Assessment of TENS-Evoked Tactile Sensations for Transradial Amputees via EEG Investigation

Yuanzhe Dong, Yuxiang Zhang, Qingge Li, Jianping Huang, Xiangxin Li, Naifu Jiang, *Member, IEEE*,
Guanglin Li, *Senior Member, IEEE*, Wenyuan Liang, *Member, IEEE*,
and Peng Fang, *Senior Member, IEEE*

***Abstract*— Most of current prostheses can offer motor function restoration for limb amputees but usually lack natural and intuitive sensory feedback. Many studies have demonstrated that Transcutaneous Electrical Nerve Stimulation (TENS) is promising in non-invasive sensation evoking for amputees. However, the objective evaluation and mechanism analysis on sensation feedback are still limited. This work utilized multi-channel TENS with diverse stimulus patterns to evoke sensations on four non-disabled subjects and two transradial amputees. Meanwhile, electroencephalogram (EEG) was collected to objectively assess the evoked sensations, where event-related potentials (ERPs), brain electrical activity maps (BEAMs), and functional connectivity (FC) were computed. The results show that various sensations could be successfully evoked for both amputees and non-disabled subjects by customizing stimulus parameters. The ERP confirmed the sensation and revealed the sensory-processing-related components like N100 and P200; the BEAMs confirmed the corresponding regions of somatosensory cortex were activated by stimulation; the FC indicated an increase of interactions between the regions of sensorimotor cortex. This study may shed light on how the brain responds to external stimulation as sensory feedback and serve as a pilot for further bidirectional closed-loop prosthetic control.**

***Index Terms*— Prosthesis, sensory feedback, transcutaneous electrical nerve stimulation, electroencephalogram.**

Manuscript received 29 January 2024; revised 29 May 2024 and 28 July 2024; accepted 21 August 2024. Date of publication 30 August 2024; date of current version 10 September 2024. This work was supported in part by the National Natural Science Foundation of China under Grant U21A20479 and Grant 81927804, in part by Chinese Academy of Sciences (CAS) Youth Innovation Promotion Association under Grant Y2022094, in part by Shenzhen Fundamental Research Program under Grant JCYJ20200109114805984, and in part by Shenzhen Engineering Laboratory of Neural Rehabilitation Technology. *(Corresponding authors: Peng Fang; Wenyuan Liang.)*

This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Institutional Review Board of Shenzhen Institute of Advanced Technology, Chinese Academy of Sciences, under Application No. SIAT-IRB-190315-H0325.

Yuanzhe Dong, Yuxiang Zhang, Qingge Li, Jianping Huang, Xiangxin Li, Naifu Jiang, Guanglin Li, and Peng Fang are with Shenzhen Institute of Advanced Technology, Chinese Academy of Sciences, Shenzhen 518055, China, and also with the University of Chinese Academy of Sciences, Beijing 100049, China (e-mail: peng.fang@siat.ac.cn).

Wenyuan Liang is with the National Research Center for Rehabilitation Technical Aids, Beijing 100176, China (e-mail: lwy123@hotmail.com).

Digital Object Identifier 10.1109/TNSRE.2024.3452153

I. INTRODUCTION

PROSTHETIC hands may provide a solution for upper-limb amputees to interact with surrounding environments behaving like a intact limb [1], [2]. Most commercial prosthetic hands have made significant progress to help amputees regain motor control and are integrated with sophisticated mechanical components, human skin-like electrodes, and advanced control algorithms. However, the existing prostheses are far away from users' expectations and the lack of tactile feedback has been recognized as a major problem causing abandonment and rejections of prostheses [3]. Users have to rely on their visual feedback which could gain only relatively accurate manipulation but without sensing the environments through their prosthetic hands. Thus, it is vital to develop advanced prostheses with sensory feedback to build a bidirectional human-machine interaction that helps amputees restore not only motor but also sensation functions [4], [5].

Many studies have concentrated on providing amputees with a natural and intuitive sensory feedback [6], [7], [8], but most achievements are still in an early stage and cannot be directly applied in clinical usage at the moment. Generally, there are two mainstream methods for restoring sensory paths: invasive and non-invasive approaches. The invasive methods [9], [10], [11] are often limited due to their inextricable technical challenges such as surgical risks, extra medical care, biological compatibility, power supply, and etc. Thus, the non-invasive stimulation approaches [12], [13], [14], [15] often serve as a substitution to transfer sensory information by stimulating the nerves underneath skin of residual limbs. Generally, the tactile sensation can be evoked through mechanotactile stimulation, vibrotactile, and electrotactile stimulation. The mechanotactile stimulation (MS) [16], [17], [18] involves applying physical pressure or deformation to skin surface, activating the mechanoreceptors beneath and producing tactile sensations. MS could provide fine-grained feedback and spatial information, enhancing the perception of surrounding environments. However, the precision and subtlety of mechanotactile stimuli can be challenging to control, and prolonged exposure to mechanical pressure might lead to discomfort and fatigue. The vibrotactile stimulation (VS) [19], [20], [21] constitutes a transmission of vibration to skin surface, eliciting tactile sensations thereby. These vibrations vary in frequency, amplitude, and duration, offering a wide range of perceptual experiences. VS is particularly effective in conveying fruitful information over the body with tiny actuators that can be integrated as wearable devices, while the stimulation precision might be limited and the sensation of vibrations could potentially lead to desensitization over time. The electric stimulation [6], [9], [22] relies on an application of electrical currents to the skin that triggers multiple tactile sensations. The evoked sensations mainly depend on stimulation parameters (current, voltage, geometric contact area), electrode types (size, material, geometric contact area), and skin properties (thickness, hydration, location, and receptor intensity).

Transcutaneous Electrical Nerve Stimulation (TENS) [23], [24], [25], [26] is one of the most used electrical stimulation methods, which involves an application of electrical currents through the skin to stimulate nerves, modulate neural pathways, and elicit physiological responses. Unlike those invasive methods, TENS bypassed the need of surgical implantation, reducing the risk of infections, tissue trauma, and procedural complications significantly. The TENS technology has evolved considerably, enabling a precise targeting of specific nerve fibers and neural networks through various electrode placements and stimulation parameters. This customization feature enhances its therapeutic efficacy across a wide range of applications, spanning pain management [27], [28], neurological rehabilitation [29], [30], and even psychological disorders [31], [32]. The ease of application, portability of devices, and potential for home-based treatment regimens further enhance the attractiveness of TENS as a patient-friendly alternative to traditional methods. Many studies have suggested that TENS can be considered a plausible non-invasive approach to convey tactile information from prosthetic devices to amputees, inducing a sense of perceptual embodiment in non-disabled subjects with a visual-tactile illusion and missing limbs of amputees with stimulation of afferent nerves. Zarei et al. [25] investigated the effect of conventional, high-frequency TENS on brain activation and perceived sensations on 40 healthy subjects. Jadidi et al. [24] explored the cortical modulation by pulse width modulation of TENS on the somatosensory cortex for the first time and conducted a comparative analysis with conventional TENS with recorded sensory evoked potentials. Vargas et al. [13] placed a 2×8 electrode grid along the upper limbs of neurologically intact subjects to determine if tactile feedback evoked by TENS can be used to perceive the objects' shape and surface topology. Chai et al. [33] recruited two non-disabled subjects and two unilateral transradial amputees to illustrate that electrotactile feedback enhancing grip force aids in improving sensorimotor control of prosthetic hands, enabling recognition of object stiffness. Besides, in the discipline of TENS-induced sensory feedback, a useful concept of phantom hand map (PHM) was introduced in many works [34], [35]. It refers to a region on the residual limb, where sensations corresponding to the amputated hand or even each individual finger can be evoked by proper non-invasive stimulation. It is reported that not all but most limb amputees have PHM and intuitive sensations can be induced by stimulating the PHM.

Up to now, most existing studies focus on the methods to evoke sensory feedback for limb amputees, but the relationships among stimulation parameters, evoked sensations, and cortex activation, together with the mechanism and process by which cerebral cortex handles the evoked sensory information, are still less explored. Some studies showed that TENS could evoke natural and intuitive sensations that are similar to real touch, and more sensory modalities and richer sensation types could be realized by exploring stimuli parameters since the involvement of more nerves located deeply beneath skin surface. However, most previous studies rarely quantify the relationship between TENS and induced sensations from an objective perspective, or some EEG analyses were performed but the brain functional connectivity corresponding to sensation evoking was neglected, i.e., the study on cortical activation behaviors by sensory feedback is insufficient [36]. Thus, the goal of this study is to characterize the PHM of evoked tactile sensations on residual limbs induced by TENS and to explore the brain connectivity and activated brain regions when stimulation is applied. In this study, subjective feelings reported by subjects and electroencephalogram (EEG) recordings synchronized with stimulation were combined to evaluate the performance of stimulation. Besides, the event-related potential (ERP), brain electrical activity map (BEAM), and functional connectivity (FC) were computed and analyzed among the non-disabled and amputated subjects to objectively evaluate the sensory feedback performance and explore the relationship between stimuli parameters and evoked EEG signals. We believe the characterization of evoked sensations and perceptual threshold may be helpful for further development of closed-loop and bidirectional bionic hands.

II. MATERIALS AND METHODS

A. Subjects

Four non-disabled volunteers (65-75 kg in weight, 175-180 cm in height, and 24-28 years in age) and two right transradial amputees (50-70 Kg in weight, 168-170 cm in height, and 35-40 years in age) were recruited in this work. All the non-disabled volunteers and amputees are right-handed. The health assessment revealed that all subjects were in a positive mental condition and fully capable of participating in the entire experiment. The experiment protocol was approved by the Institutional Review Board of the Shenzhen Institute of Advanced Technology, Chinese Academy of Sciences (*IRB Number: SIAT-IRB-190315-H0325*). All subjects agreed to participate in the study and signed informed consent permission for the publication of data for scientific and educational purposes.

B. Platform

The experiment platform, as shown in Fig. 1, contains an electrical stimulation system and an EEG acquisition system (*64-channel Quick-cap; Amplifier: SynAmps 2, Neuroscan, USA*). The electrical stimulation system includes four parts: a waveform generator (*CED Micro 1401-4, Digitimer, UK*), a bipolar constant current stimulator (*DS5, Digitimer, UK*),

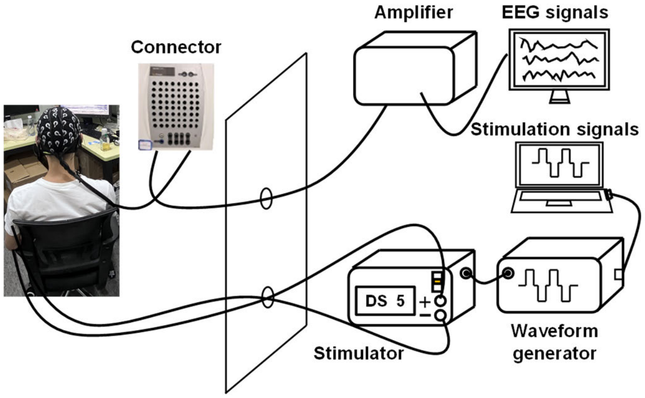

Fig. 1. Schematic show of the experiment platform.

Fig. 2. The mesh matrix marked on an amputee's residual limb to localize the stimulation position.

TABLE I
PARAMETERS OF TENS FOR SENSATION EVOKING

Frequency (Hz)	5, 30, 50, 75, 100, 150, 200
Wave width (μs)	50, 100, 150, 200, 250, 300, 350, 400
Amplitude (mA)	1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 6.0

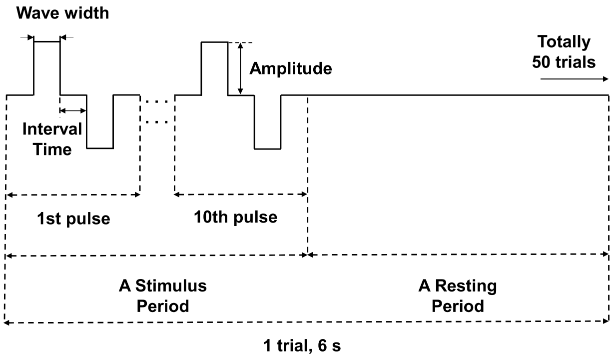

Fig. 3. Interpretation of stimulation patterns.

and a pair of hydro-electrodes (5 mm in diameter). The wave-form generator was used to generate pulses and transmit trigger signals to the EEG acquisition amplifier to synchronize the EEG and TENS systems. The bipolar constant current stimulator outputs stimulus currents corresponding to the signals from waveform generator. The customized multichannel switch controller can be manipulated manually to select stimulation channels. The subjects were asked to sit on a chair in an electro-magnetic shielding room comfortably, while the stimulation devices were set outside of the room. A pair of self-adhesive surface electrodes (5 mm in diameter) were used for stimulation. Prior to the electrode attachment, the stimulated area was sanitized by using alcohol pads to eliminate grease and cuticle, enhancing the conductivity of the electrode-skin interface.

C. Sensation Evoking

1) Stimulation Positions: The PHM distribution for the amputated subjects were firstly explored. Usually, mesh matrices can be used to identify optimal stimulus sites, which were marked on the residual limbs with a surgical marker pen, as shown in Fig. 2. Then, a tiny rod was used to apply mechanical stresses on the marked areas and the subjective feelings of the amputees, i.e., the evoked phantom sensations, were recorded to draw the maps of preliminary PHM distribution to locate the potential stimulus positions. After that, the symmetric, rectangular, and biphasic waveform electrical stimulations were performed on these positions, and the subjective feedbacks from the subjects were recorded to determine the final positions for the following experiments.

2) Stimulation Patterns: To explore the sensations evoked by different stimulation parameters, bipolar square-wave pulses involving various amplitudes, frequencies, and pulse widths were designated, as illustrated in TABLE I. For each test cycle, the stimulus period contained 10 bipolar square pulses and lasted for 1 s in all, and the rest period lasted for 5 s. A total of 50 continuous cycles were repeated in each stimulus trial which lasted for 300 s, as shown in Fig. 3. Once feeling the stimulation, subjects reported the evoked sensation types, intensities, and finger positions subjectively. The intensity of sensation is ranked in a scale from 0 to 10, where 0 indicates "no phantom finger sensation" and 10 indicates "extremely stimulated sensation". The subjective report of intensity is used to obtain the current threshold when a subject can recognize a slightly evoked sensation. The stability and generality of sensation-evoking rule were studied through long-term tracking, and the experiments were repeated every five to seven days to optimize the parameters. Besides, the same TENS experiments were applied for the non-disabled subjects, where the stimulus positions were their wrist areas corresponding to ulnar, median, and radial nerves, and the stimulus parameters were selected based on the results of amputees.

D. Data Analysis

EEG signals were analyzed by using *Python (3.8)* and *EEGLAB (v14.1.2)*. The data were band-pass filtered from 0.5 to 45 Hz corresponding to five EEG frequency bands with an 8th order zero-phase Butterworth filter with the *MATLAB* function "filtfilt", and a 4th Butterworth notch filter with 49 Hz was used to remove the baseline noise. Two earlobes, M1 and M2, were used as the referenced electrodes to ground EEG signals. In the experiments, TENS was applied and EEG signals were collected simultaneously, and markers were used to accurately synchronize the stimulation and signal recording. Thus the signals were segmented into

50 epochs by markers, which were synchronous with the stimulus. The epochs with large-amplitude drift or extremely contaminated by biological artifacts like EOG and EMG were removed by visual inspection and manual operation. Subsequently, the components related to eye movements and muscle activity were detected and extracted by the independent component analysis algorithm (Fast-ICA). The ADJUST [37] algorithm was used to identify and eliminate artifactual components based on an unsupervised learning method. Thereafter, an artifact-free EEG was reconstructed by the rest components. The ICA-processed data were averaged into one epoch and extracted into 1000 ms, i.e., from −200 to 800 ms relative to the stimulus start. Finally, the baseline correction was used to remove the pre-stimulus interval offset and individual ERP was computed by averaging epochs from various EEG channels. The EEG data were extracted from the very beginning of 500 ms after the stimulation, and a 10 ms window was applied to divide the data into segments. The BEAM in each time window was plotted by the EEGLAB with a function named "topoplot". The BEAM results could be adopted to explore the brain's electrical activities in spatial distribution and the activated brain regions when subjects receive stimulation. According to the BEAM results, the EEG channels corresponding to activated brain regions were finally selected for ERP analysis, including a comparison among different stimulus parameters.

E. Functional Connectivity Metrics

The synchronization of neuronal oscillations across different brain regions is widely used as a fundamental mechanism facilitating interaction between various brain regions. Some studies hypothesized that electrical stimulation has profound impacts on the sensorimotor cortical functional interactions, and the FC analysis of EEG could uncover the cooperation of different brain cortexes [30]. In this study, the FC matrices were computed based on phase-locked value (PLV) and coherence, and the FC matrices of the non-disabled and amputated subjects in both static and stimulated states were compared.

Coherence [38] is an important approach to estimate the functional connectivity and spatial relationships in EEG signals. It quantifies the degree of synchronization and consistency between the oscillatory activities of different electrode pairs on the scalp. Essentially, coherence reflects the extent to which two brain regions are engaged in a coordinated neural activity. When EEG electrodes exhibit high coherence, it suggests that the electrical signals are likely to be functionally connected. Mathematically, given to time series $x_{\mathrm{i}}(t)$ and $y_{\mathrm{i}}(t)$ recorded from two channels, the coherence Coh_{xy} is defined as:

$$\mathrm{Coh}_{xy} = \frac{|P_{xy}(f)|}{P_{xx}(f) \bullet P_{yy}(f)}^{2}, \tag{1}$$

where $P_{\mathrm{xy}}(f)$ is the cross-spectrum (in practice, averaged over EEG data in many epochs) and $P_{\mathrm{xx}}(f)$ and $P_{\mathrm{yy}}(f)$ are the power spectrum of signals in channel x and channel y, respectively.

Phase-Locking Value (PLV) [38] is another essential metric used for EEG connectivity analysis. Unlike the coherence, the PLV quantifies the degree of phase consistency between two signals. It assesses whether the phase of oscillatory components at specific frequencies across electrode pairs is synchronized. High PLV values indicate that the phase relationship between two signals can remain stable over time, suggesting a strong functional connectivity between the corresponding brain regions. Given bandpass-filtered brain signals from two EEG channels, the phase-locking value is defined as:

$$PLV = \frac{1}{N}\left|\sum_{t=1}^{N} e^{i(\phi_{xt}-\phi_{yt})}\right|, \tag{2}$$

where N is the number of trials and Φ_{xt}–Φ_{yt} is the difference between the instantaneous phases x and y of the two signals at time t. The PLV falls within a range of [0, 1], where "0" signifies the absence of phase synchronization and "1" indicates the relative phase between two signals can remain consistent and identical across multiple trials.

III. RESULTS

A. Sensation Evoking

In general, most non-disabled and amputated subjects in this work had similar feedbacks when they perceived stimulations. All subjects reported that the sensory intensities escalated proportionally with the stimulus amplitude and different subjects had different sensory threshold. Overall, most subjects could not detect an evoked sensation until the stimulus amplitude surpassed 1.5 mA and perceived some uncomfortable feelings when the amplitude reached 5 mA, while the pain threshold would be higher for amputated subjects. All the amputees reported that the stimulation applied on the amputated side would cause more slight sensations compared to the that on the healthy side, and their just notified threshold (JNR) and pain threshold would be higher than the non-disabled subjects. Besides, it is observed that the sensory types were predominantly determined by the stimulation frequency, which could evoke the sensation of flapping, vibrating, and pressing at around 5, 50, and 200 Hz, respectively. The parameters of TENS and types of evoked sensations are shown in TABLE II. The corresponding relationships between evoked sensations (type and intensity) and stimulus parameters (amplitude, pulse width, and frequency) remained consistent across the whole experiment cycle of this work lasting for more than eight months.

B. Event-Related Potential

According to the BEAM results that will be shown in the next section, the somatosensory cortex is activated by stimulation, and thus the corresponding electrode Fz was chosen to plot the ERP curves. Fig. 4 shows the ERP curves of the Fz channel under different stimulation parameters for the four non-disabled subjects (Figs. 4a-4d, with 0, 1.5, 2.5, and 3.5 mA under 200 μs and 200 Hz) and two amputees (Figs. 4e and 4f, with 0, 4, 5, and 6 mA under 200 μs and 200 Hz). As can be seen, two ERP components, i.e., N100 and P200, can be determined, where the time intervals of 80-140 ms and 180-250 ms are selected as the N100 and P200 components, respectively.

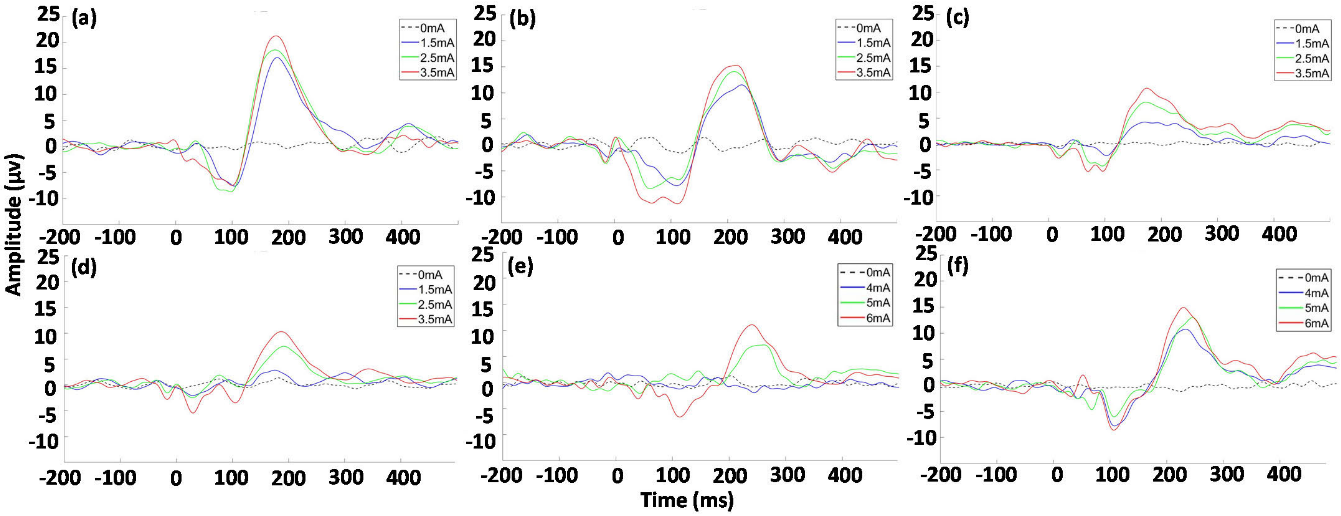

Fig. 4. The ERP curves of the Fz channels by different stimulus amplitudes of 0, 1.5, 2.5, and 3.5 mA for the four non-disabled subjects (a, b, c, and d) and 0, 4, 5, 6 mA for the two amputees (e and f).

TABLE II
PARAMETERS OF TENS AND TYPES OF EVOKED SENSATIONS

Stimulation Parameters		Types of Sensations
Frequency (Hz)	**Wave width (μs)**	
5	200	Taping
50	200	Vibration
200	200	Pressing

1) N100: The N100 is a negative deflection occurring approximately 100 ms after the presentation of a stimulus, often associated with early sensory processing and attentional mechanisms. For N100, in the amputee group, the mean latency is 111.0±4.0 ms and the mean amplitude is -4.38 ± 2.21 μv; in the non-disabled group, the mean latency is 99.5.0±12.6 ms and the mean amplitude is -6.48 ± 3.14 μv. The latency of amputees is close to that of non-disabled subjects, but the amplitudes of amputees are generally smaller than those of the non-disabled subjects by the same stimulus current.

2) P200: The P200 is commonly linked to the responses to stimulation of varying significance or novelty. For P200, in the amputee group, the mean latency is 243.0±2.0 ms and the mean amplitude is 9.28±1.80 μV; in the non-disabled group, the mean latency is 202.75±22.14 ms and the mean amplitude is 13.52±5.29 μV. Compared to the amputees, the non-disabled subjects have shorter latency and higher potential than amputees.

C. Brain Electrical Activity Map

Fig. 5 illustrates the BEAM of a stimulated state for a representative amputee, with 50 segmented time windows from the beginning of to 500 ms after the stimulation. The primary somatosensory cortex is only activated when phantom finger sensations are evoked, and noticeable electrical activities can be observed within the time around 210 to 280 ms after the stimulus beginning, generally corresponding to the P200 component.

D. Functional Connectivity

Fig. 6 shows the FC matrices for a representative non-disabled subject and the same amputee in Fig. 5, with the results of PLV and coherence. The subgraphs Figs. 6a and 6b are for the non-disabled subject without and with stimulation, respectively; Figs. 6c and 6d are for the amputee with stimulation on his amputated and healthy side, respectively. It is clear that there is no obvious activation on the brain regions without a stimulation, and the somatosensory cortex is activated for both non-disabled and amputee subjects when they receive stimulations. Besides, the stimulus on the amputee's amputated side and healthy side results in similar patterns in FC matrices. The FC analysis for the other amputee shows similar results but is not displayed here due to the limited space of the paper. Additionally, we conducted two times of one-way ANOVA statistical analysis to study the difference between four groups of data (for the non-disabled: "stimulation" and "non-stimulation"; for amputees: "stimulation on the healthy side" and "stimulation on the amputated side") in the functional connectivity analysis, where the results of $p < 0.05$ were achieved in both statistical tests. Considering the parameters for the two statistical analyses are independent, it can be proved that there are significant differences in the data from respective non-disabled and amputated subjects.

Fig. 7 exhibits the EEG connectivity map [39] for the same amputee in Fig. 5 when he received stimulation on his amputated side, in different frequency bands of Delta, Theta, Alpha, Beta, Gamma, and all spectrum. The result shows that the connectivity efficiency is higher in low-frequency bands (Delta, Theta, and Alpha) and lower in high-frequency bands (Beta and Gamma).

IV. DISCUSSION

For the individuals grappling with limb amputation, prostheses emerge as a viable option to restore their basic

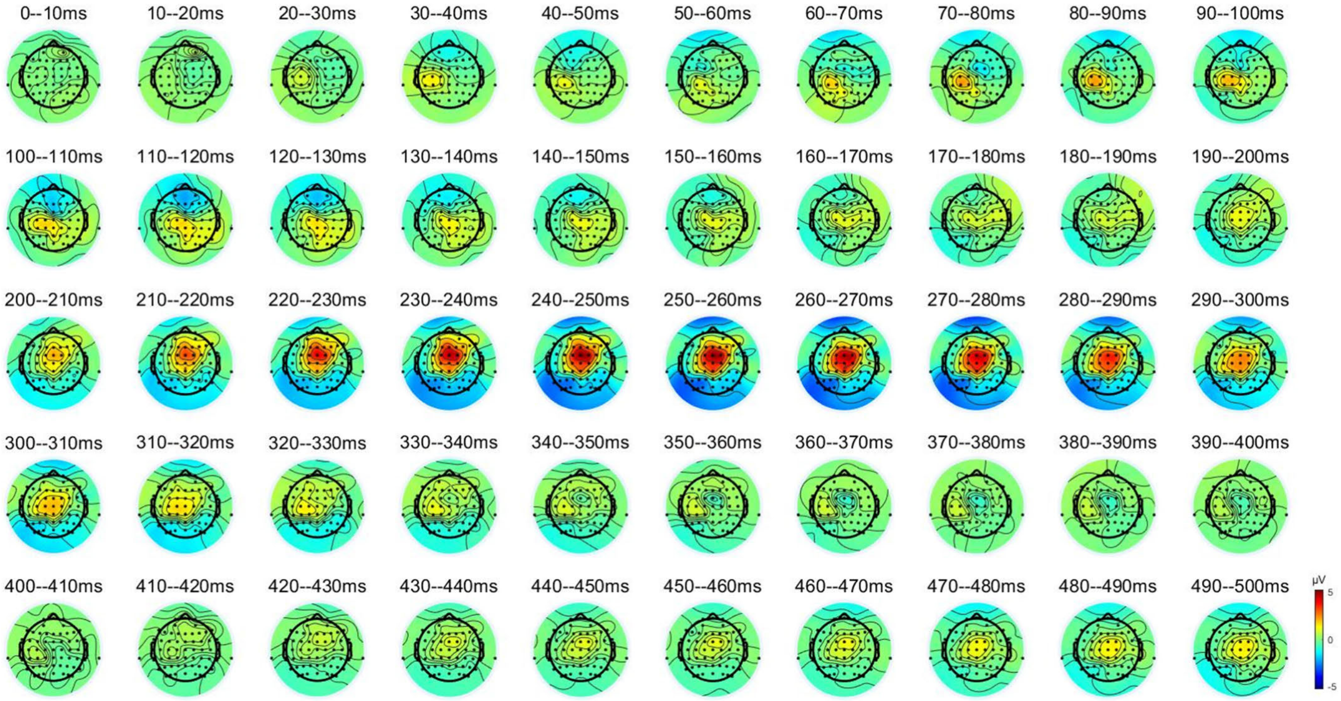

Fig. 5. The brain electrical activity map across 50 segmented time windows from the beginning of to 500 ms after the stimulation, when the amputee received stimulation (amplitude = 6 mA, frequency = 200 Hz, pulse width = 200 μs) and a pressing sensation on this phantom finger was evoked by TENS.

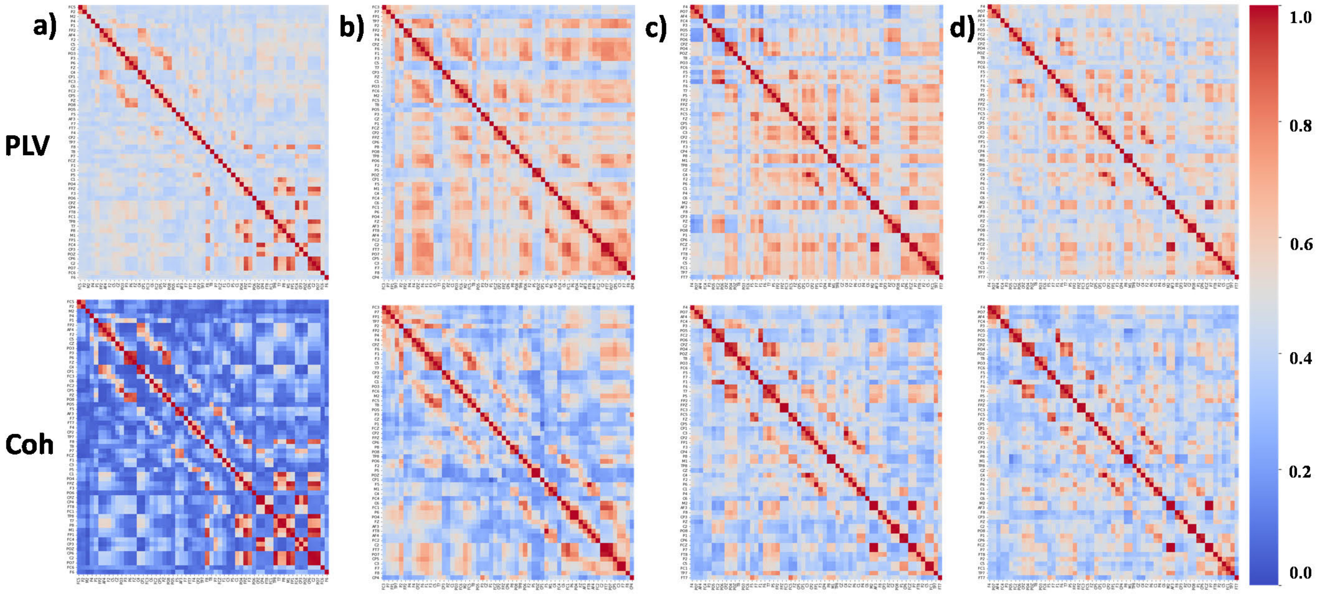

Fig. 6. The functional connectivity matrices for an non-disabled subject and the same amputee in Fig. 5, with the metrics of phase locked value and coherence, for a) the non-disabled subject without stimulation; b) the non-disabled subject with stimulation; c) the amputee with stimulation on his amputated side; d) the amputee with stimulation on his healthy side.

motor function. However, the absence of sensory feedback in most current prostheses hampers the user's ability to interact seamlessly with the environments. The deficiency in sensory function not only compromises the overall experience but also poses a challenge in performing everyday tasks with confidence. Thus, exploring a possible way to establish intuitive sensory feedback for limb amputees has been a hot spot in the discipline of neurorehabilitation and human-machine interaction.

Numerous studies have achieved noteworthy successes in eliciting diverse intuitive phantom finger sensation for upper-limb amputees by applying invasive electrical stimulation either on sensory cortexes or peripheral nerves [9], [10], [11]. Although these discoveries mark a substantial advancement in recovering sensory perceptions for amputees, the invasive nature of this approach may present many risks. The clinical operation is always constrained and the acceptance of an invasive procedures is generally lower, which is primarily

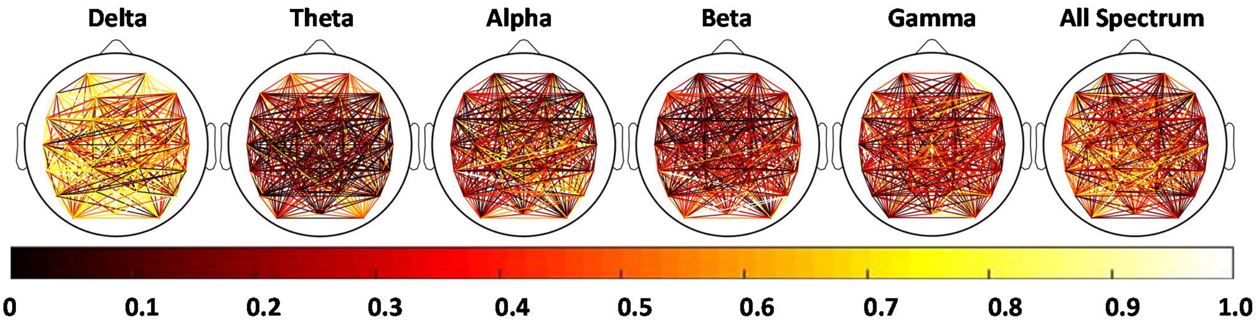

Fig. 7. The EEG connectivity map for the same amputee in Fig. 5 when he received stimulation on his amputated side, in different frequency bands of Delta, Theta, Alpha, Beta, Gamma, and all spectrum.

due to the potential complications arising post-surgery. These complications, ranging from infection to more intricate issues, contribute to the hesitancy surrounding the widespread adoption of invasive stimulation in rehabilitation of sensory function for amputees.

Conversely, the non-invasive stimulation methods are much more acceptable by most amputees and can still gain relatively satisfactory performance [12], [13], [14], [15]. Mechanical stimulation has shown some capacity to induce sensations for limb amputees, albeit with limit in the diversity of sensation types that can be evoked [16], [17], [18]. On the other hand, TENS stands out as a versatile and promising alternative, which has been demonstrated to evoke a broader spectrum of intuitive sensations, making it a suitable candidate for enhancing sensory feedback for amputees [23], [24], [25], [26]. Some pilot studies have successfully demonstrated the feasibility of TENS in evoking natural and intuitive sensations [40], [41]. However, the exploration of brain activities connected with sensation evoking upon different stimulus configurations is inadequate and unsatisfactory. Therefore, this work intended to study the TENS-based sensation evoking performance from the aspect of EEG, which may serve as a crucial objective tool to assess the brain activation behaviors. Comparisons between the amputees and non-disabled subjects, and between the amputees' amputated and healthy sides, were both explored.

Implementing mechanical stresses on amputees' stump surface can unveil their PHMs corresponding to different phantom fingers, offering valuable guidance for localization of precise TENS positions. The modulation of TENS parameters, including amplitude, wave width, and frequency, plays a crucial role in eliciting various sensations [40]. Notably, amplitude and wave width are primary determinants of sensation intensity, influencing the perceived sensation strength and depth experienced by subjects. Higher amplitudes or larger wave widths generally result in more pronounced and intense sensations, which can be explained by the enhanced energy transfer to the stimulated nerves. In another aspect, a variance in frequency will leads to different sensation types, where increasing frequency can cause a sensation from flapping to vibrating, and eventually to pressing [40], [41]. This phenomenon is likely attributed to the activation of different nerve fibers in response to stimulus frequency change. The rationale behind this behavior lies in the logical progression where high-frequency flapping triggers a vibrating sensation, and similarly, the brain interprets high-frequency vibrating as a continuous pressing sensation. It is worth noting that a mixture of sensations for different fingers was pretty common in subjects, which may be attributed to the co-activation of different nerve fibers corresponding to different fingers.

The synchronously acquired EEG data may provide a way to objectively evaluate the sensory feedback performance, where various EEG analyses including ERP, BEAM, FC, and connectivity map, were implemented in this study. According to the experimental results, distinct ERP peaks were observable only upon stable electrical stimulation. Both amputees and non-disabled subjects exhibiting similar ERP components, which might prove the evoked sensations on amputees are as natural and intuitive as the non-disabled subjects. The N100 wave, associated with the initial phase of sensory processing that occurs independently of conscious awareness of stimulus, is believed to primarily originate from the secondary somatosensory cortices. The P200 is considered to be responsible for translating a perceived stimulation into a conscious perception [25], [41]. Therefore, the ERP findings featuring N100 and P200 in the experiments may be suggested as a cognitive biomarker for sensory processing induced by TENS, offering a means to validate the reliability of the evoked sensations. Besides, compared with the non-disabled subjects, the amputees' ERP curves have smaller amplitudes even by a more intense stimulation, which may indicate that the amputees need a stimulus with higher amplitude or larger wave width, i.e, more energy transfer, to evoke a sensation, and therefore they have a higher JNR. This phenomenon could be attributed to the fact that individuals who have undergone amputation surgery may possess fewer effective or sensitive nerve fibers to perceive external stimulations, requiring a higher stimulus intensity for sensation evoking. Another possible explanation may be that the peripheral nerve fibers are regenerated in the stump, and these fibers may have different structures, performance, and characteristics from the original ones before amputation. The BEAM results show that the somatosensory cortices are noticeably activated only when sensations are effectively induced by electrical stimulation, and the activation time indicated by BEAM is in agreement with the time for the ERP curves, which would jointly confirm the reliability of TENS-evoked sensory feedback.

The FC matrices and EEG connectivity maps for amputees and non-disabled subjects are compared, which demonstrate that sensory stimulations can elicit measurable effects on the whole-brain cortical functional connectivity among all the subjects. The FC analysis shows similar results when applying TENS on the non-disabled subjects, the amputees' healthy side, and the amputees' amputated side, which proves the hypothesis that TENS could induce sensations for the amputees as natural and intuitive as for the non-disabled subjects. Besides, the FC matrices and connectivity maps both indicate that the sensory stimulation can lead to an increased speed of information transfer and number of interactions between the brain regions of sensorimotor cortex, which enhances functional interactions between the somatosensory and multisensory processing systems [30].

Overall, this study re-established a sensory pathway between the external environment and brain for transradial amputees through TENS, which is validated by a comprehensive analysis of synchronous EEG recordings. Considering the small sample size is a limitation of this work, more amputees with different amputation conditions will be recruited to generalize the present findings in the future. Furthermore, a precise stimulation may enable targeted activation of specific nerves with proper spatial resolution, and thus some novel microelectrodes like microneedle array electrodes are suggested to be a possible solution for more precise sensation evoking. Compared with the invasive sensory feedback method, the non-invasive approach consistently grapples with the limitation of pattern diversity. For future efforts, it is recommended to explore different combinations of multi-parameters to enhance and diversify the sensory feedback for upper- and low-limb amputees.

V. CONCLUSION

In this work, four non-disabled subjects and two transradial amputees were recruited to explore an effective non-invasive sensory feedback method in restoring the lost sensory function for upper-limb amputees. Phantom finger sensations were successfully evoked by TENS for amputees and different sensation types were generated by modifying the stimulus configurations. The synchronously acquired EEG with multiple analysis of ERP, BEAM, and FC was used to objectively evaluate the brain's response to the evoked sensations. The subjective feelings reported by the subjects and objective EEG evaluation together proved that TENS can be utilized to evoke natural and intuitive sensations and recover the sensory function for amputees.

REFERENCES

[1] B. Maat, G. Smit, D. Plettenburg, and P. Breedveld, "Passive prosthetic hands and tools: A literature review," *Prosthetics Orthotics Int.*, vol. 42, no. 1, pp. 66–74, 2018.

[2] R. G. E. Clement, K. E. Bugler, and C. W. Oliver, "Bionic prosthetic hands: A review of present technology and future aspirations," *Surgeon*, vol. 9, no. 6, pp. 336–340, Dec. 2011.

[3] E. A. Biddiss and T. T. Chau, "Upper limb prosthesis use and abandonment: A survey of the last 25 years," *Prosthetics Orthotics Int.*, vol. 31, no. 3, pp. 236–257, 2007.

[4] S. J. Bensmaia, D. J. Tyler, and S. Micera, "Restoration of sensory information via bionic hands," *Nature Biomed. Eng.*, vol. 7, no. 4, pp. 443–455, Nov. 2020.

[5] J. A. George et al., "Biomimetic sensory feedback through peripheral nerve stimulation improves dexterous use of a bionic hand," *Sci. Robot.*, vol. 4, no. 32, Jul. 2019, Art. no. eaax2352.

[6] B. Geng, J. Dong, W. Jensen, S. Dosen, D. Farina, and E. N. Kamavuako, "Psychophysical evaluation of subdermal electrical stimulation in relation to prosthesis sensory feedback," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 26, no. 3, pp. 709–715, Mar. 2018.

[7] G. Chai, D. Zhang, and X. Zhu, "Developing non-somatotopic phantom finger sensation to comparable levels of somatotopic sensation through user training with electrotactile stimulation," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 25, no. 5, pp. 469–480, May 2017.

[8] G. Chai, X. Sui, S. Li, L. He, and N. Lan, "Characterization of evoked tactile sensation in forearm amputees with transcutaneous electrical nerve stimulation," *J. Neural Eng.*, vol. 12, no. 6, Dec. 2015, Art. no. 066002.

[9] E. K. Brunton, C. Silveira, J. Rosenberg, M. A. Schiefer, J. Riddell, and K. Nazarpour, "Temporal modulation of the response of sensory fibers to paired-pulse stimulation," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 27, no. 9, pp. 1676–1683, Sep. 2019.

[10] P. D. Ganzer et al., "Restoring the sense of touch using a sensorimotor demultiplexing neural interface," *Cell*, vol. 181, no. 4, pp. 763–773, May 2020.

[11] G. Preatoni, G. Valle, F. M. Petrini, and S. Raspopovic, "Lightening the perceived prosthesis weight with neural embodiment promoted by sensory feedback," *Current Biol.*, vol. 31, no. 5, pp. 1065–1071, 2021.

[12] M. Hao et al., "Restoring finger-specific sensory feedback for transradial amputees via non-invasive evoked tactile sensation," *IEEE Open J. Eng. Med. Biol.*, vol. 1, pp. 98–107, 2020.

[13] L. Vargas, H. Huang, Y. Zhu, and X. Hu, "Object shape and surface topology recognition using tactile feedback evoked through transcutaneous nerve stimulation," *IEEE Trans. Haptics*, vol. 13, no. 1, pp. 152–158, Jan. 2020.

[14] B. Stephens-Fripp, R. Mutlu, and G. Alici, "A comparison between separated electrodes and concentric electrodes for electrotactile stimulation," *IEEE Trans. Med. Robot. Bionics*, vol. 3, no. 1, pp. 241–252, Feb. 2021.

[15] L. Vargas, H. Huang, Y. Zhu, D. Kamper, and X. Hu, "Resembled tactile feedback for object recognition using a prosthetic hand," *IEEE Robot. Autom. Lett.*, vol. 7, no. 4, pp. 10977–10984, Oct. 2022.

[16] B. Stephens-Fripp, R. Mutlu, and G. Alici, "A comparison of recognition and sensitivity in the upper arm and lower arm to mechanotactile stimulation," *IEEE Trans. Med. Robot. Bionics*, vol. 2, no. 1, pp. 76–85, Feb. 2020.

[17] K. R. Schoepp, M. R. Dawson, J. S. Schofield, J. P. Carey, and J. S. Hebert, "Design and integration of an inexpensive wearable mechanotactile feedback system for myoelectric prostheses," *IEEE J. Transl. Eng. Health Med.*, vol. 6, pp. 1–11, 2018.

[18] L. Meli, I. Hussain, M. Aurilio, M. Malvezzi, M. K. O'Malley, and D. Prattichizzo, "The hBracelet: A wearable haptic device for the distributed mechanotactile stimulation of the upper limb," *IEEE Robot. Autom. Lett.*, vol. 3, no. 3, pp. 2198–2205, Jul. 2018.

[19] G.-H. Yang, W. Lee, and S. Kang, "Development of vibrotactile pedestal with multiple actuators and application of haptic illusions for information delivery," *IEEE Trans. Ind. Informat.*, vol. 15, no. 1, pp. 591–598, Jan. 2019.

[20] K. Niwa, Y. Tanaka, K. Kitamichi, T. Kuhara, K. Uemura, and T. Saito, "Vibrotactile feedback system from the fingertip to the temples for perceptual enhancement of contracture palpation," *IEEE Trans. Haptics*, vol. 14, no. 2, pp. 285–290, Apr. 2021.

[21] S. Oh and S. Choi, "Effects of contact force and vibration frequency on vibrotactile sensitivity during active touch," *IEEE Trans. Haptics*, vol. 12, no. 4, pp. 645–651, Oct. 2019.

[22] L. Seminara et al., "Dual-parameter modulation improves stimulus localization in multichannel electrotactile stimulation," *IEEE Trans. Haptics*, vol. 13, no. 2, pp. 393–403, Apr. 2020.

[23] Y. Cho, B. Lee, Y. Lee, and K.-S. Kim, "Simultaneous sensory feedback strategy for force and position of gripper based on TENS," *IEEE Robot. Autom. Lett.*, vol. 8, no. 9, pp. 5291–5298, Sep. 2023.

[24] A. F. Jadidi, W. Jensen, A. A. Zarei, and E. R. Lontis, "Alteration in cortical activity and perceived sensation following modulated TENS," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 31, pp. 875–883, 2023.

[25] A. A. Zarei, A. F. Jadidi, E. R. Lontis, and W. Jensen, "Short-term suppression of somatosensory evoked potentials and perceived sensations in healthy subjects following TENS," *IEEE Trans. Biomed. Eng.*, vol. 68, no. 7, pp. 2261–2269, Jul. 2021.

[26] Y. Zheng and X. Hu, "Elicited finger and wrist extension through transcutaneous radial nerve stimulation," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 27, no. 9, pp. 1875–1882, Sep. 2019.

[27] J-L. Salazar-Terrón, R. Martinez-Mendez, and G. Vazquez-Guzmán, "System for application of contrast therapy and transcutaneous electrical nervous stimulation for pain treatment," in *Proc. Int. Conf. Electron., Commun. Comput. (CONIELECOMP)*, Feb. 2015, pp. 178–183.

[28] Y. Enomoto, S. He, S. Y. Huang, and W. Yu, "Effect of changes in skin thickness on pain-relief transcutaneous electrical nerve stimulation (TENS)," in *Proc. 43rd Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. (EMBC)*, Nov. 2021, pp. 6504–6510.

[29] L. Vargas, J. Baratta, and X. Hu, "Distribution of M-wave and H-reflex in hand muscles evoked via transcutaneous nerve stimulation: A preliminary report," in *Proc. 43rd Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. (EMBC)*, Nov. 2021, pp. 5897–5900.

[30] K. Ding et al., "Towards machine to brain interfaces: Sensory stimulation enhances sensorimotor dynamic functional connectivity in upper limb amputees," *J. Neural Eng.*, vol. 17, no. 3, Jun. 2020, Art. no. 035002.

[31] D. N. Taylor, C.-T. Lee, and J. J. Katims, "Effects of cranial transcutaneous electrical nerve stimulation in normal subjects at rest and during psychological stress," *Acupuncture Electro-Therapeutics Res.*, vol. 16, no. 1, pp. 65–74, Jan. 1991.

[32] M. H. Cameron, E. Lonergan, and H. Lee, "Transcutaneous electrical nerve stimulation (TENS) for dementia," *Cochrane Database Systematic Rev.*, vol. 2010, no. 1, Jul. 2003, Art. no. CD004032.

[33] G. Chai, H. Wang, G. Li, X. Sheng, and X. Zhu, "Electrotactile feedback improves grip force control and enables object stiffness recognition while using a myoelectric hand," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 30, pp. 1310–1320, 2022.

[34] A. Björkman, U. Wijk, C. Antfolk, I. Björkman-Burtscher, and B. Rosén, "Sensory qualities of the phantom hand map in the residual forearm of amputees," *J. Rehabil. Med.*, vol. 48, no. 4, pp. 365–370, 2016.

[35] A. Akhtar, M. Nguyen, L. Wan, B. Boyce, P. Slade, and T. Bretl, "Passive mechanical skin stretch for multiple degree-of-freedom proprioception in a hand prosthesis," in *Haptics: Neuroscience, Devices, Modeling, and Applications* (Lecture Notes in Computer Science). Berlin, Germany: Springer, 2014, pp. 120–128.

[36] Y. Wang et al., "Effective evaluation of finger sensation evoking by non-invasive stimulation for sensory function recovery in transradial amputees," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 30, pp. 519–528, 2022.

[37] H.-J. Park, D.-U. Jeong, and K.-S. Park, "Automated detection and elimination of periodic ECG artifacts in EEG using the energy interval histogram method," *IEEE Trans. Biomed. Eng.*, vol. 49, no. 12, pp. 1526–1533, Dec. 2002.

[38] B. He et al., "Electrophysiological brain connectivity: Theory and implementation," *IEEE Trans. Biomed. Eng.*, vol. 66, no. 7, pp. 2115–2137, Jul. 2019.

[39] V. C. Pezoulas et al., "FCLAB: An EEGLAB module for performing functional connectivity analysis on single-subject EEG data," in *Proc. IEEE EMBS Int. Conf. Biomed. Health Informat. (BHI)*, Las Vegas, NV, USA, Mar. 2018, pp. 96–99.

[40] D. Zhang, F. Xu, H. Xu, P. B. Shull, and X. Zhu, "Quantifying different tactile sensations evoked by cutaneous electrical stimulation using electroencephalography features," *Int. J. Neural Syst.*, vol. 26, no. 2, Mar. 2016, Art. no. 1650006.

[41] W. Liang, C. Qin, A. Sun, X. Zhang, N. Lan, and S. Bi, "Study of tactile sensation somatotopy and homology between projected fingers in residual limb and natural fingers in intact limb," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 31, pp. 636–645, 2023.