CL), and Mastoid Process (MP). Timing of stimulation and user interface (gray background) for the four psychophysical experiments performed by the participants: (C) Sensation discrimination, (D) Perception threshold, (E) Amplitude just-noticeable difference and (F) frequency just-noticeable difference tests. The tests are explained in detail in the text.

Mathworks, US) to adaptively set simulation amplitudes and frequencies while recording user responses. The bone transducer was driven by an ESP32 microcontroller (Espressif Systems, CN) that delivered sinusoidal signals via a digital-to-analog converter (DAC). The frequency and amplitude were programmable within the 0.1–10 kHz range. To ensure signal compatibility with standard audio playback devices, the sinusoidal waveform was amplified using an LM386 audio amplifier (Texas Instruments, US) before being delivered to the bone transducer (B-81, Radioear, US) [20]. Prior to testing, the transducer output was calibrated using an artificial mastoid (Model 4930, Brüel & Kjær, Denmark) to ensure accuracy in amplitude and frequency [23].

In the present experiment, the bone transducer was positioned on four bony landmarks associated with the upper limb joints and head: the pisiform bone (PB) at the wrist, olecranon (OL) at the elbow, clavicle (CL) at the shoulder, and mastoid process (MP) at the skull. The bone transducer was placed at the PB, OL, and MP using a 3D-printed support and secured with adjustable elastic bands and Velcro straps to ensure stability [19]. The flat surface of the bone transducer was in direct contact with the target bone. The placement procedure aimed to achieve a contact force in the range of 3–5 N, which is consistent with previous osseoperception studies [18], [19].

Owing to anatomical constraints at the CL, the custom fixation structure used at the other landmarks could not be

reliably positioned. Therefore, the transducer was secured using medical-grade elastic tape (3 M, US), covered by cohesive elastic bandage (Comomed, IT), following a fixation approach previously reported [18]. The procedure targeted the contact force between 3 and 5 N, consistent with the remaining anatomical landmarks; however, this force was not directly measured during the experiment nor continuously monitored across trials for any of the landmarks and should therefore be interpreted as an estimated range rather than a precisely controlled value. Furthermore, the order of the four anatomical landmarks (PB, OL, CL, and MP) was pseudorandomized across participants, such that each participant experienced a different presentation sequence to reduce potential order and fatigue effects.

C. Psychophysical experiments

1) Sensation type

This experiment assessed the type of sensation perceived when varying the amplitude and frequency of bone-conducted stimulation. A single stimulus (1 s) was delivered in each trial, and participants were asked to classify the perceived sensation by selecting one of four options on the GUI: vibrotactile (V), auditory (A), both simultaneously (V + A), or no perceived sensation (Fig. 1C).

Stimulation frequencies were selected from three values, 293, 349, and 440 Hz, which fall within the range commonly

> REPLACE THIS LINE WITH YOUR MANUSCRIPT ID NUMBER (DOUBLE-CLICK HERE TO EDIT) <

investigated in osseoperception studies because they correspond to perceptually distinct frequency bands [17]. Stimulation amplitudes were chosen from nine values equidistantly distributed across the entire output range of the transducer (0-1 N vibrational force). Each combination of frequency and amplitude was repeated twice, and the combinations were presented in random order, resulting in 54 trials per participant (3 frequencies $\times$ 9 amplitudes $\times$ 2 trials).

For the data analysis, we followed an approach similar to that used in [17], [19]. Responses were first organized separately for each participant, anatomical site, stimulation frequency, and amplitude. Because each frequency–amplitude combination was presented twice, the response at each amplitude was first expressed as the proportion of trials assigned to each perceptual category (0, 0.5, or 1). These proportions were then summed across the nine stimulation amplitudes for each participant, anatomical site, and frequency. Thus, each participant-level probability estimate for a given anatomical site and stimulation frequency was based on responses from up to 18 trials (9 amplitudes $\times$ two repetitions), with trials classified as "no sensation" excluded from the denominator.

Final modality probabilities were obtained by dividing the summed proportion for each perceptual category (V, A, or V+A) by the total summed proportions across all perceived sensations, excluding "no sensation" responses from the denominator. Consequently, each participant contributed one probability estimate per perceptual modality for every anatomical site $\times$ stimulation frequency combination, and these participant-level probabilities were used in repeated-measures statistical analyses.

2) Perception Threshold (PT)

The amplitude perception threshold (i.e., the minimum stimulus amplitude detectable by each participant) was measured at the same stimulation frequencies as those used in the sensation discrimination experiment [18]. A standard two-interval forced-choice (2IFC) paradigm was used (Fig. 1C). Each trial comprised two 1 s stimulus intervals separated by a 0.7 s interstimulus interval. This timing was adopted from previous osseoperception studies employing comparable psychophysical procedures, in which the same stimulus duration and interstimulus interval were used successfully [17], [19], [21]. The vibrotactile stimulus was presented in one of two intervals selected randomly, whereas the bone transducer remained inactive during the other interval (null, no-stimulation condition). The participants were instructed to indicate which interval contained the stimulus.

The vibration amplitude in each trial was controlled by a stochastic-approximation staircase (SAS) algorithm implementing an adaptive step-size rule:

$$A_{n+1} = A_n - \frac{c}{2+m}(Z_n - \phi) \quad (1)$$

where A_n is the stimulus amplitude at trial n , c is a subject-specific scaling constant estimated from a preliminary method-of-limits procedure comprising two ascending and two

descending series, m is the number of reversals, $Z_n = 1$ for a correct response, $Z_n = 0$ for an incorrect response, $\phi = 0.85$ is the target detection probability [17], [19]. Accordingly, the stimulus amplitude decreased following the correct responses and increased following the incorrect responses, with the step size progressively decreasing as the number of reversals increased. Therefore, the staircase was designed to converge to the stimulus amplitude corresponding to an 85% correct response probability in the 2IFC task [17].

Each staircase ran independently for each frequency and was terminated after 50 trials or once seven reversals were reached, whichever occurred first [24]. The maximum of 50 trials was selected a priori based on standard psychophysical staircase procedures, which typically yield stable threshold estimates within this range [17], [18], [24]. The reversal was defined as an incorrect response following a correct response or vice versa.

The perception threshold was defined as the predicted amplitude for the 51st trial, or—if convergence occurred earlier—as the oscillation point estimated from the last seven reversals. The oscillation point is computed as the average of the amplitudes of the seven reversals [24].

3) Just Noticeable Difference (JND) in amplitude

JND is defined as the minimum change in a stimulation parameter that a participant can detect. A lower JND indicates higher sensitivity to changes, and hence, a potentially higher resolution of the feedback. The JND stimulation amplitude was measured using a 2IFC paradigm, following a procedure analogous to that used in the PT experiment. To reduce the experimental duration and participant fatigue, only two stimulation frequencies (293 and 440 Hz) were tested. These frequencies were selected to sample two perceptual regimes predicted by bone-conduction theory: lower frequencies tend to produce predominantly vibrotactile percepts (e.g., <400 Hz), whereas sufficiently high frequencies ($\geq \sim 400$ Hz) increasingly evoke auditory percepts [17], [18]. Accordingly, 293 Hz was chosen to sample the presumed vibrotactile-biased region and 440 Hz to sample the auditory-biased region.

Each trial comprised two consecutive 1 s intervals separated by a 0.7 s pause. One interval contained a reference stimulus with an amplitude equal to $1.5 \times$ the participant's PT, whereas the other contained a test stimulus with the amplitude adjusted based on the participant's response; the order of the two stimuli was randomized. The participants were instructed to indicate which stimulus was perceived as more intense. For vibrotactile sensations, intensity was defined as the vibration strength, and for auditory sensations, as perceived loudness [19], [22]. The SAS procedure (Equation 1), including the adaptive step-size rule, stopping criteria, and threshold estimation from the oscillation point, was identical to that used in the PT experiment (see the previous section). The JND was computed as the difference between the oscillation point and the reference stimulus, and expressed as a percentage of the reference.

4) JND in frequency

The JND in vibration frequency was measured using the

> REPLACE THIS LINE WITH YOUR MANUSCRIPT ID NUMBER (DOUBLE-CLICK HERE TO EDIT) <

same procedure as for the JND in amplitude; however, in this case, the test stimulus changed the frequency. Both test and reference stimuli were delivered at an amplitude of $1.5 \times$ the participant's PT. The JND was measured at two frequencies (293 Hz and 440 Hz). The reference stimulus was delivered at the reference frequency (293 or 440 Hz), whereas the frequency of the test stimulus was adjusted based on the participants' responses. For the assessment of JND at 293 Hz, the test stimulus was initially set to $1.5 \times$ the reference value (≈ 440 Hz), whereas for the 440 Hz condition, it was initialized to $0.5 \times$ the reference frequency (≈ 220 Hz). The participants were instructed to indicate which of the two stimuli had a higher frequency. For vibrotactile stimuli, a higher frequency corresponded to a higher vibration velocity, whereas for auditory stimuli, it corresponded to a higher perceived pitch. [19], [22]. The other procedures were identical to those used to assess the JND amplitude.

D. Statistical Analysis

For sensation discrimination analyses, participant-level modality probabilities were used for the statistical analyses. The normality of the data distributions was assessed using the Lilliefors test. As the assumption of normality was not satisfied, nonparametric statistical methods were used. For each sensation type (V, A, and V+A), a rank-based repeated-measures analysis of variance was performed to assess the main effects of anatomical landmark and stimulation frequency, as well as their interaction. When significant effects were observed, post-hoc pairwise comparisons were conducted using Wilcoxon signed-rank tests with Bonferroni correction for multiple comparisons.

To identify the predominant sensation at each anatomical landmark, probability values were subsequently averaged across both stimulation amplitudes and frequencies, yielding one probability value per participant and landmark for each sensation category. For each anatomical landmark, the probabilities of the three sensation categories (vibrotactile, auditory, and mixed) were compared using Friedman's test. When significant effects were detected, Bonferroni-corrected Wilcoxon signed-rank tests were performed for post-hoc pairwise comparisons between the sensation categories.

For the PT and JND experiments, the data were grouped by the stimulation frequency and anatomical landmarks for each participant. Normality was again assessed using the Lilliefors test and, because the distributions were non-normal, nonparametric repeated-measures analysis of variance and Bonferroni-corrected Wilcoxon signed-rank tests were used for the statistical analyses.

Bayes factors (BF_{10}) were additionally computed for pairwise comparisons to quantify evidence supporting the alternative hypothesis relative to the null hypothesis. For simplicity, the Bayes factors are reported as BF throughout the manuscript.

To double-check the validity of the obtained JNDs, one-sample Wilcoxon signed-rank tests were performed to determine whether the estimated JNDs were significantly different from zero.

A priori power analysis was performed using G*Power 3

(repeated-measures ANOVA, within-subject factors). The analysis was based on the primary outcome of the study, namely the comparison of osseoperceptive responses across the four anatomical landmarks (PB, OL, CL, and MP), which constituted four repeated measurements per participant. A medium-to-large effect size (Cohen's $f = 0.40$) was assumed based on the magnitudes of the effect observed in our previous psychophysical study investigating osseoperception at the wrist [19]. Assuming a significance level of $\alpha = 0.05$ and a desired statistical power of 0.90, the estimated sample size was 12 participants [25]. All results are reported as median {interquartile range, IQR}.

III. RESULTS

A. Sensation Discrimination (SD)

The probabilities of perceiving vibrotactile, auditory, or mixed sensations were assessed across the amplitudes and frequencies of the bone transducer for each bony landmark (Fig. 2, blue bars vs. gray and brown bars). Overall, vibrotactile sensations were most frequently reported in the PB and OL, whereas auditory and mixed sensations were predominantly perceived in the MP and CL, respectively. Higher frequencies and amplitudes tend to increase the perception of mixed sensations, particularly at 440 Hz. No-sensation responses were infrequent overall (8.7% of all trials; PB: 2.08%, OL: 4.17%, CL: 2.43%, MP: 0%) and were excluded from the modality analyses, as explained in Methods section.

A significant main effect of bony landmarks was observed for vibrotactile sensations ($p = 0.031$), whereas neither the frequency ($p = 0.083$) nor the landmark $\times$ frequency interaction ($p = 0.095$) reached significance. Overall, vibrotactile sensations were significantly more probable in PB and OL than in CL and MP across the tested frequencies in most cases (Fig. 3A, Supplementary Table S1). The overall median and IQR were 0.31 {0.32} and 0.38 {0.21} for PB and OL vs. 0 {0.10} and 0 {0} for CL and MP, respectively.

For auditory sensations, significant main effects of landmark ($p = 0.014$) and frequency ($p = 0.009$) as well as a significant landmark $\times$ frequency interaction ($p = 0.014$) were observed. The probability of auditory perception was consistently the highest at the MP across all frequencies, with overall median and IQR of 0.97 {0.21} (Fig. 3B). It was significantly higher than that in PB (0 {0.07}), OL (0 {0.15}), and CL (0.04 {0.29}) in all cases, except for CL (0.20 {0.51}) at the highest frequency (Supplementary Table S1). Within each landmark, auditory probabilities generally increased with frequency, with statistically significant changes observed in OL between 349 Hz and 440 Hz ($p=0.026$, $BF = 1.69$), and in CL pairwise between all three frequencies ($p<0.001$, $BF=1.58$, $p=0.034$, $BF=1.45$).

For mixed sensations, a significant main effect of landmarks was observed ($p = 0.024$), whereas neither the frequency ($p = 0.090$) nor the interaction term ($p = 0.078$) reached significance. Mixed sensations were most likely at CL across frequencies, with an overall median and IQR of 0.89 {0.13} (Fig. 3C). Post-hoc comparisons revealed that the mixed-sensation probability at the CL was significantly higher than that at the MP across conditions (Supplementary Table S1).

> REPLACE THIS LINE WITH YOUR MANUSCRIPT ID NUMBER (DOUBLE-CLICK HERE TO EDIT) <

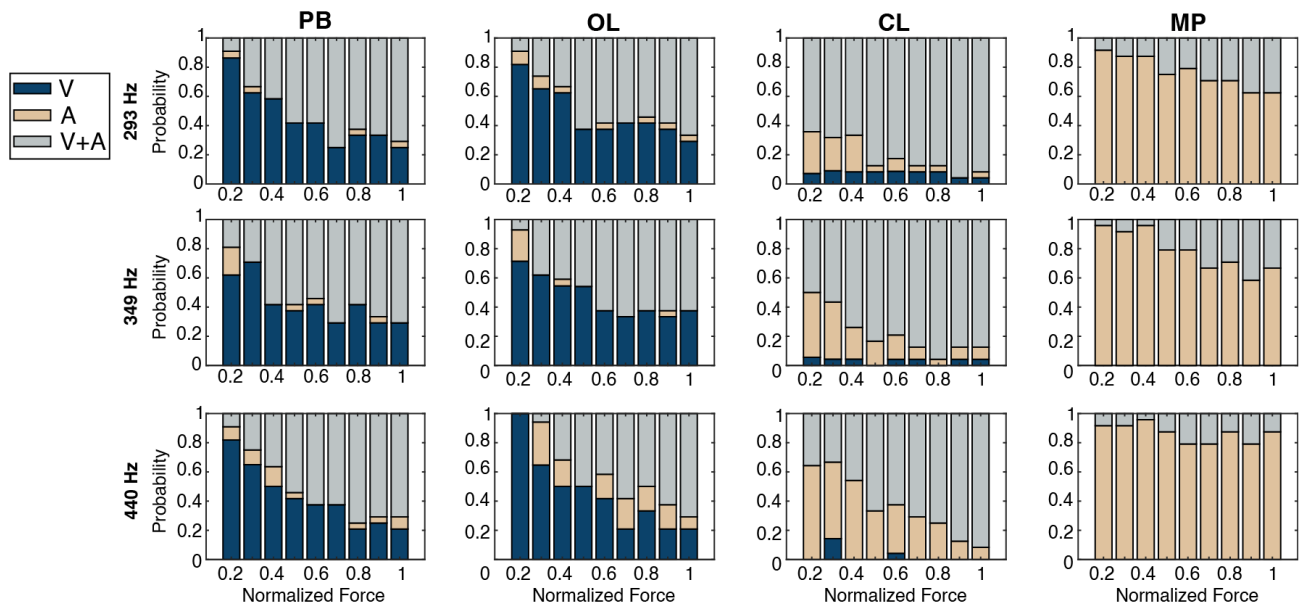


Fig. 2. Group-averaged probabilities of perceived sensations as a function of stimulation amplitude and frequency at four anatomical sites (PB: pisiform bone; OL: olecranon; CL: clavicle; MP: mastoid process). Sensation types: V = vibrotactile, A = auditory, V+A = mixed.

When modality probabilities were analyzed within each landmark, distinct perceptual profiles emerged across the four anatomical landmarks (Fig. 4, $p < 0.001$).

PB and OL exhibited the same pattern, where vibrotactile (PB: 0.38 {0.29}, OL: 0.37 {0.40}) and mixed sensations (PB: 0.59 {0.31}, OL: 0.49 {0.31}) were not significantly different, whereas they were significantly more probable than auditory sensations (PB: 0.01 {0.05}; $p < 0.001$, OL: 0.03 {0.14}, $p < 0.001$).

At CL, mixed sensations predominated (0.84 {0.38}), showing significantly higher probabilities than both auditory (0.09 {0.31}; $p < 0.001$) and vibrotactile sensations (0.02 {0.08}; $p < 0.001$). Furthermore, auditory sensations were significantly more probable than vibrotactile sensations ($p = 0.046$). In contrast, in the MP, auditory sensations predominated (0.94 {0.26}) and were significantly more probable than both vibrotactile (0 {0}; $p < 0.001$) and mixed sensations (0.06 {0.26}; $p < 0.001$). Mixed sensations were also significantly more probable than vibrotactile sensations ($p = 0.024$).

Taken together, perceptual outcomes were strongly dependent on anatomical landmarks, revealing distinct modality-specific profiles: PB and OL predominantly elicited vibrotactile sensations, MP predominantly elicited auditory sensations, and CL predominantly elicited mixed sensations. Frequency had a comparatively smaller influence, primarily modulating auditory perception.

B. Psychometric parameters

Figure 5 shows the staircase trajectories for one representative participant obtained when measuring the PT (Fig. 5A), amplitude JND (Fig. 5B), and frequency JND (Fig. 5C). At the beginning of each staircase, the participant consistently identified the comparison stimulus correctly, because the initial amplitude or frequency differences were large. As the stimulus level approached the baseline, participants' responses became less reliable, producing the expected sequence of reversals around the decision boundary. For this participant, the estimated PT was 0.10 N (Fig. 5A), the amplitude of JND relative to a 0.13 N reference was 69%

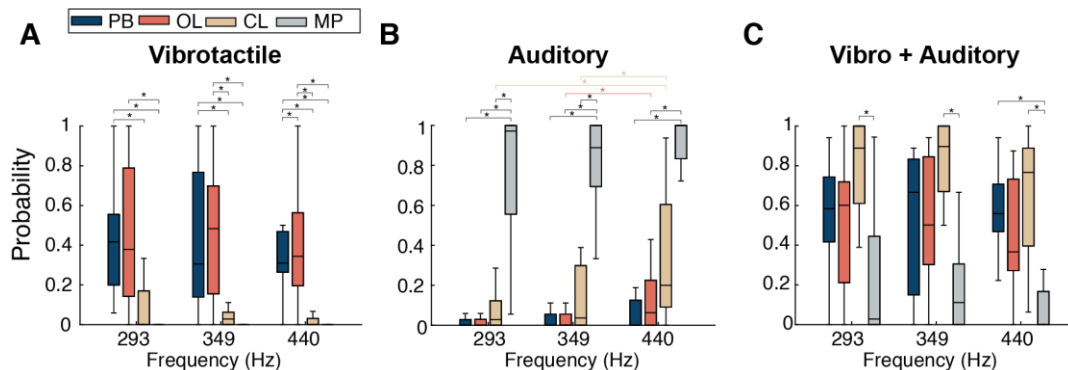


Fig. 3. Perceptual response probabilities across frequencies and segments for each sensory modality: (A) Vibrotactile, (B) Auditory, and (C) Vibrotactile + Auditory. Each boxplot shows the median (black line) and interquartile range. Asterisks (*) indicate statistically significant differences between conditions ($p < 0.05$).

> REPLACE THIS LINE WITH YOUR MANUSCRIPT ID NUMBER (DOUBLE-CLICK HERE TO EDIT) <

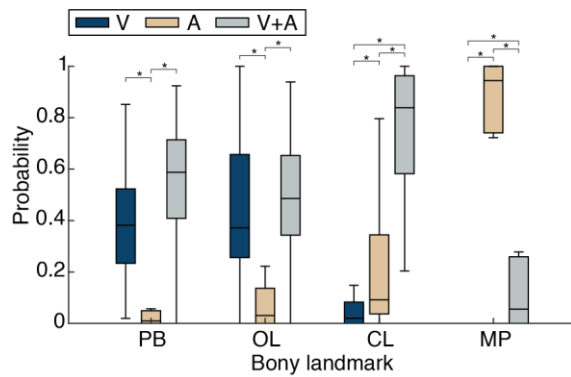


Fig. 4. Perceptual response probabilities for each bony landmark. Each boxplot shows the median (black line) and interquartile range. Asterisks (*) indicate statistically significant differences between conditions ($p < 0.05$).

(Fig. 6B), and the frequency JND relative to a 440 Hz reference was 11.6% (Fig. 5C). The mean and standard deviation of the number of trials required to reach convergence in the PT and JND procedures were 42.53 ± 7.53 .

B.1. Perception threshold

For PT, significant main effects of landmark ($p = 0.004$) and frequency ($p = 0.006$), as well as a significant landmark $\times$ frequency interaction ($p < 0.001$), were observed. Overall, the perception thresholds at the MP (overall median and IQR: 0.01 N {0.03}) were significantly lower than those at the OL (0.11 N {0.06}), CL (0.07 N {0.05}), and PB (0.07 N {0.03}) across all tested frequencies (Fig. 6A, Supplementary Table S2). There were no significant differences among PB, OL and CL.

Interestingly, perception thresholds tended to increase with frequency across bony landmarks. At PB, the thresholds increased significantly across all frequencies. In OL, significant increases were observed between 293 and 349 Hz, and between 293 and 440 Hz. At the CL and MP, significant differences were found only between 293 and 440 Hz (Fig. 6A).

Overall, perception thresholds were primarily determined by anatomical location, with the MP showing the highest sensitivity to bone-conducted stimulation as reflected by the lowest thresholds across frequencies. Thresholds were higher and comparable across the PB, OL, and CL, indicating distinct sensitivity differences

between the mastoid and these landmarks. Increasing the frequency generally elevated perception thresholds, although the magnitude of this effect depended on the stimulation site.

B.2. Just noticeable difference (JND)

For JND amplitude, no significant main effects of landmark ($p = 0.512$), frequency ($p = 0.093$), or landmark $\times$ frequency interaction ($p = 0.264$) were observed (Fig. 6B, Supplementary Table S3). The overall median and interquartile range were 45% {22%} for PB, 48% {36%} for OL, 50% {50%} for CL, and 48% {46%} for MP (Fig. 6B). Furthermore, all amplitude JND values were significantly greater than zero ($p < 0.001$).

For the frequency JND, no significant main effects of landmark ($p = 0.512$), frequency ($p = 0.093$), or landmark $\times$ frequency interaction ($p = 0.264$) were observed (Fig. 6C). The overall median and interquartile ranges were 47% {18%}, 37% {39%}, 33% {43%}, and 27% {25%} for PB, OL, CL, and MP, respectively. Likewise, all the frequency JND values were significantly greater than zero (all $p < 0.001$).

Overall, the discrimination ability for both amplitude and frequency was comparable across anatomical sites, suggesting broadly similar resolution of bone-conducted stimuli across landmarks despite differences in the perceived modalities of sensation.

IV. DISCUSSION AND CONCLUSIONS

This study investigated osseoperception in healthy participants by applying vibrotactile stimulation to four anatomical sites along the upper limb and head: the pisiform bone (PB), olecranon (OL), clavicle (CL), and mastoid process (MP). Four psychophysical experiments—sensation discrimination, perception threshold (PT), and just-noticeable difference (JND) in amplitude and frequency—were used to characterize the influence of frequency, amplitude, and anatomical location on the perception of bone-conducted stimuli to inform the design of better osseoperceptive feedback.

A. Frequency- and site-dependent sensation modalities

The probability of perceiving a specific sensory modality systematically shifted across bony landmarks of the upper limb (Supplementary Table S1). Distal sites, such as the PB and OL, predominantly evoke vibrotactile sensations. In contrast, more

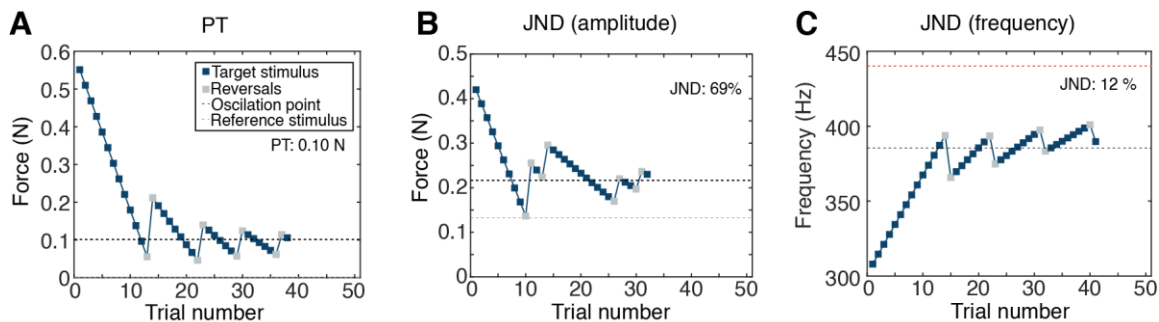


Fig. 5. Illustrative examples from one repetition of the experiment with each of the three two-interval forced-choice experiments (A: PT; B: JND in amplitude; C: JND in frequency) for one representative subject. Each panel shows trial-to-trial variations for a tested parameter measured across the 50 trials. The dashed black line indicates the oscillation level estimated by averaging parameter values at reversal points, while dashed red line indicates the reference stimulus.

> REPLACE THIS LINE WITH YOUR MANUSCRIPT ID NUMBER (DOUBLE-CLICK HERE TO EDIT) <

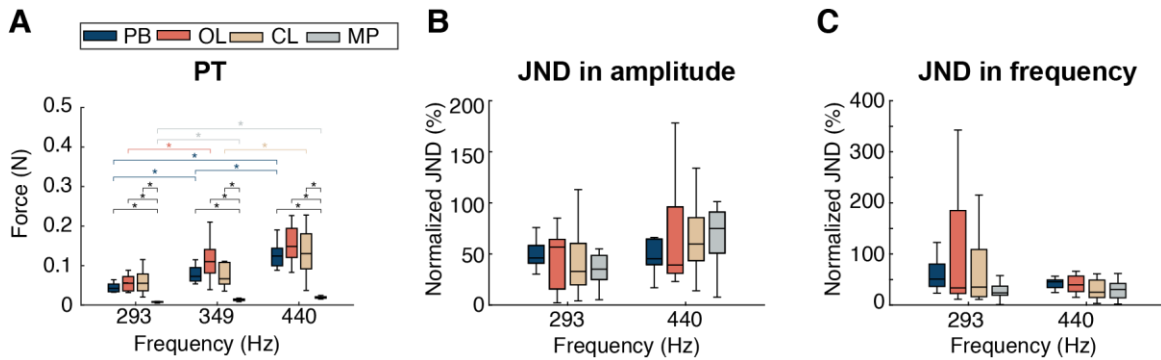


Fig. 6. Psychophysical thresholds across four anatomical sites. (A) Perception thresholds, (B) JND in amplitude, (C) JND in frequency. Boxes represent the interquartile range; black lines indicate medians. Asterisks (*) indicate statistically significant differences between sites ($p < 0.05$).

proximal sites, including the CL and MP, showed a gradual transition from mixed (vibrotactile + auditory) to predominantly auditory sensations (Fig. 2). This pattern highlights clear distal-to-proximal modulation of osseoperceptive responses across the upper limb.

Vibrotactile sensations were most frequently reported at the PB and OL, with both sites showing significantly higher probabilities than the CL and MP (Fig. 3A). Two factors could explain this pattern. First, the distance between these sites and the cochlea affects transmission: longer propagation paths through the skeletal structure likely attenuate and distort high-frequency components, thereby reducing the probability of mixed or auditory perception [17], [19]. Second, peripheral mechanoreceptor density may contribute, as distal regions, particularly near the hand, contain higher concentrations of mechanoreceptors sensitive to vibration, including the Pacinian and Meissner corpuscles [2], [17], [26]. Furthermore, the periosteum of the long bones, such as the ulna, also contains specialized receptors that may mediate vibrotactile osseoperception [15], [27].

Mixed sensations (simultaneous vibrotactile and auditory) were significantly more frequent at the CL than at the MP across all tested frequencies, and the likelihood of eliciting such sensations was higher at 440 Hz than at the pisiform bone (PB) (Fig. 3C). Within the clavicle itself, the probability of mixed percepts decreased from 293 Hz to 440 Hz, consistent with a shift toward predominantly auditory sensations at higher frequencies at this site [22]. Together, these findings suggest that the clavicle functions as an intermediate region in which vibrotactile and auditory pathways overlap, with the balance between modalities modulated by the stimulation frequency. Its anatomical position—integrated into the thoracic skeleton yet still proximal enough to preserve peripheral mechanoreceptor influence—may support the co-propagation of both sensory channels [17], [22].

Interestingly, although the MP was expected to primarily evoke auditory sensations, several participants also reported mixed percepts (Fig. 4). This can be attributed to two main factors. First, the inherent mechanical vibration generated by bone transducers is difficult to isolate from the tactile component, particularly at frequencies below 1 kHz, where Pacinian corpuscles remain responsive [23]. Second, despite using earplugs and active noise-cancelling headphones,

complete isolation from air-conducted sound in this particular zone is challenging, which may have led to cross-modal interference between vibration and sound perception [19]. Additionally, vibrotactile and auditory sensations may act as perceptual distractors for one another, and participants may have reported both sensations when they were not clearly dominated [28]. Alternatively, some mixed responses may reflect genuine perceptual integration of the two modalities rather than uncertainty in the participant's judgment.

As expected, the probabilities of auditory perception at the MP were significantly higher than those at all other bony landmarks across all frequencies. This finding aligns with the established mechanism of bone conduction, in which vibrations reach the cochlea through direct skull transmission with minimal attenuation [22]. Consequently, auditory perception was more easily evoked at the MP than at other sites (Fig. 3B).

Interestingly, although the CL showed notably lower auditory probabilities than the MP at 440 Hz, this difference was not significant, in contrast to PB or OL where the probability was substantially lower compared to MP in all cases. This suggests that the clavicle could also serve as an effective site for eliciting auditory sensations through bone conduction at high frequencies. Furthermore, previous studies on humeral osseointegrated implants have reported that stimulation at approximately 400 Hz can elicit auditory percepts, supporting this zone-related finding [17].

As the frequency increased, the probability of auditory sensations increased significantly in the CL. This reciprocal trend that can be observed in all upper-limb bony landmarks suggests a perceptual trade-off between sensory modalities, potentially reflecting the differential activation of mechanoreceptive and auditory pathways [17].

B. PT depends on frequency and on site

The PT results revealed that MP consistently exhibited the lowest PT across all frequencies, which was significantly lower than that at other sites (Supplementary Table S2). This result was expected because of its proximity to the cochlea and the high sensitivity of the auditory system [22]. In contrast, no significant differences in PT were observed between the PB, OL, and CL. The associated Bayes factors ranged from anecdotal evidence in favor of the null hypothesis to inconclusive evidence, suggesting that perception thresholds

> REPLACE THIS LINE WITH YOUR MANUSCRIPT ID NUMBER (DOUBLE-CLICK HERE TO EDIT) <

may be broadly comparable across upper-limb locations, although the present data are insufficient to conclusively establish equivalence (Supplementary Table S2).

At PB and OL, PT increased significantly with frequency, and the same trend was noted for CL and MP, but in the latter two cases, the effect was not statistically significant (Fig. 6A). This contrasts with the typical patterns observed in vibrotactile and electrotactile feedback studies, where higher frequencies correspond to lower thresholds [29]. A possible explanation is that frequency-dependent changes in bone-conducted sensitivity may alter the relative contribution of different perceptual cues (e.g., tactile vs. auditory), thereby changing the overall threshold of the composite sensation. Similar frequency-dependent effects have been reported in bone-anchored prosthetic users [17]. From an auditory perspective, this behavior may also be consistent with loudness perception characteristics, where sensitivity varies with frequency at equal intensity levels [19], [22].

C. Amplitude and frequency discrimination were independent of anatomical site

No significant differences in the amplitude or frequency of the JND were observed across the upper-limb landmarks. Bayes factors provided anecdotal-to-moderate evidence regarding the absence of site effects (Supplementary Table S3), suggesting that discrimination performance may be broadly comparable across anatomical locations, although subtle site-dependent differences could not be excluded with the present sample size. Therefore, larger studies are warranted to confirm the apparent similarity in the discrimination performance across anatomical sites.

For both amplitude and frequency discrimination, JND values were significantly greater than zero. Although this result primarily confirms that participants required a finite change in stimulus intensity or frequency to reliably discriminate the comparison stimulus from the reference, it also provides baseline psychophysical values for stimulation frequencies and anatomical sites that have not been previously characterized, particularly the clavicle and mastoid process [17], [18], [19]. These findings suggest that bone-conducted stimulation at all evaluated locations can support perceptual discrimination, which is an important prerequisite for designing sensory-feedback systems based on graded amplitude or frequency modulation [5].

D. Implications and perspectives

Overall, these findings indicate that osseoperceptive sensations depend on both the stimulation frequency and anatomical location. Distal landmarks, such as PB and OL, predominantly elicited vibrotactile sensations, whereas proximal landmarks, particularly CL and MP, were more frequently associated with auditory or mixed percepts. This pattern is consistent with the differential contributions of peripheral mechanoreception and bone-conducted cochlear stimulation across anatomical sites.

This mapping of sensory response profiles along the limb provides a foundation for designing osseoperceptive sensory feedback interfaces for people with sensorimotor disabilities, e.g., people with amputations. We have previously demonstrated that osseoperceptive feedback, when the bone

transducer is placed on the wrist, can be useful in providing dual information (grip force and touch) during myoelectric robotic hand use by selectively eliciting vibrotactile and auditory sensations through frequency modulation [20]. This multimodal feedback resulted in improved success rates, motor coordination, and grip force control in a task involving a simulated fragile object. However, this approach cannot be applied when the wrist is unavailable, as in transradial or transhumeral amputees. Nevertheless, the outcomes of this study demonstrate that osseoperception can also be used to provide sensory substitution feedback in these cases. Specifically, we found that PB and OL lead to similar osseoperceptive responses. Therefore, the bone transducer can be placed on the OL in people with transradial amputation or elbow disarticulation. For transhumeral amputees, a bone transducer can be positioned on the CL. Note that bone stimulation elicited both vibrotactile- and auditory-related percepts in both OL and CL (Fig. 4). The landmark analysis revealed distinct perceptual profiles at these sites, with OL showing higher probabilities of vibrotactile and mixed sensations than auditory sensations, whereas CL showed a predominance of mixed sensations. Although some variation in modality probabilities was observed across stimulation conditions, frequency did not produce a significant main effect or landmark $\times$ frequency interaction, indicating that frequency alone does not reliably determine perceptual modality. Overall, these findings suggest that anatomical location, rather than frequency, was the primary determinant of perceptual outcomes, with multimodal feedback remaining possible at more proximal sites.

Previous work has shown that osseoperceptive cues can effectively encode the grasping force through amplitude modulation when controlling a virtual hand using sEMG, with the bone transducer positioned at the elbow [18]. In that study, participants were able to discriminate coarse frequency categories as a secondary task, suggesting that bone-conducted vibration can support multiparametric feedback by combining amplitude and frequency modulation. Our findings extend this perspective by identifying the PB as a particularly sensitive site for vibrotactile osseoperception, with low perception thresholds and a predominance of vibratory sensations. Given the importance of spatial proximity between feedback location and effector representation in virtual or teleoperated tasks [30], PB may offer a more natural and intuitive feedback channel compared with more proximal sites.

Our findings complement those of [21] by extending the psychophysical characterization of non-invasive osseoperception to more proximal stimulation sites and by demonstrating that the type of elicited sensation strongly depends on the anatomical location. In that study, the authors investigated perceptual thresholds across different regions of the elbow in both healthy participants and transradial amputees, showing that perception thresholds can vary within the same general anatomical area depending on the precise stimulation site. This highlights that even small spatial variations within a given joint region may influence the vibrotactile perception.

In our study, we aimed to control for intra-site variability across participants by consistently targeting the ulnar olecranon region for elbow-based measurements and extending the

> REPLACE THIS LINE WITH YOUR MANUSCRIPT ID NUMBER (DOUBLE-CLICK HERE TO EDIT) <

analysis to additional anatomical locations. However, direct comparison with [21] remains limited due to methodological differences, including differences in the range of stimulation amplitudes and frequencies evaluated, as well as differences in the set of perceptual outcomes assessed. Despite these differences, both studies demonstrated that not only the choice of anatomical site, but also the precise spatial location of stimulation, play a critical role in shaping osseoperceptive responses. This has direct implications for the design of artificial sensory feedback systems, where both site selection and the spatial precision of stimulation may influence the resulting perceptual quality and modality.

To our knowledge, this is the first study to compare the psychometric parameters (both quality and intensity) of osseoperception across upper-limb bony landmarks and the mastoid process, the canonical site for bone-conduction devices [22], [23]. Notably, we found that the clavicle provides a promising alternative site to the MP, as the perceptual responses observed here are the most similar to those at the mastoid in terms of vibrotactile and auditory perception. Auditory sensations can be elicited in the CL, particularly at higher stimulation frequencies.

Our findings have two important implications. First, auditory feedback has been reported to improve certain aspects of prosthetic control, including grasp performance, grip-force regulation, and the development of stronger internal models of myoelectric control [14]. However, traditional implementations often rely on external devices such as headphones, which may limit their practical usability [14], [28]. In contrast, osseoperception through a bone transducer placed on available bony landmarks, such as the clavicle, may provide an alternative pathway for delivering auditory-related cues without the need for head-mounted audio devices, potentially improving comfort and usability. Furthermore, the possibility of eliciting multimodal percepts at proximal sites may be particularly relevant for higher-level amputations, where distal residual limb sites are unavailable and multi-actuator feedback systems may be challenging to implement [31]. At the same time, our findings at more distal landmarks highlight the broader potential of osseoperception as a multimodal feedback approach for individuals with different amputation levels. Overall, our results suggest that a single bone transducer can elicit both vibrotactile and auditory-related percepts, supporting further investigation of osseoperceptive strategies for multimodal prosthetic feedback systems [4], [6], [10].

Beyond sensory substitution for prosthetic applications, bone-conducted stimulation at the MP may also have implications for immersive human-machine interfaces. Previous studies have shown that mastoid bone-conducted vibrations of approximately 500 Hz can modulate visually induced self-motion perception (vection), suggesting an interaction with the vestibular system under specific experimental conditions [32]. Although vestibular responses were not assessed in the present study and no such sensations were reported by participants, this possibility highlights an additional avenue for future research, namely the integration of osseoperceptive stimulation with virtual and augmented reality systems.

E. Limitations and future work

While this study provides novel insights into osseoperception, several limitations should be noted. First, the participant sample was rather uniform with a narrow age range (22–32 years), which may limit generalizability. Future studies should recruit larger and more diverse cohorts to investigate inter-individual variability in osseoperceptive responses. Second, a different transducer fixation method was required at the clavicle compared with the other anatomical landmarks owing to anatomical constraints. Although the adopted fixation approach was intended to provide comparable contact conditions [18], the contact force was not directly measured and its potential influence on the observed responses could not be completely excluded. Third, subjective confidence ratings or qualitative reports were not collected; therefore, it was not possible to distinguish genuine mixed percepts from uncertainty in the sensation categorization. Future studies should incorporate subjective measures to disentangle these possibilities better. Fourth, although we minimized air-conducted sound using earplugs, active noise-cancelling headphones, and verified the transducer range, such acoustic isolation may not be practical in real-world prosthetic applications [4], [28]. Nevertheless, this can be addressed by integrating the bone transducer inside the socket, which minimizes air conduction. Future work will evaluate osseoperception in participants with osseointegrated implants, where direct transducer-bone contact may enhance vibrotactile and auditory perception [17].

ACKNOWLEDGMENT

The authors sincerely thank all participants for their valuable contribution to this study.

REFERENCES

- [1] N. Lan, C. M. Niu, M. Hao, C.-H. Chou, and C. Dai, "Achieving Neural Compatibility With Human Sensorimotor Control in Prosthetic and Therapeutic Devices," *IEEE Trans. Med. Robot. Bionics*, vol. 1, no. 3, pp. 122–134, Aug. 2019, doi: 10.1109/TMRB.2019.2930356.
- [2] R. S. Johansson and J. R. Flanagan, "Coding and use of tactile signals from the fingertips in object manipulation tasks," *Nat. Rev. Neurosci.*, vol. 10, no. 5, pp. 345–359, May 2009, doi: 10.1038/nrn2621.
- [3] D. M. Wolpert, J. Diedrichsen, and J. R. Flanagan, "Principles of sensorimotor learning," *Nat. Rev. Neurosci.*, vol. 12, no. 12, pp. 739–751, Dec. 2011, doi: 10.1038/nrn3112.
- [4] M. Markovic *et al.*, "The clinical relevance of advanced artificial feedback in the control of a multi-functional myoelectric prosthesis," *J. Neuroeng. Rehabil.*, vol. 15, no. 1, p. 28, Dec. 2018, doi: 10.1186/s12984-018-0371-1.
- [5] C. F. Blanco-Diaz, E. Vendrame, C. Cipriani, S. Dosen, and L. Cappello, "Recent Advances in Supplementary Haptic Feedback for Human-Machine Interfaces in Upper Limb Assistance and Rehabilitation," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, pp. 1–20, Apr. 2026, doi: 10.1109/TNSRE.2026.3687960.
- [6] J. W. Sensinger and S. Dosen, "A Review of Sensory Feedback in Upper-Limb Prostheses From the Perspective of Human Motor Control," Jun. 23, 2020, *Frontiers Media S.A.* doi: 10.3389/fnins.2020.00345.
- [7] E. D'Anna *et al.*, "A closed-loop hand prosthesis with simultaneous intraneural tactile and position feedback," *Sci. Robot.*, vol. 4, no. 27, Feb. 2019, doi: 10.1126/scirobotics.aau8892.
- [8] S. N. Flesher *et al.*, "A brain-computer interface that evokes tactile sensations improves robotic arm control," *Science (1979)*, vol. 372, no. 6544, pp. 831–836, May 2021, doi: 10.1126/science.abd0380.

> REPLACE THIS LINE WITH YOUR MANUSCRIPT ID NUMBER (DOUBLE-CLICK HERE TO EDIT) <

- [9] A. S. Ivani, F. Barontini, M. G. Catalano, G. Grioli, M. Bianchi, and A. Bicchi, "Characterization, Experimental Validation and Pilot User Study of the Vibro-Inertial Bionic Enhancement System (VIBES)," *IEEE Trans. Haptics*, vol. 18, no. 1, pp. 32–44, Jan. 2025, doi: 10.1109/TOH.2024.3435588.
- [10] M. A. Garenfeld, M. Strbac, N. Jorgovanovic, J. L. Dideriksen, and S. Dosen, "Closed-Loop Control of a Multifunctional Myoelectric Prosthesis With Full-State Anatomically Congruent Electrotactile Feedback," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 31, pp. 2090–2100, 2023, doi: 10.1109/TNSRE.2023.3267273.
- [11] A. S. Ivani, F. Barontini, M. G. Catalano, G. Grioli, M. Bianchi, and A. Bicchi, "Prosthetic Upper-Limb Sensory Enhancement (PULSE): a Dual Haptic Feedback Device in a Prosthetic Socket," in *2024 IEEE International Conference on Robotics and Automation (ICRA)*, IEEE, May 2024, pp. 9652–9658, doi: 10.1109/ICRA57147.2024.10610327.
- [12] L. Vargas, H. Huang, Y. Zhu, and X. Hu, "Object Recognition via Evoked Sensory Feedback during Control of a Prosthetic Hand," *IEEE Robot. Autom. Lett.*, vol. 7, no. 1, pp. 207–214, Jan. 2022, doi: 10.1109/LRA.2021.3122897.
- [13] P. D. Marasco *et al.*, "Neurobotic fusion of prosthetic touch, kinesthesia, and movement in bionic upper limbs promotes intrinsic brain behaviors," *Sci. Robot.*, vol. 6, p. 3368, 2021.
- [14] A. W. Shehata, L. F. Engels, M. Controzzi, C. Cipriani, E. J. Scheme, and J. W. Sensinger, "Improving internal model strength and performance of prosthetic hands using augmented feedback," *J. Neuroeng. Rehabil.*, vol. 15, no. 1, p. 70, Dec. 2018, doi: 10.1186/s12984-018-0417-4.
- [15] I. Klineberg *et al.*, "A consensus statement on osseoperception," *Clin. Exp. Pharmacol. Physiol.*, vol. 32, no. 1–2, pp. 145–146, Jan. 2005, doi: 10.1111/j.1440-1681.2005.04144.x.
- [16] M. Örgel *et al.*, "Osseoperception in transcutaneous osseointegrated prosthetic systems (TOPS) after transfemoral amputation: a prospective study," *Arch. Orthop. Trauma Surg.*, vol. 143, no. 2, pp. 603–610, Aug. 2021, doi: 10.1007/s00402-021-04099-1.
- [17] F. Clemente *et al.*, "Touch and Hearing Mediate Osseoperception," *Sci. Rep.*, vol. 7, Mar. 2017, doi: 10.1038/srep45363.
- [18] R. M. Mayer *et al.*, "Tactile Feedback in Closed-Loop Control of Myoelectric Hand Grasping: Conveying Information of Multiple Sensors Simultaneously via a Single Feedback Channel," *Front. Neurosci.*, vol. 14, Apr. 2020, doi: 10.3389/fnins.2020.00348.
- [19] C. F. Blanco-Diaz, M. Pedone, S. Skach, C. Baselli, and L. Cappello, "Investigating Osseoperception in Distal Regions of the Upper Limb for Augmented Sensory Feedback," in *2025 International Conference on Rehabilitation Robotics (ICORR)*, Chicago, 2025, pp. 744–748, doi: 10.1109/ICORR66766.2025.11063035.
- [20] C. F. Blanco-Diaz *et al.*, "Humans can use multimodal osseoperceptive sensory feedback to enhance their sensorimotor control of a robotic hand," *Robotics and Automatization Letters*, vol. 11, pp. 554–561, Nov. 2025, doi: 10.1109/LRA.2025.3632715.
- [21] R. M. Mayer, A. Mohammadi, Y. Tan, G. Alici, P. Choong, and D. Oetomo, "Temporal and spatial characteristics of bone conduction as non-invasive haptic sensory feedback for upper-limb prosthesis," *Front. Neurosci.*, vol. 17, pp. 1–10, 2023, doi: 10.3389/fnins.2023.1113009.
- [22] S. Stenfelt and M. Zeitooni, "Loudness functions with air and bone conduction stimulation in normal-hearing subjects using a categorical loudness scaling procedure," *Hear. Res.*, vol. 301, pp. 85–92, Jul. 2013, doi: 10.1016/j.heares.2013.03.010.
- [23] K.-J. F. Jansson, B. Håkansson, L. Johannsen, and T. Tengstrand, "Electro-acoustic performance of the new bone vibrator Radioear B81: A comparison with the conventional Radioear B71," *Int. J. Audiol.*, vol. 54, no. 5, pp. 334–340, May 2015, doi: 10.3109/14992027.2014.980521.
- [24] S. Gholinezhad, S. Dosen, and J. Dideriksen, "Continuous Transition Impairs Discrimination of Electrotactile Frequencies," *IEEE Trans. Haptics*, vol. 15, no. 4, pp. 753–758, Oct. 2022, doi: 10.1109/TOH.2022.3208332.
- [25] F. Faul, E. Erdfelder, A.-G. Lang, and A. Buchner, "G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences," *Behav. Res. Methods*, vol. 39, no. 2, pp. 175–191, May 2007, doi: 10.3758/BF03193146.
- [26] R. T. Verrillo, "Vibrotactile sensitivity and the frequency response of the Pacinian corpuscle," *Psychon. Sci.*, vol. 4, no. 1, pp. 135–136, Jan. 1966, doi: 10.3758/BF03342215.
- [27] I. Pyykkö, M. Färkkilä, J. Toivanen, O. Korhonen, and J. Hyvärinen, "Transmission of vibration in the hand-arm system with special reference to changes in compression force and acceleration," *Scand. J. Work Environ. Health*, vol. 2, no. 2, pp. 87–95, Jun. 1976, doi: 10.5271/sjweh.2820.
- [28] L. F. Engels, A. W. Shehata, E. J. Scheme, J. W. Sensinger, and C. Cipriani, "When Less Is More – Discrete Tactile Feedback Dominates Continuous Audio Biofeedback in the Integrated Percept While Controlling a Myoelectric Prosthetic Hand," *Front. Neurosci.*, vol. 13, Jun. 2019, doi: 10.3389/fnins.2019.00578.
- [29] J. Dideriksen, M. Markovic, S. Lemling, D. Farina, and S. Dosen, "Electrotactile and Vibrotactile Feedback Enable Similar Performance in Psychometric Tests and Closed-Loop Control," *IEEE Trans. Haptics*, vol. 15, no. 1, pp. 222–231, Jan. 2022, doi: 10.1109/TOH.2021.3117628.
- [30] A. Frisoli and D. Leonardi, "Wearable haptics for virtual reality and beyond," *Nature Reviews Electrical Engineering*, vol. 1, no. 10, pp. 666–679, Sep. 2024, doi: 10.1038/s44287-024-00089-8.
- [31] J. Tchiminio, R. L. Hansen, P. H. Jørgensen, J. Dideriksen, and S. Dosen, "Application of EMG feedback for hand prosthesis control in high-level amputation: a case study," *Sci. Rep.*, vol. 14, no. 1, p. 31676, Dec. 2024, doi: 10.1038/s41598-024-80828-x.
- [32] T. Kondo, Y. Hirao, T. Narumi, and T. Amemiya, "Effects of bone-conducted vibration stimulation of various frequencies on the vertical vection," *Sci. Rep.*, vol. 13, no. 1, p. 15759, Sep. 2023, doi: 10.1038/s41598-023-42589-x.



Cristian Felipe Blanco-Diaz (Graduate Student Member, IEEE) received the B.S. degree in Biomedical Engineering from Antonio Nariño University, Colombia, in 2020, and the M.Sc. degree in Electrical Engineering from the Federal University of Espírito Santo (UFES), Brazil, in 2023. He is currently pursuing the Ph.D. degree in Biorobotics with the Scuola Superiore Sant'Anna, Pisa, Italy. During his bachelor studies, he was a visiting student at the Biorobotics Laboratory, École Polytechnique Fédérale de Lausanne (EPFL), Switzerland. During his master studies, he was a visiting student at the International Institute for Neurosciences of Natal – Edmond and Lily Safra, Brazil. As part of his Ph.D. studies, he was a visiting student with the Neurorehabilitation Systems Research Group, Aalborg University, Denmark, and with the Mechatronics and Haptic Interfaces Lab, Rice University, USA. His research interests include biosignal processing, neuroengineering, human-machine interfaces, rehabilitation and assistive robotics, and sensory feedback. Mr. Blanco-Diaz is a Student Member of the IEEE Engineering in Medicine and Biology Society (EMBS), the IEEE Robotics and Automation Society (RAS), and the International Consortium for Rehabilitation Robotics (ICORR).



Leonardo Cappello (Senior Member, IEEE) received the B.S. degree in Mechanical Engineering in 2009 and the M.S. degree in Biomedical Engineering in 2011 from the University of Florence, Italy, and the Ph.D. degree in Robotics, Cognition, and Interaction Technologies from the University of Genoa, Italy, in 2016. During his Ph.D. studies, he was a visiting student at the Robotics Research Centre, Nanyang Technological University, Singapore, from 2014 to 2015. From 2016 to 2017, he was a Postdoctoral Researcher with Harvard University and the Wyss Institute for Biologically Inspired Engineering, USA, and from 2017 to 2022, he was a Postdoctoral Researcher with the BioRobotics Institute, Scuola Superiore Sant'Anna, Italy. He is currently an Assistant Professor with the BioRobotics Institute, where he founded and leads the Textile Robotics Laboratory within the Artificial Hands Area. He was the recipient of European Research Council Starting Grant (ERC StG) for the project MUsculoSkeletal Expansion (MUSE). His main research interests include haptics, assistive and rehabilitation robotics, prosthetics and orthotics, and motor neuroscience.

> REPLACE THIS LINE WITH YOUR MANUSCRIPT ID NUMBER (DOUBLE-CLICK HERE TO EDIT) <



Strahinja Dosen (Member, IEEE) received the Diploma of Engineering in electrical engineering and the M.Sc. degree in biomedical engineering from the Faculty of Technical Sciences, University of Novi Sad, Serbia, in 2000 and 2004, respectively, and the Ph.D. degree in biomedical engineering from the Center for Sensory-Motor Interaction, Aalborg University, Aalborg, Denmark, in 2008. From 2011 to 2017, he was a Research Scientist with the Institute for Neurorehabilitation Systems, University Medical Center Gottingen, Germany, and then as an Associate

Professor with the Department of Health Science and Technology, Aalborg University, Aalborg Denmark. He is currently a Full Professor with the Department of Health Science and Technology, Rehab Robotics, where he leads a research group on Neurorehabilitation Systems. He is a Principal Investigator for AAU and HST in several EU (Tactility, Wearplex, Sixthsense, and SimBionics) and nationally (Robin, Remap, and Climb) funded projects. He has authored or coauthored more than 90 manuscripts in peer-reviewed journals. His main research interests include closed-loop control of movements and assistive systems, including human-machine interfacing, control of bionic limbs and rehabilitation robotics, artificial sensory feedback, and functional electrical stimulation. He is a Member of EMBS.