Effective Evaluation of Finger Sensation Evoking by Non-Invasive Stimulation for Sensory Function Recovery in Transradial Amputees

Yingying Wang, Peng Fang, *Senior Member, IEEE*, Xi Tang, Naifu Jiang, *Member, IEEE*, Lan Tian, Xiangxin Li, Yue Zheng, Jianping Huang, Oluwarotimi Williams Samuel, *Senior Member, IEEE*, Hui Wang, Kai Wu, and Guanglin Li, *Senior Member, IEEE*

***Abstract*—Synergetic recovery of both somatosensory and motor functions is highly desired by limb amputees to fully regain their lost limb abilities. The commercially available prostheses can restore the lost motor function in amputees but lack intuitive sensory feedback. The previous studies showed that electrical stimulation on the arm stump would be a promising approach to induce sensory information into the nervous system, enabling the possibility of realizing sensory feedback in limb prostheses. However, there are currently limited studies on the effective evaluation of the sensations evoked by transcutaneous electrical nerve stimulation (TENS). In this paper, a multichannel TENS platform was developed and the different stimulus patterns were designed to evoke stable finger sensations for a transradial amputee. Electroencephalogram (EEG) was recorded simultaneously during TENS on the arm stump, which was utilized to evaluate the evoked sensations. The experimental results revealed that different types of sensations on three phantom fingers could be stably evoked for the amputee by properly selecting TENS patterns. The analysis of the event-related potential (ERP) of EEG recordings further confirmed the evoked sensations, and ERP latencies and curve characteristics for different phantom fingers showed significant differences. This work may provide insight for an in-depth understanding of how somatosensation could be restored in limb amputees and offer technical support for the applications of non-invasive sensory feedback systems.**

***Index Terms*—Amputee, sensory feedback, transcutaneous electrical nerve stimulation, electroencephalogram, event-related potential.**

I. INTRODUCTION

In the human sensorimotor system, the brain receives sensory information acquired from skin receptors [1] that initiate motor commands to muscles, activating the limb movements closing the loop of sensorimotor control [2], [3]. In the case of limb amputation, the described closed-loop (efferent and afferent) pathway is cut off [4], leading to a loss of motor and sensory function. Advanced prosthetic devices are built to help upper-limb amputees recover their motor function, however, restoration of intuitive sensory function in limb amputees is still a challenge [5], [6]. Amputees often rely on visual feedback [7]–[9] to control their prosthetic hands and many of them choose to abandon their devices due to lack of natural and intuitive sensory feedback [10]. Towards realizing feedback function in prosthetic hands, researchers have proposed a variety of artificial sensors that could mimic skin receptors for acquiring sensory information such as grip strength, pressure, rigidity, texture, and shape of objects among others [11], [12]. Additionally, a number of prosthetic hands can self-adaptively adjust grip strength according to the information acquired by artificial sensors integrated within [13]. Nevertheless, sensory information has rarely been transmitted through the afferent nerve pathway to the brain hence hindering progress towards the successful provision of intuitive sensory feedback for amputees [4], [10].

It has been demonstrated that electrical stimulation, which is based on implantable peripheral or central nervous interface

---

Manuscript received October 24, 2021; revised January 30, 2022; accepted February 27, 2022. Date of publication March 2, 2022; date of current version March 11, 2022. This work was supported in part by the National Natural Science Foundation of China under Grant 61773364, Grant U21A20479, Grant U1913601, and Grant 82050410452; in part by the National Key Research & Development Program of China under Grant 2017YFA0701103; in part by the CAS Youth Innovation Promotion Association under Grant 2018395; in part by the Shenzhen Basic Research Program under Grant JCYJ20200109114805984; in part by the Guangdong Basic and Applied Basic Research Foundation Outstanding Youth Project 2021B1515020064; and in part by the Shenzhen Engineering Laboratory of Neural Rehabilitation Technology. *(Corresponding authors: Peng Fang; Guanglin Li.)*

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 the Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences, under Approval No. SIAT-IRB-190315-H0325.

Yingying Wang, Peng Fang, Xi Tang, Lan Tian, Xiangxin Li, Yue Zheng, Oluwarotimi Williams Samuel, and Guanglin Li are with the CAS Key Laboratory of Human-Machine Intelligence-Synergy Systems and the Shenzhen Engineering Laboratory of Neural Rehabilitation Technology, Shenzhen Institutes of Advanced Technology, Shenzhen 518055, China, and also with the Shenzhen College of Advanced Technology, University of Chinese Academy of Sciences, Shenzhen 518055, China (e-mail: peng.fang@siat.ac.cn; gl.li@siat.ac.cn).

Naifu Jiang, Jianping Huang, and Hui Wang are with the CAS Key Laboratory of Human-Machine Intelligence-Synergy Systems and the Shenzhen Engineering Laboratory of Neural Rehabilitation Technology, Shenzhen Institutes of Advanced Technology, Shenzhen 518055, China.

Kai Wu is with the School of Material Science and Engineering, South China University of Technology, Guangzhou 511442, China.

This article has supplementary downloadable material available at https://doi.org/10.1109/TNSRE.2022.3155756, provided by the authors.

Digital Object Identifier 10.1109/TNSRE.2022.3155756

technologies [5], [14], is an effective approach to activate afferent nerve fibers and induce sensory information into the nervous system of amputees [2], [6]. Stimulating electrodes, for example, the Utah electrode arrays, are often implanted on the median, ulnar, and radial nerves of upper-limb amputees, or sensory-motor cortex of them, for either intraneural or intracortical microstimulation [15]–[17]. Besides, several intuitive sensations including tapping, pressure, slight touch, vibration, etc. can be induced using the described stimulation technique [18], [19]. Selection of stimulus parameters is necessary to ensure accurate induction of sensations [20], and the stress response of mechanoreceptors on palm surface has been shown to enhance stimulation strategies for sensory feedback [20], [21]. However, clinic applications of sensory feedback via invasive electrical stimulation technologies are limited mainly due to long-term biological incompatibility of implanted electrodes and post-surgery complications [4], [12].

Previous studies have indicated that for some amputees, there exists a phantom hand map (PHM) on their residual limb surface, and natural sensations can be induced by stimulating the PHM areas non-invasively, using either mechanical or electrical method [2], [22], [23]. Mechanical stimulation can evoke a feeling of pressure on phantom fingers, but it is impractical in clinical applications due to the limited kinds of sensations, difficulty in device miniaturization, and high energy consumption [4], [12], [24]. Electrical stimulation on PHM areas, also known as Transcutaneous Electrical Nerve Stimulation (TENS) [2], is conducted on the skin surface of residual limbs to induce phantom finger sensations for amputees [25], [26]. Feelings of different types and intensities can be evoked by adjusting TENS configurations including stimulus current frequency, amplitude, and pulse width, as well as stimulation position [4], [27], [28]. In another aspect, the selection of optimal stimulation positions remains a major challenge due to individual differences in amputation conditions among amputees [4], [29]. Additionally, a slight displacement in electrode positions (as small as 1 mm) can cause significant variation in phantom finger sensation. Moreover, TENS can be influenced by the physical status of the skin, environmental conditions, and experimental settings [4], [29], [30]. The above factors may hinder the realization of the long-term stability of TENS-evoked sensations, which is essential for clinical applications [4], [12].

Objective evaluation of evoked sensations is another interesting topic that can aid the understanding of the neuro mechanism of sensory feedback [31]. It has been established that there are responses in amputees' encephalic regions, i.e., motor-sensory cortex, when phantom finger sensations are induced by stimulating the PHM area [22], [23], indicating a mapping relationship between brain and PHM. Recent studies showed that cortical topographic maps based on magnetoencephalography (MEG) or electroencephalography (EEG) are useful in analyzing cortex activities corresponding to evoked sensations, where connections between stimulation, sensation, and cerebral cortex activities for limb amputees might be revealed [28], [32]–[34]. However, investigation of the relationships among stimulation configurations, evoked sensations, and cerebral cortex activities for limb amputees has rarely been conducted to the best of our knowledge. Also, the mechanism of how the cerebral cortex processes the evoked sensory information is still unclear [31], [35].

In order to address the above-highlighted issues, this study developed a TENS experimental platform, based on which distribution of PHM and stimulation configurations for a transradial amputee were studied. During stimulation sessions, EEG signals were simultaneously acquired, from which brain electrical activity mapping (BEAM) and event-related potential (ERP) were determined and used to assess the evoked sensations. Besides, all the experiments were performed on additional four able-bodied subjects, whose datasets were used for comparison and validation in the study. Findings from this study may provide an in-depth insight that can facilitate the development of non-invasive sensory feedback-driven rehabilitation technology for limb-amputees.

II. Materials and Methods

A. Subjects

A male subject whose left forearm was amputated for over 13 years (35 years in age, 168 cm in height, and 68 kg in weight) and four able-bodied subjects (including three males and one female, with an average age of 27 ± 3 years, an average height of 170 ± 5 cm, and an average weight of 65 ± 5 kg) were recruited in the study. The outcomes of preliminary health examinations showed that all subjects were in a good mental state and met the eligibility criteria of the study. The experimental protocol of the study was approved by the Institutional Review Board of Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences (IRB Number: SIAT-IRB-190315-H0325). All the subjects agreed to participate in the study and gave written informed consent with permission for publication of their data/photographs for scientific and educational purposes.

B. Experiment Platform

The experiment platform included an electrical stimulation system and an EEG acquisition system (*64-channel Quik-Cap*; *Amplifier: SynAmps 2, Neuroscan, USA*), as shown in Fig. 1. The electrical stimulation system consists of four components described as follows:

a) A waveform generator (*CED Micro1401-4, Digitimer, UK*) to output pulses and send trigger signals to the EEG acquisition amplifier that synchronizes the TENS and EEG acquisition;

b) An isolated bipolar constant current stimulator (*DS5, Digitimer, UK)* to output stimulus currents according to the signals from waveform generator;

c) A custom-made multichannel switch-controller which allows a manual selection of stimulation channels;

d) A 20-channel electrode array (*CV033E, YKD Technology Co. Ltd, China*) was used for electrical stimulation. Each electrode was bowl-shaped with 1 cm in diameter and attached to the subjects' skin by using medical conductive gel (*GT-20, Greentek Pty. Ltd, China*).

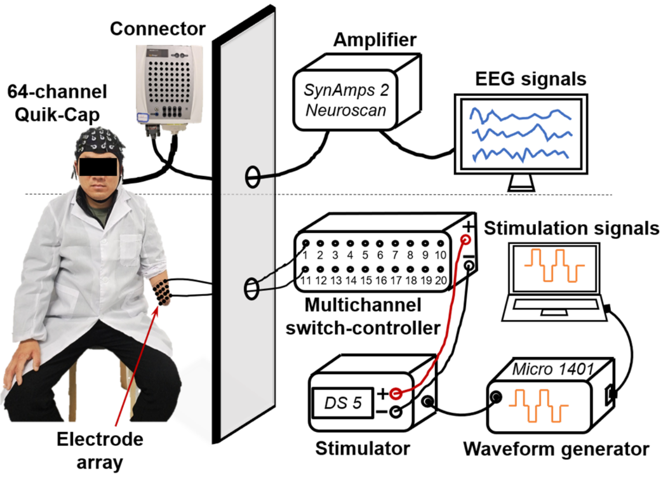

Fig. 1. Experimental platform for TENS and EEG acquisition.

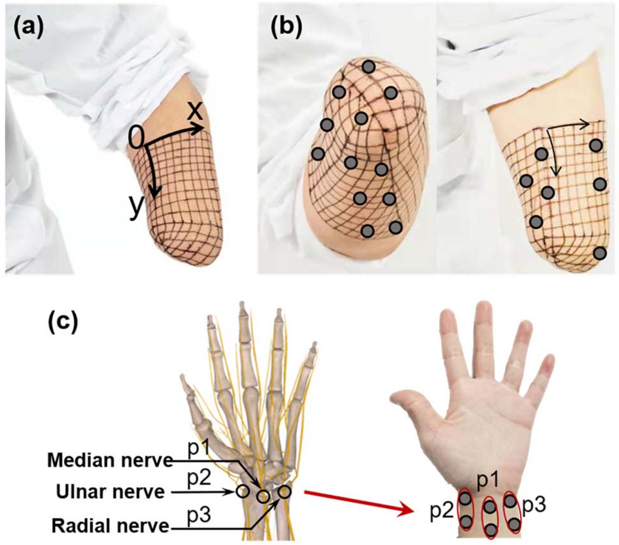

Fig. 2. (a) Mesh matrix on the amputee's stump for PHM study; (b) Selected positions of electrical stimulation for the amputee; c) Selected positions (p1, p2, and p3) of electrical stimulation for the able-bodied subjects.

During the experimental sessions, subjects were required to be relaxed and sit on a chair in a room with good electromagnetic shielding, and the equipment was placed outside the room as shown in Fig. 1.

C. Sensation Evoking

1) Stimulation Positions: Before initiating the electrical stimulation, the PHM distribution for the transradial amputee was firstly investigated. A mesh matrix with a size of 5 mm × 5 mm for each mesh was marked on the amputee's stump with a surgical marker pen, as shown in Fig. 2(a). Then, mechanical stress was manually applied on each mesh using a hard stick, and the subjective feelings of phantom fingers were reported by the amputee, which was recorded as his preliminary PHM distribution.

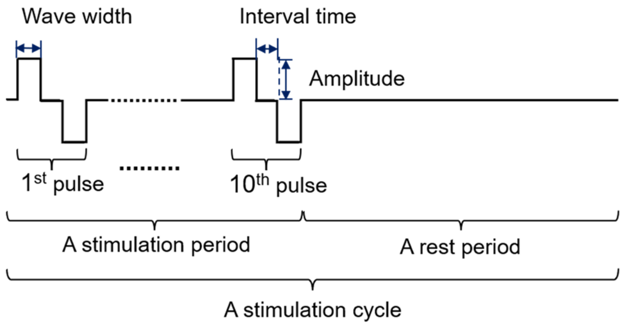

Fig. 3. Interpretation of the stimulation current.

TABLE I
PARAMETERS OF TENS USED TO EVOKE SENSATIONS

Amplitude (mA)	1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5
Frequency (Hz)	5, 10, 20, 50, 75, 100, 150, 200
Wave width (μs)	50, 100, 150, 200, 250, 300, 350, 400, 500
Interval time (μs)	200

Thereafter, electrical stimulation was performed on the stimulation positions preliminarily selected according to the PHM distribution, as shown in Fig. 2(b), to verify the PHM distribution. A series of bipolar square-wave pulses [25], [26], [28], [35] with a frequency of 50 Hz, a wave width of 200 μs, an interval time of 200 μs, and adjustable amplitude ranging from 1 to 5 mA, as shown in Fig. 3, were applied on the preliminarily selected stimulation positions at the amputee's stump to evoke phantom finger sensations. During the stimulation, the amputee was asked to subjectively report his real feelings of the phantom fingers, and this enabled us to determine proper stimulation positions for TENS.

2) Stimulation Patterns: To examine the influence of different TENS configurations on the evoked phantom finger sensations, bipolar square-wave pulses with various amplitudes, frequencies, and wave widths were applied, as presented in TABLE I. As shown in Fig. 3, a stimulus cycle lasted for 1 s, including a stimulation period that contained 10 bipolar square-wave pulses and a rest period. Meanwhile, the amputee's subjective feelings with respect to his phantom fingers in terms of position (digit or palm), type, and intensity were recorded. The intensity of sensation was rated with a scale from 0 to 10, where 0 was "no sensation was induced", 10 was "light finger movement or discomfort feeling." In this study, the sensation intensity was recorded mainly to obtain the threshold of the stimulus current when the amputee began to feel a slight evoked sensation. The experiments were repeated every three to five days and a total of eight repetitions were performed, to screen out a set of optimal stimuli parameters from those in TABLE I.

Finally, the performance like stability and validity in long-term use of the selected stimuli parameters and positions was tested. The stimuli pulses that had the same waveform as shown in Fig. 3 were used, and a stimulus cycle lasted for 6 s. A total of 50 continuous cycles were repeated in each stimulus trial which lasted for 300 s. The experiments were also repeated every three to five days, and totally eight repetitions were performed to verify the stability of evoked sensations.

In addition, similar TENS experiments were performed on four able-bodied subjects for comparison, where the stimulation was applied on the subjects' wrist area that corresponded to their median, ulnar and radial nerves, as shown in Fig. 2(c). The stimulus parameters (bipolar square-wave pulses in Fig. 3) were directly selected based on the result of the amputee.

D. Evaluation of Evoked Sensation

To realize an objective evaluation of the evoked sensation, 64-channel EEG signals were recorded simultaneously during each stimulus trial. Meanwhile, the following steps were performed in processing and analyzing the acquired signals:

a) A band-pass filter from 1 to 45 Hz was used to remove baseline drift and decrease interferences from high-frequency noises. Afterward, Independent Component Analysis (ICA) algorithm was used to extract and eliminate artifacts caused by electrical stimulation.

b) The EEG signal was extracted from the beginning of stimulation to 500 ms, i.e., the signal length was 500 ms. A time window of 10 ms was used to divide the signals into 50 smaller segments. The Brain Electrical Activity Mapping (BEAM) in each time window was plotted with EEGLab (*University of California, San Diego, USA*) and MATLAB software, from which the most active brain areas corresponding to the evoked sensations could be determined.

c) According to the BEAMs obtained in step *b*), the EEG channels were selectively extracted for ERP analysis, including the comparison of ERP curves with and without evoked sensations, as well as those for the amputee and able-bodied subjects. In each extracted channel, the ERP values were then averaged across eight experiment repeats for the amputee, and for the able-bodied, the ERP values were averaged across four subjects.

d) In order to compare the evoked sensations of different phantom fingers for the amputee, EEG channels were further selected from step *c*), and the ERP values were averaged across the selected channels. The latency for the averaged-ERP was calculated as the time from the beginning of stimulation to the highest peak of the averaged-ERP curve, and then the average values and standard deviations of the latencies for the different phantom fingers were calculated. Therein the standard values could demonstrate the longitudinal change of the ERP latencies for the same stimulation across days. Finally, the differences in ERP latencies and curve features were determined using ANOVA statistical analysis.

III. RESULTS

A. PHMs Induced by Mechanical Stimulation

Fig. 4 shows the PHMs for the amputee, which were marked based on mechanical stress stimulation. As it can be observed from the figure, sensations for all the five phantom fingers can be evoked. The evoked sensations can be seen to spread across different regions in a non-unique manner. Also, stimulating a specific position in the PHM may trigger sensations of multiple phantom fingers simultaneously. More specifically, a congruent relationship was observed between the sensation-evoking areas and the corresponding fingers. For instance, the stimulation area for the phantom thumb is mostly along the ulnar nerves, as shown in Fig. 4(a). The distribution of sensation-evoking areas is unequal for all the phantom fingers, and the one for the mixed phantom ring and little fingers covers most areas of the stump region. Fig. 4(b) indicates the sensation-evoking areas which correspond to only an individual phantom finger, which are quite limited except for the one corresponding to the phantom little finger.

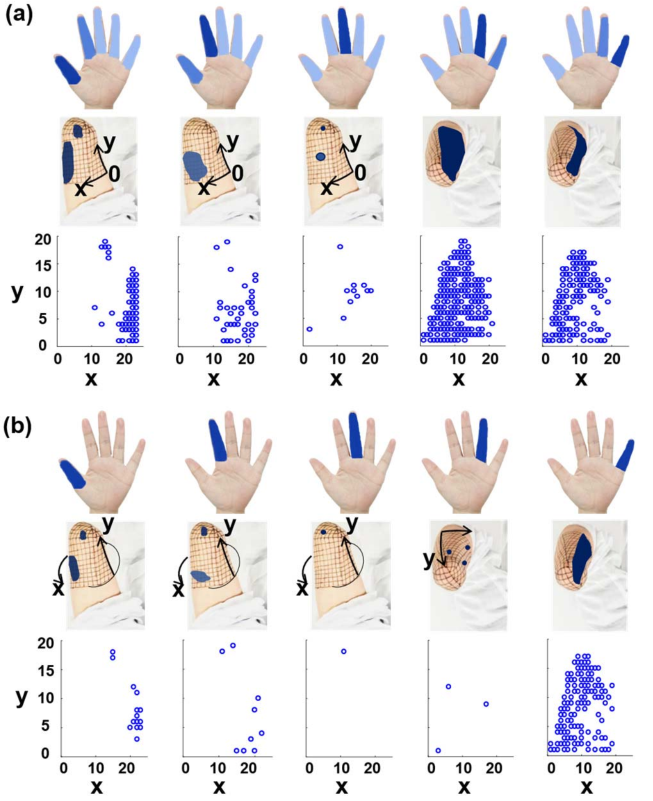

Fig. 4. PHMs achieved by mechanical stimulation for (a) mixed sensations of multi-fingers, where the sensation intensity is marked according to color depth; and (b) sensations of only an individual finger. The X and Y axes indicate the mesh number, where each mesh is 5 mm × 5 mm in size.

B. Sensations Evoked by TENS

Based on the PHMs analysis described in section III. *A.*, several positions were selected and verified for electrical stimulation, as mentioned in Fig. 2(b). Afterward, six positions were finally chosen for sensation evoking by TENS, as shown in Fig. 5. The sensations of phantom thumb, index, middle, ring, and little fingers, as well as palm, could be evoked by TENS at the stimulation positions of E1, E2, E3, E4, E5, and E6 in Fig. 5. The corresponding relationship between

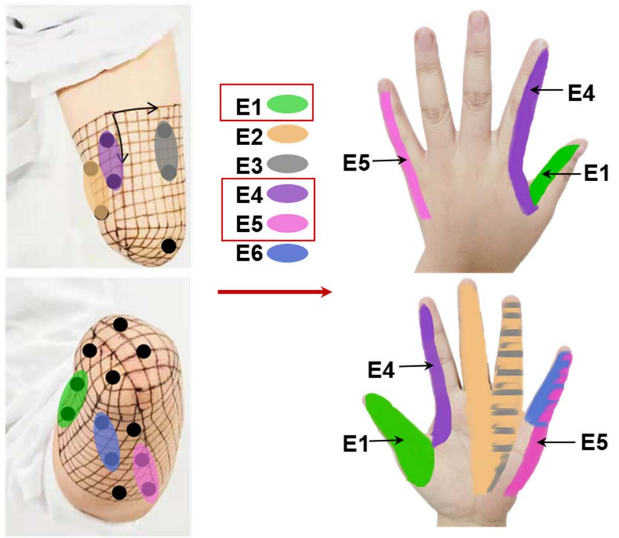

Fig. 5. The selected six positions of electrical stimulation (E1-E6) to evoke phantom finger sensations, where E1, E4, and E5 are proved to realize stable sensations. The positions of evoked sensations on phantom fingers and palm are also marked.

the sensation locations and the stimulation positions remained consistent over different days. Besides, eight repeated experiments demonstrated that stable sensations of phantom thumb, index, and little fingers could be individually evoked at the positions E1, E4, and E5.

In terms of the stimuli parameters, by adjusting the TENS configurations performed on the positions of E1-E6 at the stump, i.e., current amplitude, frequency, and wave width presented in TABLE I, different phantom finger sensations such as flapping, vibrating, pressing, touching, pain, itching, and tingling were evoked for the amputee. After eight repeated tests, the relationship between stimuli parameters and elicited phantom finger sensations was obtained and demonstrated in TABLE II. The amputee could not feel any phantom finger sensation when the current amplitude was less than 2.5 mA, indicating an amplitude threshold for sensation evoking. By increasing the current amplitude up to higher than 3 mA, stable sensations could be evoked, as reported by the subject. With relatively small wave width between 50-150 μs, slight sensations of touching or vibrating were reported, but when the wave width was increased to 200-300 μs stable flapping, vibrating, or pressing sensations were reported, using frequencies between 5 and 200 Hz. Besides, it was observed that there was sometimes a mixture of vibrating and pressing sensations within a parameter range. As expected, too high a current will evoke some uncomfortable or nociception like pain, itching, or tingling if the wave width is larger than 350 μs. Furthermore, the sensation types and corresponding parameters are the same for the three phantom fingers of the amputee. In addition, the corresponding relationship between sensation types and frequencies of TENS also remained consistent across different days, i.e., 5 Hz - flapping, 50 Hz - vibrating, and 200 Hz - vibrating and pressing. The TENS was also performed on the four able-bodied subjects' wrists skin to stimulate their median, ulnar and radial nerves, by using similar configurations as those used for the amputee, with the same frequencies (5, 50, and 200 Hz) and wave widths (200 and 300 μs) but different stimulus amplitudes (as shown in TABLE IV in the supplementary manuscript). Interestingly, experiment results showed that sensations of four able-bodied subjects' intact thumb, middle, and little fingers could also be evoked by TENS applied on wrist. Besides, the sensations types evoked for the able-bodied were the same as those for the amputee.

TABLE II
PARAMETERS OF TENS AND TYPES OF EVOKED SENSATIONS

Stimulation parameters			Types of sensations
Amplitude (mA)	**Frequency (Hz)**	**Wave width (μs)**	
1-2.5	5-200	5-500	No stable sensation
3-5	5-200	50-150	Light touching or light vibrating
3-5	5-20	200-300	Flapping
3-5	50	200-300	Vibrating
3-5	75-200	200-300	Vibrating and pressing
3-5	50-200	350-500	Pain, itching, or tingling

TABLE III
THE AVERAGE ± STANDARD DEVIATION OF ERP LATENCIES CORRESPONDING TO A PRESSING SENSATION ON THE AMPUTEE'S THREE PHANTOM FINGERS

Phantom fingers	ERP Latencies (ms)	*p*-value
Thumb	156.5±4.0	0.018
Index	150.4±1.7	
Little	167.8±5.2	

C. Brain Electrical Activity Mapping (BEAM)

The BEAM was investigated when sensations on the phantom thumb, index, and little fingers were stably evoked for the amputee via TENS. Fig. 6 shows the BEAM obtained when 50 segmented time windows, in the case of pressing on the phantom thumb was induced. As it can be seen, obvious electrical activities were noticed on the part of the scalp corresponding to the evoked phantom fingers. The activities were reinforced within the time period that is about 120 to 190 ms after the start of stimulation, as distinguishable according to the color changes in BEAM. Meanwhile, the scalp areas with intensive activities correspond to the following 16 EEG channels: F1, Fz, F2, F4, FC1, FCz, FC2, FC4, C1, Cz, C2, C4, CP1, CPz, CP2, and CP4. For the purpose of comparison, the BEAM obtained when no sensation was evoked by TENS due to low current (1mA) is illustrated in Fig. 7. That is, there is no noticeable electric activity in the BEAM since the TENS current is too low to evoke a sensation. The analysis of the BEAM for phantom index and little finger sensations of the amputee, as well as for the thumb, middle,

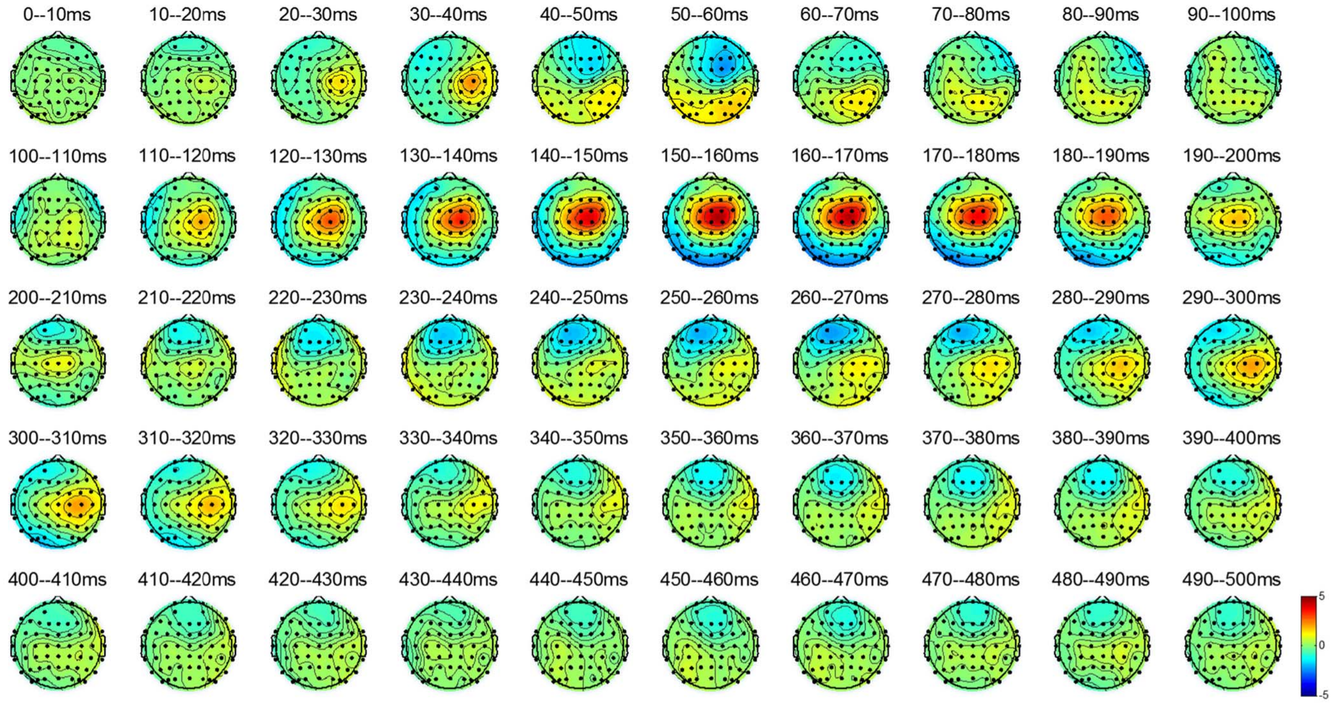

Fig. 6. The brain electrical activity mapping in 50 segmented time windows from the beginning of stimulation to 500 ms, when a pressing sensation on phantom thumb of the amputee was evoked by TENS (current amplitude = 5 mA, frequency = 200 Hz, pulse width = 300 μs).

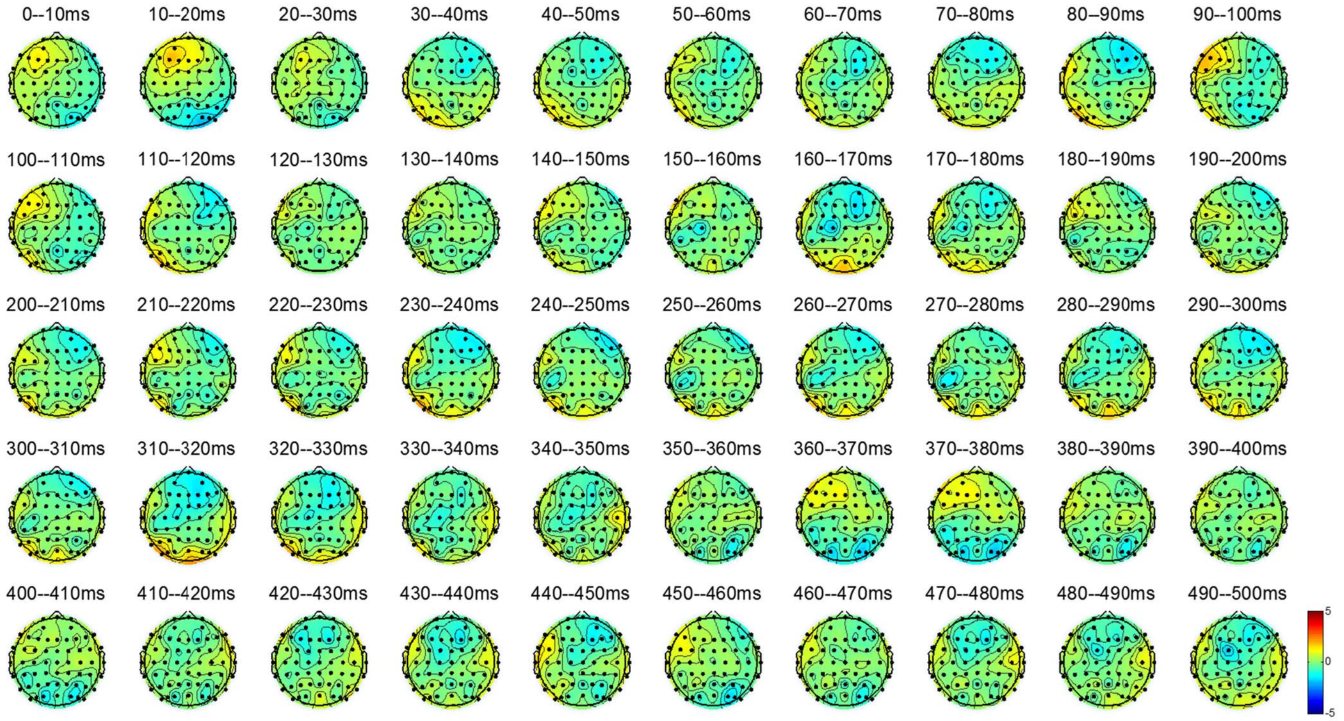

Fig. 7. The brain electrical activity mapping in 50 segmented time windows from the beginning of stimulation to 500 ms, when no sensation on phantom finger of the amputee was evoked by TENS (current amplitude = 1 mA, frequency = 200 Hz, pulse width = 300 μs).

and little finger sensations of the able-bodied subjects, showed consistent results as presented in Figs. 6 and 7, which are displayed in the attached files due to limited space of this article.

D. ERP Feature Analysis

EEG recordings from sixteen channels with intensive activities, i.e., F1, Fz, F2, F4, FC1, FCz, FC2, FC4, C1, Cz, C2, C4, CP1, CPz, CP2, and CP4 as mentioned in the above section,

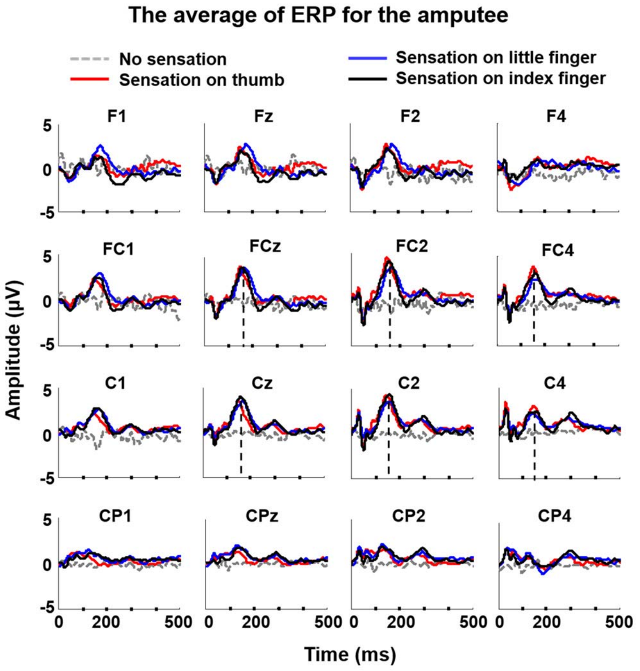

Fig. 8. The average ERP curves of eight experimental repetitions corresponding to a pressing sensation on the amputee's phantom thumb, index, and little fingers and to no sensation.

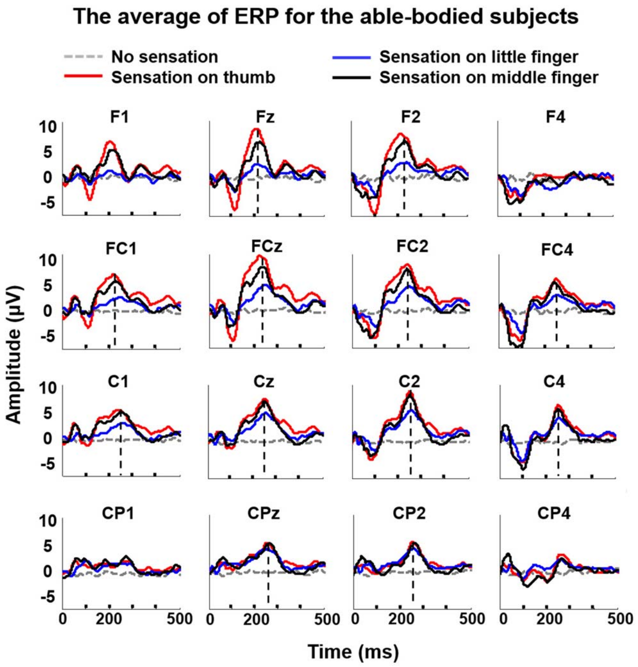

Fig. 9. The average ERP curves of four able-bodied subjects corresponding to a pressing sensation on their intact thumb, middle, and little fingers and to no sensation.

were extracted for the ERP analysis. Fig. 8 shows the averaged ERP curves across eight TENS experimental repetitions for the amputee. It can be seen that there are obvious peaks on the ERP curves in the time period of 100-200 ms when the phantom finger sensations are evoked, especially at channels of FCz, FC2, FC4, Cz, C2, and C4, with maximum amplitude up to 5 mA. No obvious ERP peak is observed without any sensation has been evoked. Interestingly, similar results were achieved with the dataset of the able-bodied subjects, in which the ERP curves are averaged across the subjects to calculate the able-bodied group value. As shown in Fig. 9, a significant peak occurs upon the evoked sensations in the time period of 200-300 ms, especially at the channels Fz, F2, FC1, FCz, FC2, FC4, C1, Cz, C2, C4, CPz, and CP2, and the maximum amplitude was up to 10 mA.

Subsequently, the ERP curves for the amputee were averaged across the six EEG channels that showed obvious peaks, i.e., FCz, FC2, FC4, Cz, C2, and C4, in each experimental repetition. Fig. 10(a) shows the averaged ERP curves for the different evoked phantom finger sensations across the eight experimental repetitions. Meanwhile, the analysis showed that there exists a significant difference ($p < 0.05$) among the three curves across eight experimental repetitions in the time periods of 48-64 ms, 81-96 ms, and 200-237 ms, as marked in Fig. 10(b). Besides, the average values and standard deviations of the latencies for the averaged ERP curves are presented in TABLE III. It is demonstrated that ERP latencies were changing over days but the differences were in a certain range, i.e., 152.5-160.5 ms for the thumb, 149.7-152.1 ms for the index finger, and 162.6-172.0 ms for the little finger. In a word, different phantom fingers show different ERP latencies, and the difference in ERP latencies among the evoked phantom thumb, index, and little fingers is statistically significant ($p < 0.05$).

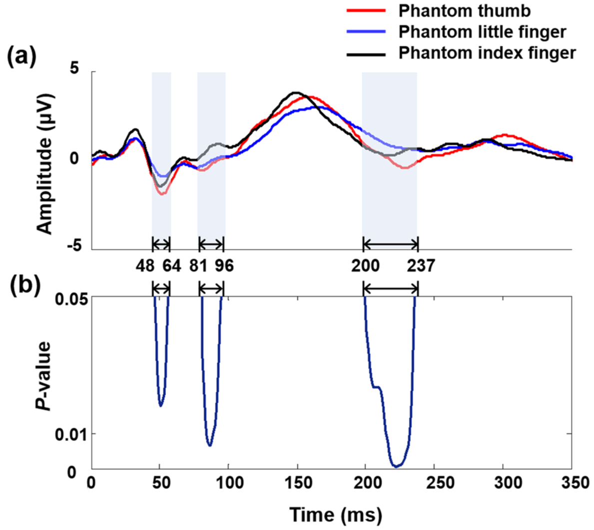

Fig. 10. (a) The averaged-ERP curves corresponding to a pressing sensation on the amputee's three phantom fingers, and (b) the calculated p-values where the difference is statistically significant (<0.05).

IV. DISCUSSION

Establishing intuitive sensory feedback for limb amputees has been a hot research topic in the field of neurorehabilitation and human-machine interaction in recent years. Several studies have successfully evoked different kinds of intuitive phantom finger sensations for limb amputees by using invasive electrical stimulation on the sensory cortex or peripheral nerves. However, such an invasive method is less acceptable, and its clinical application is limited partly due to post-surgery complications. It has been shown that sensations of phantom fingers can be induced by stimulating PHM on stump surfaces, which indicates the possibility of adopting a non-invasive approach for sensory feedback restoration. Interestingly, mechanical stimulation, e.g., pressure or vibration on PHM, can allow limb amputees to perceive the sensation of phantom fingers. Nevertheless, mechanical apparatus are often characterized by complicated structures that are not suitable for wearable applications, especially in the context of limb prostheses. In addition, mechanical stimulation can only induce relatively fewer types of sensation, which may not offer much benefit to amputees. In fact, mechanical stimulation is mostly used in scientific research for method exploration. In order to achieve an intuitive, multi-type, non-invasive, and easy to perform approach for sensory feedback restoration, researchers tried to use TENS to stimulate peripheral nerve endings on the residual stumps. TENS is a non-invasive and safe stimulation method that has been widely used in rehabilitation, and different stimulation patterns are easily realized by adjusting stimulus parameters. Some pilot studies have demonstrated TENS can evoke intuitive phantom finger sensations for limb amputees, and its effectiveness, safety, and stability have been preliminarily studied. In another aspect, clinic application of TENS-based sensory feedback is seldom seen up to now, and some still existing challenges may prevent this method, including accurate positions and effective parameters for stimulation. Therefore, in this work, we firstly focused on the sensory feedback method for limb amputees, where TENS of different patterns was used to evoke various sensations in different phantom fingers. Besides, mechanical stimulation was used to study the PHM on the amputee's stump in detail before adopting electrical stimulation in the current study. Thereafter, EEG was used as an objective tool to evaluate the sensations evoked when TENS with various configurations was utilized, and a comparison between the amputee and able-bodied subjects was also studied. Some interesting phenomena were observed in the experiments and statistically significant results were achieved, which are discussed in the following paragraphs.

By stimulating the amputee's stump surface with mechanical stress, the PHM corresponding to different phantom fingers could be easily determined. This result demonstrates that there exist nerve branches associated with the motor functions of lost fingers and such nerve branches may have regenerated on the stump after amputation. Overall, the results of the PHM analysis align with our expectation, where the stimulation positions for the thumb mostly correspond to the ulnar nerve, while for ring and little fingers, the positions correspond to regions near the radial nerve. It should be noted that the areas where sensations were evoked for different fingers are unequal, and the stimulation areas for the ring and little fingers obviously exceed those for the other three fingers. Additionally, sensations were felt on multiple fingers when stimulating a single position within the PHM. A possible reason is that the regenerated nerve fibers originally dominated multi-fingers. Another reason could be the irregular regeneration of the nerve branches/fibers for the different fingers. The sensation-evoking areas responsible for an individual phantom finger are quite small except for the little finger, which makes it difficult to locate accurate stimulation positions. Normally, inaccurate stimulation position is a shortcoming of the non-invasive method compared with the invasive approach, which can stimulate nerves directly with high accuracy. Nevertheless, mechanical stimulation can guarantee effective sensation-evoking areas for electrical stimulation. And the subsequently applied electrical stimulation proved that sensations of all five phantom fingers and the palm were successfully induced for the amputee in the study. After eight experimental repetitions which lasted for more than one-month, stable sensations of the phantom thumb, index, and little fingers were confirmed by the amputee and recognized for the subsequent experiments.

TENS configurations were varied by adjusting the stimulation parameters including amplitude, frequency, and wave width of the current, with which different types of sensation were successfully evoked for the amputee. A minimum amplitude of 2.5 mA is required to trigger a stable phantom finger sensation across the whole frequency and the wave width range adopted in this work. In general, the higher the amplitude, the stronger the sensation felt. Wave width is another parameter that determines the sensation intensity, where larger wave widths result in stronger phantom finger feelings, and too large wave widths may cause uncomfortable feelings or even hurt the subject. As we know, the current amplitude and wave width together decide the stimulus energy, and high amplitude and large wave width mean more energies are transmitted to the nerve system, resulting in a large number of recruited nerve fibers and strong responses of the sensory cortex. From another aspect, stimulus frequency determines the types of phantom finger sensation. When amplitude and wave width are fixed, increasing the frequency will make the sensations from flapping to vibrating and then to pressing, which is probably because different types of nerve fibers are fired by changes in stimulus frequency. This phenomenon is reasonable since high-frequency flapping leads to vibration sensation, and high-frequency vibrating can be recognized as continuous pressing by the brain. Besides, it is noted that there is always a mixture of sensations, like vibrating and pressing, because there might be a transition region between both kinds of sensations, in addition, the amputee's subjective judgments can be varied by different factors.

The stimulation experiments were performed on four able-bodied subjects, where similar TENS configurations were applied on their wrist areas corresponding to the ulnar, median, and radial nerves. Interestingly, intuitive sensations of the subjects' intact thumb, middle, and little fingers could be evoked in this way. In other words, by electrically stimulating their wrists, the able-bodied subjects reported intuitive feelings of their fingers. Furthermore, the sensation types that can be evoked are the same as those for the amputee, only with different stimulus parameters. This result could complement the evoking of intuitive phantom finger sensations for the amputee by stimulating the regenerated nerve fibers in the stump, i.e., a sensory pathway is established. In addition, results on the able-bodied subjects demonstrate that intuitive sensations of intact fingers can be induced by stimulating the wrist area, which may provide an alternative information afferent pathway. And this may aid the realization of some potential applications in the field of human-machine interaction systems.

The EEG recordings were used to objectively evaluate the performance of the sensory feedback approach in the current study. Thus, the BEAMs and ERP features were analyzed and the results were used to validate the evoked sensations reported by both amputee and able-bodied subjects. For instance, the BEAMs show that activities on specific areas of the scalp are visibly enhanced only when sensations are successfully induced by electrical stimulation, and these scalp areas correspond to the somatosensory cortex region. Also, the computed ERP peaks were observed only when stable sensations were reported by the subjects during the experimental sessions. On the other part, it is observed that there are some differences between the amputee and the able-bodied with respect to the characteristics of the evoked sensation. For the amputee, both the amplitude and latency of the maximum ERP peaks were smaller than those for the able-bodied. Some possible explanations can be analyzed, one is that the peripheral nerves regenerated in the stump were different in structure, performance, and characteristics from the intact nerve endings before amputation. The nerve fibers innervating the phantom fingers in the residual stump may be fewer, and less sensitive compared to those in the intact limb. The second explanation may be that the neural pathways of sensory information between the amputee and able-bodied subjects can be different. For the amputee, the TENS directly actives nerve endings (which were regenerated in the stump after amputation) and evokes sensations, so the sensory information is directly transferred from the stump to the brain. However, for the able-bodied subjects, the TENS actives the median, ulnar, and radial nerves, the electrical signals should be firstly transferred to nerve branches endings in the intact palm, and then sensations would be evoked and transferred from the palm to the brain. Besides, the extensive cerebral reorganization after amputation may result in differences in how the brains process information on amputees and able-bodied subjects [22], [36]. Based on the phenomenon observed in this study, some in-depth mechanism study on more subjects are expected. Additionally, statistical analysis shows that the difference among the ERP curves for the three phantom fingers is insignificant in most time intervals, especially within 50 ms before and after the maximum peak. It is statistically significant only within some limited time intervals, which may indicate the distinction in processing afferent sensory information of different phantom fingers during electrical stimulation by the amputee's brain. As for the ERP latency, their average ± standard values were shown in TABLE III, therein the standard values could represent the longitudinal change of the ERP latencies for the same stimulation across days. It demonstrated that ERP latencies were changing over days but the differences were in a certain range, i.e., 152.5-160.5 ms for the thumb, 149.7-152.1 ms for the index finger, and 162.6-172.0 ms for the little finger. Furthermore, the ERP latencies for the three fingers were significantly different. Therefore, there is a significant difference among the three phantom fingers, which may come from a different number, distribution, and sensitivity of the nerve fibers associated with different phantom fingers.

In summary, this work has re-established a sensory pathway between the lost hand and brain for upper-limb amputee based on stimulation via TENS while EEG recordings were used to verify the pathway. Nevertheless, it should be noted that there are still some limitations that need to be addressed. The amputee recruited in this study always has stable phantom limb sensations since his amputation occurred 13 years ago, and his PHM was easily located and then proved by stimulating the stump surface. However, not all limb amputees have phantom limb sensations, and the relationship between PHMs and phantom limb sensations is still not very clear, which will be studied on more amputee subjects in our future work. In the study, stable sensations of only three phantom fingers were verified while a few sensation types were recognized. Compared to the invasive sensory feedback method, the limited patterns and stimulation accuracy are always a shortcoming of the non-invasive method. In the future, a combination of multi-parameters including waveform, frequency, amplitude, and other indexes is suggested to increase the sensation types for more amputees. A model to simulate electric field distribution in skin and muscle is also suggested to achieve more accurate stimulations. For sensory feedback evaluation, in-depth analyses of functional connections in the sensory-motor cortex region of the brain should be studied to understand the complex brain activities related to sensory feedback.

V. CONCLUSION

In this work, we confirmed the effectiveness of a non-invasive sensory feedback approach in recovering the lost sensory function for an upper-limb amputee. PHM is determined and verified on the amputee's stump surface while intuitive and stable sensations of the phantom thumb, index, and little fingers were successfully induced by stimulating the PHM using TENS, as reported by the amputee. Different sensation types of flapping, vibrating, and pressing on the phantom fingers were achieved by adjusting the TENS configurations. Besides, it was found that intuitive sensations of intact fingers for the able-bodied subjects can be induced by TENS when applied on their wrist surface, which further demonstrates the established afferent pathway for sensory information. What is more, the evoked sensations were objectively evaluated with EEG, where BEAM and ERP features proved the brain's responses to the induced sensations.

REFERENCES

[1] F. Clemente *et al.*, "Intraneural sensory feedback restores grip force control and motor coordination while using a prosthetic hand," *J. Neural Eng.*, vol. 16, no. 2, Apr. 2019, Art. no. 026034.

[2] S. J. Bensmaia, D. J. Tyler, and S. Micera, "Restoration of sensory information via bionic hands," *Nature Biomed. Eng.*, Nov. 2020, doi: 10.1038/s41551-020-00630-8.

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

[4] B. Stephens-Fripp, G. Alici, and R. Mutlu, "A review of non-invasive sensory feedback methods for transradial prosthetic hands," *IEEE Access*, vol. 6, pp. 6878–6899, 2018.

[5] S. Flesher *et al.*, "Intracortical microstimulation as a feedback source for brain-computer interface users," in *Brain-Computer Interface Research* (Springer Briefs in Electrical and Computer Engineering), vol. 6. Cham, Switzerland: Springer, 2017, pp. 43–54, doi: 10.1007/978-3-319-64373-1_5.

[6] 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.

[7] L. H. Smith, T. A. Kuiken, and L. J. Hargrove, "Evaluation of linear regression simultaneous myoelectric control using intramuscular EMG," *IEEE Trans. Biomed. Eng.*, vol. 63, no. 4, pp. 737–746, Apr. 2015.

[8] M. Velliste, S. Perel, M. C. Spalding, A. S. Whitford, and A. B. Schwartz, "Cortical control of a prosthetic arm for self-feeding," *Nature*, vol. 453, no. 7198, pp. 1098–1101, Jun. 2008.

[9] 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, Art. no. eaau8892.

[10] A. Masteller, S. Sankar, H. B. Kim, K. Ding, X. Liu, and A. H. All, "Recent developments in prosthesis sensors, texture recognition, and sensory stimulation for upper limb prostheses," *Ann. Biomed. Eng.*, vol. 49, no. 1, pp. 57–74, Nov. 2020.

[11] L. E. Osborn *et al.*, "Prosthesis with neuromorphic multilayered e-dermis perceives touch and pain," *Sci. Robot.*, vol. 3, no. 19, Jun. 2018, Art. no. eaat3818.

[12] K. Li, Y. Fang, Y. Zhou, and H. Liu, "Non-invasive stimulation-based tactile sensation for upper-extremity prosthesis: A review," *IEEE Sensors J.*, vol. 17, no. 9, pp. 2625–2635, Mar. 2017.

[13] G. Gu *et al.*, "A soft neuroprosthetic hand providing simultaneous myoelectric control and tactile feedback," *Nature Biomed. Eng.*, Aug. 2021, doi: 10.1038/s41551-021-00767-0.

[14] L. Zollo *et al.*, "Restoring tactile sensations via neural interfaces for real-time force-and-slippage closed-loop control of bionic hands," *Sci. Robot.*, vol. 4, no. 27, Feb. 2019, Art. no. eaau9924.

[15] G. Risso *et al.*, "Optimal integration of intraneural somatosensory feedback with visual information: A single-case study," *Sci. Rep.*, vol. 9, no. 1, pp. 1–10, May 2019.

[16] D. M. Page *et al.*, "Motor control and sensory feedback enhance prosthesis embodiment and reduce phantom pain after long-term hand amputation," *Frontiers Hum. Neurosci.*, vol. 12, p. 352, Sep. 2018.

[17] S. N. Flesher *et al.*, "Intracortical microstimulation of human somatosensory cortex," *Sci. Translational Med.*, vol. 8, no. 361, Oct. 2016, Art. no. 361ra141.

[18] D. M. Page *et al.*, "Discriminability of multiple cutaneous and proprioceptive hand percepts evoked by intraneural stimulation with Utah slanted electrode arrays in human amputees," *J. Neuroeng. Rehabil.*, vol. 18, no. 1, pp. 1–19, Dec. 2021.

[19] D. W. Tan, M. A. Schiefer, M. W. Keith, J. R. Anderson, J. Tyler, and D. J. Tyler, "A neural interface provides long-term stable natural touch perception," *Sci. Transl. Med.*, vol. 6, no. 257, Oct. 2014, Art. no. 257ra138.

[20] G. Valle *et al.*, "Biomimetic intraneural sensory feedback enhances sensation naturalness, tactile sensitivity, and manual dexterity in a bidirectional prosthesis," *Neuron*, vol. 100, pp. 1–9, Oct. 2018.

[21] H. P. Saal *et al.*, "Simulating tactile signals from the whole hand with millisecond precision," *Proc. Nat. Acad. Sci. USA*, vol. 114, no. 28, pp. 5693–5702, Jul. 2017.

[22] A. Bj?rkman *et al.*, "Sensory qualities of the phantom hand map in the residual forearm of amputees," *J. Rehabil. Med.*, vol. 48, no. 4, pp. 365–370, 2016.

[23] A. Akhtar *et al.*, "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), vol. 8619. Berlin, Germany: Springer, Oct. 2014.

[24] 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.

[25] 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.

[26] 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.

[27] 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.

[28] K. Choi, "Two-channel electro-tactile stimulation for sensory feedback of fingers of prosthesis," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst (IROS)*, Oct. 2016, pp. 1133–1138.

[29] K. A. Kaczmarek, J. G. Webster, P. Bach-y-Rita, and W. J. Tompkins, "Electrotactile and vibrotactile displays for sensory substitution systems," *IEEE Trans. Biomed. Eng.*, vol. 38, no. 1, pp. 1–16, Jan. 1991.

[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] H. Shin, Z. Watkins, H. Huang, Y. Zhu, and X. Hu, "Evoked haptic sensations in the hand via non-invasive proximal nerve stimulation," *J. Neural Eng.*, vol. 15, no. 4, Aug. 2018, Art. no. 046005.

[32] E. D'Anna *et al.*, "A somatotopic bidirectional hand prosthesis with transcutaneous electrical nerve stimulation based sensory feedback," *Sci. Rep.*, vol. 7, no. 1, pp. 1–15, Sep. 2017.

[33] 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.

[34] G. Granata *et al.*, "Phantom somatosensory evoked potentials following selective intraneural electrical stimulation in two amputees," *J. Int. Fed. Clin. Neurophysiol.*, vol. 129, pp. 20–1117, 2018.

[35] H. Wang *et al.*, "Towards determining the afferent sites of perception feedback on residual arms of amputees with transcutaneous electrical stimulation," in *Proc. 37th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. (EMBC)*, Aug. 2015, pp. 3367–3370.

[36] I. Strauss *et al.*, "Characterization of multi-channel intraneural stimulation in transradial amputees," *Sci. Rep.*, vol. 9, no. 1, pp. 1–14, Dec. 2019.