Study of Tactile Sensation Somatotopy and Homology Between Projected Fingers in Residual Limb and Natural Fingers in Intact Limb

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***Abstract*— Object: Based on the comparisons of the somatosensory event-related potentials (ERPs), the object of this study is to investigate the underlying cognition mechanism of somatotopy and the homology of tactile sensation between the projected fingers in the residual limb and the natural fingers in the intact limb. Methods: One amputee subject and three able-bodied subjects were recruited. The forearm amputee had a clear projected finger mapping (PFM) that could evoke the tactile sensation of the entire five missing fingers. Transcutaneous electrical nerve stimulation (TENS) was used to evoke the sensation pattern of touch. Stimulation locations were divided into three groups: the locations of Group PA (projected-finger of amputee-subject) were located on the entire five projected fingers for the amputee subject, the locations of Group NA (natural-finger of amputee-subject) were located on the entire five natural fingers for the amputee subject, and the locations of Group NH (natural-finger of healthy-subject) were located on the bilateral natural index fingers for the able-bodied subjects. The somatosensory ERPs evoked by the stimulations were recorded. We measured the latency and amplitude of the ERP components and made statistical analyses for them. Main results: Since the ERP components of the early-stage are similar for both the stimulation in the projected fingers and the natural fingers, it can infer that the delivery pathway of the projected finger was similar to that of the natural finger. The second finding of the study is that, as the processing of sensory sensation in the cortex of the three groups is similar, it can also infer that the somatosensory evoked by the external stimuli are also similar. Conclusion: The present findings suggest that the somatotopy and the homology of tactile sensation between the projected fingers in the residual limb and the natural fingers in the intact limb have evident uniformity. We infer that the median nerve and the ulnar nerve of the peripheral nerve may divaricate new pathways, and these pathways would have been linked to the PFM.**

***Index Terms*— Projected finger mapping (PFM), tactile sensation, somatosensory mechanism, transcutaneous electrical nerve stimulation (TENS), event-related potential (ERP).**

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This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Local Ethics Committee.

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I. Introduction

THE tactile sensation of the hand plays an important role in contact and manipulation with the physical world for human beings [1], [2]. For amputees, they would lose the target of the motor control (related to the efferent pathway) and the function of the tactile sensory feedback (related to the afferent pathway) corresponding to the lost hands [2], [3]. In recent decades, with the development of technology, scientist and engineer worked together to develop myoelectric prosthetic hands to restore voluntary motor control [4], [5], [6]. Currently, control of myoelectric prosthetic hands is guided via vision. Visual feedback could improve the control of the myoelectric prosthetic hand to some extent. However, for able-bodied subjects with intact limbs, interaction with the physical world of the hand mostly relies on tactile sensory feedback. Without sensory information, current prosthetic hands cannot achieve amputees' expectations, and thus leads to the amputee would hardly elicit the embodiment of the prosthetic hand into the body of the user [7], [8], [9]. And then amputees would reject using prosthetic hands [3]. Because of the drawbacks of current prosthetic hands, it is important to develop novel prosthetic hands with sensory feedback to help the user realize the restoration of tactile sensation.

Tactile sensory feedback has become an important research topic in recent years [3], [10], [11], [12] since sensory feedback restoration enables amputees to interact with the environment intuitively and effectively. Several approaches [3], [10], [11], [12] have been proposed to build artificial interfaces

for the prosthetic hand to interact with the residual sensory nerve pathway. By imitating the function of the receptor in the intact limb, the restoration mechanism is realized via artificial interfaces to transduce external stimuli into electrical signals and then transfer them to the brain. The classification of the artificial interface has two manners. First, in view of the type of interface, the artificial interface could have two types, invasive and non-invasive interfaces. For the invasive interface, the tactile stimulus is directly delivered into the brain [13], [14] or the nerves [15], [16], [17], [18]. For the non-invasive interface, tactile stimuli are indirectly delivered to the brain [19] or nerves [20], [21], [22], [23], [24]. For example, researchers found that stimulation on the different areas of the stump skin could evoke the sensation in the different missing fingers and named the area related to the missing finger as the projected finger, thus implying that this mapping phenomenon (called as projected finger mapping) could be exploited to convey sensory feedback [25]. Compared to the invasive interface, the non-invasive interface is much more acceptable for amputees [3]. Second, considering the type of restoration, the artificial interface could have two types, sensory rebuild [15], [16], [17], [18], [21] and sensory substitution [22], [23]. Compared to the sensory substitution that is building a new sensory stream to the brain and needs the users to learn via days of training [26], the sensory rebuild is trying to connect the tactile stimulation via the residual nerve pathway, where thus sensory rebuild is a natural way to be able to deliver more kinds of tactile sensations intuitively without learning [3], [27].

By considering the application potential for practical prosthetic hands, we are focusing on the techniques that can combine the non-invasive and sensory rebuild. Among non-invasive interface and sensory rebuild technologies, projected finger mapping (PFM) combined with TENS is capable of building a stable sensory interactive interface of tactile sensations of the lost hand [21], [27], [28]. The PFM is located in the skin of the distal of the forearm stump, and can evoke the tactile sensation of the missing fingers while different parts of the PFM are stimulated by mechanical or electrical stimuli. The evoked tactile sensation (ETS) is as if the missing finger is being touched, where, by adopting magnetoencephalography (MEG) and electroencephalogram (EEG), researchers have shown that the location and characteristic of the cortex activity of the projected finger are similar to that of the natural finger [21], [29]. Based on previous research, the restoration approach based on PFM accords with the characteristics of somatotopy and homology to some extent. In the somatotopy aspect, the projected finger in the PFM matches the location of the corresponding phantom finger. For example, when the projected finger of the index in the specific part of PFM is pressed, the phantom finger of the index in the contralateral cortex will perceive the mechanical pressure [21]. In the homology aspect, the stimuli on the projected finger will intuitively evoke a similar sensation for the corresponding phantom finger. By encoding the electrical stimulation parameters, the projected finger can evoke the phantom finger to generate sensation patterns such as touch, buzz, vibration, numbness, and tingling [27], [30].

Previous research had revealed the neural basis of PFM via MEG [21], implying that there may be a neural pathway between the cutaneous mechanoreceptors under the skin of the projected finger and the contralateral somatosensory area of the phantom finger in the brain. In [21], the results also showed that the activation region evoked by the projected finger was mirror symmetric with the activation region of the contralateral healthy finger in the sensory cortex. Research by [27] revealed that ETS has psychophysical characteristics of various perceptual elements and provided the feasibility to realize multimodal perceptual information coding via using ETS.

Studies have successfully used PFM to restore the nerve pathway of tactile sensory feedback and control the next-generation prosthetic hand that enables amputees to identify the size, stiffness, and texture of the object in the physical world [21]. However, the sensory mechanism underlying the cognition processing of tactile sensory feedback from the PFM to the cortex remains elusive. Furthermore, limited by the samples, the complete cognition comparison of all five fingers (thumb, index, middle, ring, and little) between the PFM and the natural hand has not been reported. We also would like to find more evidence to support the application of non-invasive sensory feedback restoration which is based on the PFM and TENS.

For this reason, we recruited an amputee subject whose PFM could evoke the tactile sensation of the entire five fingers of the missing hand and three able-bodied subjects. Then we adopted the TENS to stimulate the projected finger and the nature finger respectively and recorded the scalp EEG to evaluate the similarity and difference in the evoked cortex activity between the PFM and the natural hand. The purpose of this paper is to study tactile sensation somatotopy and homology between projected fingers in the residual limb and natural fingers in the intact limb. The main contributions of this study are as follows. 1) How tactile sensory feedback improves the rehabilitation of amputees is still unclear, where in this study it offers the opportunity to investigate the rehabilitation mechanism in the aspect of cognition mechanism for tactile sensation. 2) Based on the analysis of the somatotopy and homology, this study supports the inference that there may have a link between the cutaneous mechanoreceptors under the skin of the projected finger and the contralateral somatosensory area of the phantom finger in the brain just as the natural finger has.

II. Materials and Methods

A. Subjects

One forearm amputee subject (male, 55 years old) and three able-bodied subjects (all male; mean age $\pm$ SD $= 25 \pm 1$) are recruited. The identity of the recruited amputee is a farmer, and the identities of the three able-bodied subjects are graduate students. The right forearm of the recruited amputee has been lost in a traffic accident 8 years ago. In our early screening, we found that the recruited amputee had a clear PFM which could evoke the tactile sensation of the entire five fingers (thumb, index, middle, ring, and little) and palm of the missing hand, and was even able

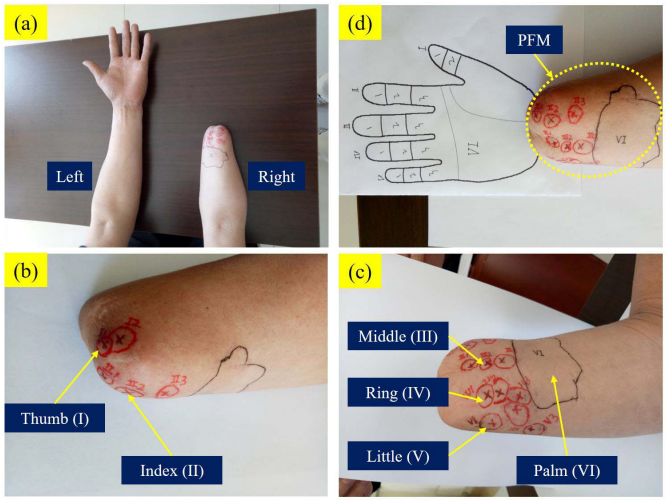


Fig. 1. One recruited forearm amputee with the evoked tactile sensation of the whole five missing fingers in PFM. (a) Right residual limb and left healthy limb. (b) Lateral view of the PFM that corresponds to Thumb (I) and Index (II) fingers. (c) Front view of the PFM that corresponds to Middle (III), Ring (IV), Little (V) fingers, and the Palm (VI). (d) Whole view of the PFM.

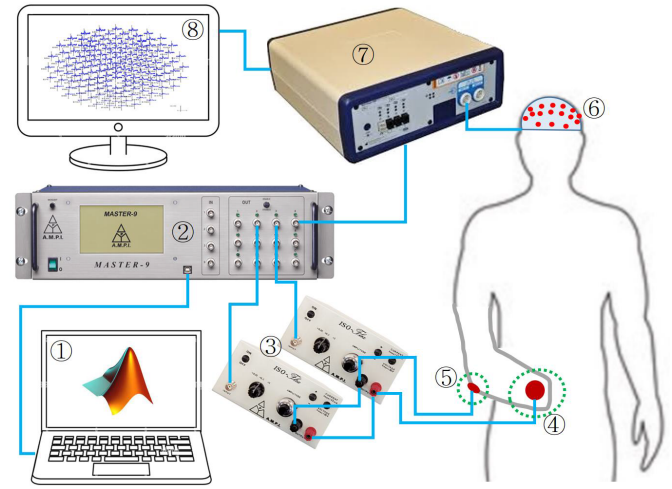
to distinguish the finger sections. The PFM configuration is shown in Fig. 1. Each subject was informed of the procedure of the experiment and signed written informed consent. The study was approved by the local Ethics Committee. In addition, each subject does not have a mental disease and take drugs in recent three months.

B. Experimental Platform

The experimental platform is shown in Fig. 2. Different than FES (functional electrical stimulation) which is usually used to stimulate the muscles to induce the movements of muscles and joints, TENS is usually used to stimulate the nerves to induce kinds of sensation. The TENS stimulator is composed of a Master-9 stimulator and two isolators (A.M.P.I Com., Israel). The Master-9 stimulator is a programmable device, where through the program, different types of stimulation parameters (current amplitude, frequency, and pulse width) could evoke different patterns of tactile sensation [21], [27]. In Fig. 2, a Matlab-installed computer is used to control and program the Master-9 stimulator. According to previous research [21], [22], [27], [29], multi-pulse of biphasic, rectangular, and charged-balanced current pulses are produced to evoke tactile sensation (see Fig. 3(a)). Two surface electrodes (circle, 2 cm in diameter) are used in this experiment. One surface electrode is located on the skin surface of the specific projected finger in the PFM, and the other is located on the skin surface of the olecranon. In this experimental platform, an EEG acquisition device (EGI Com., USA) with 256 channels is used. The synchronization between electrical stimuli and EEG acquisition is realized by using a single of Transistor-Transistor Logic (TTL) pulse as the synchronization single.

C. Stimulation Paradigm

The stimulation paradigm and the stimulation parameters are shown in Fig. 3. The stimulation paradigm is in the form



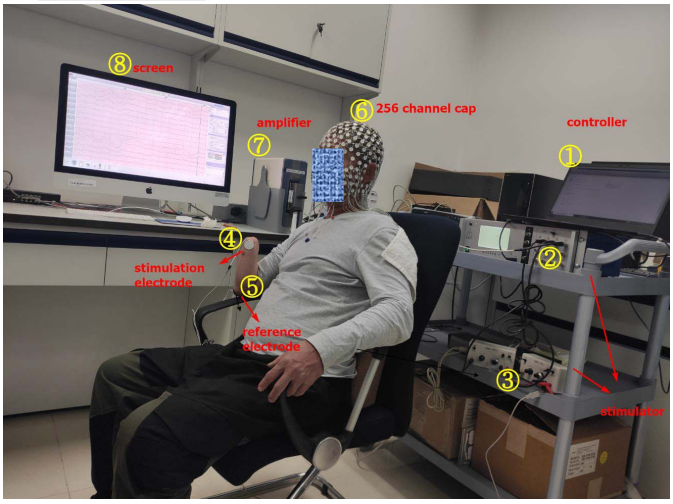


Fig. 2. Schematic plot and actual figure of the experimental platform. ① controller; ② Master-9 stimulator; ③ ISO-Flex isolators; ④ stimulation electrode in PFM; ⑤ reference electrode; ⑥ EEG cap; ⑦ EGI EEG amplifier; ⑧ screen.

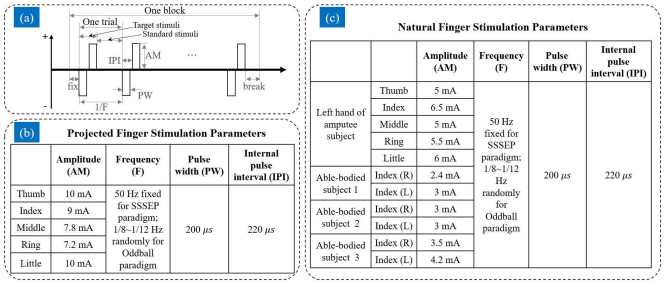


Fig. 3. Stimulation paradigm and stimulation parameters. (a) Stimulation paradigm. (b) Projected finger stimulation parameters. (c) Natural finger stimulation parameters.

of multi-pulse of biphasic, rectangular, and charged-balanced current pulses. According to previous research, the pulse width (PW) is set as 200 μs, and the internal pulse interval (IPI) was set as 220 μs [21], [31].

The experiment is divided into two parts, a preliminary experiment, and a formal experiment. The purpose of the preliminary experiment is to determine the PFM stimulation

parameters. The purpose of the formal experiment is to evoke cortex EEG corresponding to the TENS.

In the preliminary experiment, the SSSEP paradigm (steady-state somatosensory evoked potential) is considered as a suitable paradigm to evoke a strong somatosensory sensation [22]. Since the PFM configuration had been obtained in the screening procedure, the preliminary experiment is necessary to further determine the stimulation parameters. In early studies [21], [22], [32], it is suggested that the stimulation frequency ranged from 20 to 50 Hz, where high frequent stimulation (50 Hz) evokes buzzing and low frequent stimulation (20 Hz) evokes vibration. Since the buzz sensation has the advantage of owning a wide modulation range [21], this advantage can be used to find the boundary for the wide range of tactile sensations. Therefore, a stimulation frequency of 50 Hz was used throughout the preliminary experiment. Via setting pulse width, the purpose of using high frequency (50 Hz) is to evoke a wide, strong, and clear sensation response of tactile to find the infimum and supremum thresholds of the finger ETS for each projected finger in PFM and then determine the current amplitude of the stimulation. The current amplitude is modulated at a rate of 1 mA ranging from 2 to 15 mA to obtain the rough boundary of the stimulation threshold quickly, and then the current amplitude is modulated at a rate of 0.1 mA ranging from rough infimum/supremum thresholds – 1 mA to rough infimum/supremum thresholds + 1 mA to obtain the accuracy infimum threshold and supremum threshold. In the procedure of finding the threshold, the amputee is asked to self-report the sensation feeling of stimulation in the projected finger. In order to stimulate with the same level of tactile sensation, the authors adopt the approach that the amplitude of stimulation current is set as 1.5 times the infimum threshold for each projected finger and natural finger [29]. The current amplitude of stimulation for each projected finger in PFM is listed in Fig. 3(b). The stimulation parameters for natural fingers are listed in Fig. 3(c). In the preliminary experiment, one block would last about 60 seconds.

In the formal experiment, the purpose of the stimulation based on the Oddball paradigm [33] is to elicit the ERP. Oddball paradigm tends to be perceptually more novel than the repeated stimulus (such as SSSEP) and more relevant to the ongoing task and can be used to investigate sensory and cognitive processing [34]. For the Oddball paradigm, stimuli that are rare and intrusive are more likely to elicit ERP. Therefore, as shown in Fig. 3(a), each trial includes two phases, the standard stimuli phase, and the target stimuli phase. In the standard stimuli phase, blank without any electrical stimulation is set as frequent stimuli; in the target stimuli phase, random electrical stimulation is set as rare stimuli. During the standard stimuli phase, the recruited subject is requested to start counting when the target stimuli had disappeared and stop counting when the next target stimuli appeared [35], [36]. The stimulation frequency of the target stimuli was randomly changed from 1/8 to 1/12 Hz, so the duration of the interval between two neighboring target stimuli was randomly changed from 8 to 12 seconds. In the formal experiment, one block included 15 trials and each task included 10 blocks, where one task is related to one corresponding finger. Therefore, the amputee subject needs to complete 5 fingers $\times$ 10 blocks $\times$ 15 trials $=$ 750 trials for each unilateral upper limb; each able-bodied subject needs to complete 1 finger $\times$ 10 blocks $\times$ 15 trials $=$ 150 trials for each unilateral upper limb.

D. Evaluation Method

All experimental results are divided into three groups (named Group PA, Group NA, and Group NH, respectively) based on three different stimulation conditions. The stimulation condition of Group PA is the stimuli stimulated in the projected fingers of the amputee subject. The stimulation condition of Group NA is the stimuli stimulated in the natural fingers of the amputee subject. The stimulation condition of Group NH is the stimuli stimulated in the natural fingers of the healthy able-bodied subjects.

In the formal experiment, the evaluation is objective. The evaluation is based on the EEG recording data. The EEG epoch for EEG signal extraction is from -200 to 500 ms, where the time of the corresponding target stimuli is 0 ms. The original sampling rate of the EEG recording is 1000 Hz. Electrodes are placed according to the 10-20 systems. The reference electrodes are bilateral mastoid electrodes. The ground electrode is the COM (short for Common ground) electrode. A band-pass filter is set as 1 to 30 Hz. A 49-51 Hz notch filter is used to diminish power line interference. The Independent Component Analysis (ICA) algorithm is used to optimize artifact rejection. To reduce the calculation cost reasonably, the major 150 scalp channels are extracted from 256 channels.

1) EEG Evaluation: In this experiment, the Cz channel of the cap is selected for ERP analysis. ERP values are averaged among the corresponding 150 trials for each projected finger or natural finger. The comparison of averaged-ERP would be between the stimulations in the projected finger and the natural finger. The latency and amplitude of the peaks in the averaged-ERP are recorded.

By analyzing the peaks in averaged-ERP, the corresponding mapping of brain electrical activity can show the temporal and spatial changes of the cortex activities.

2) Statistical Analysis: For the latency and the amplitude of each peak of the ERP component, Spearman correlation analysis is performed since the samples are limited. The factor of the correlation analysis is the grade of different groups (stimulation condition: Group PA versus Group NA versus Group NH). One-tailed Spearman correlation test is used in the statistical analysis. The statistical significance is set as Sig. < 0.05.

III. Results

A. Stimulation Results

In our experiment, one right forearm amputee subject and three healthy able-bodied subjects were recruited. For the amputee, the target stimulations were five projected fingers in his right upper limb and five natural fingers in his left upper limb, respectively. For able-bodied subjects, the target stimulations were the corresponding right and left natural index fingers. The justification for choosing the index finger is

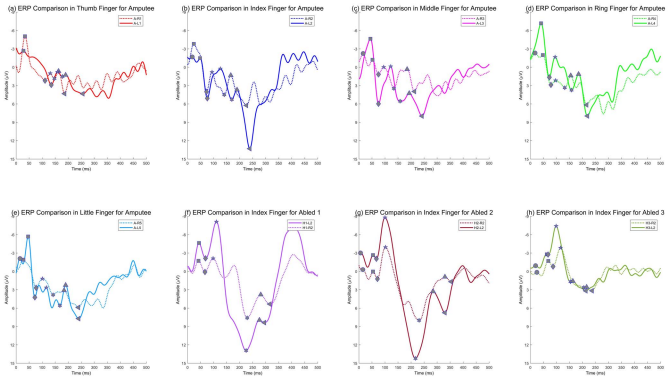


Fig. 4. Averaged-ERP results for the corresponding fingers. Each ERP curve in (a) ∼ (h) was labeled with (A/H1∼3) – (R1∼5/L1∼5): A was short for amputee; H1∼3 represented the first to the third able-bodied subject; R1∼5/L1∼5 represented the corresponding right or left finger. The circle, square, diamond, pentagram, hexagram, upper triangle, and left triangle denoted the peaks of N20, N50, P80, N100, P200, N200, and P300, respectively.

based on the concerns on the balance of sample numbers, neuromechanism [42], hand function [47], and sensitive level [48].

All the subjects reported that the electrical stimulations could evoke the tactile sensation at the level of touch sensation. The mean current amplitudes of electrical stimulation are 8.8 ± 1.2728 mA, 5.6 ± 0.6519 mA, and 3.1833 ± 0.608 mA for the projected fingers of the amputee subject, the natural fingers of the amputee subject, and the natural fingers of the able-bodied subjects, respectively.

From the stimulation results, it is evident that the current amplitudes of the electrical stimulation for the projected fingers are much larger than those for the natural fingers. The correlation coefficient is -0.947 (Sig. $= 1.29\text{e-}8 < 0.05$).

B. EEG Results

Our data consists of four subjects' EEG recording data. We chose the averaged-EEG response of electrode Cz to analyze the somatosensory components in the evoked potentials. The mean ERP waveforms are shown in Fig. 4. In Fig. 4, there are seven components in the ERP waveforms, N20, N50, P80, N100, P200, N200, and P300, in which the last six components can be found in the ERP waveforms of each subject. N20, N50, and P80 are the early-stage components; N100 and P200 are the middle-stage components; N200 and P300 are the later-stage components. The detailed information including latency and amplitude of each component is shown in Fig. 5.

C. Detailed Information of ERP Components

In Fig. 4 and Fig. 5, they show the components of ERP waveforms as temporal distribution. The results of the spatial distribution of the components are shown in the grand-averaged brain electrical activity mapping (see Fig. 6). In the spatial distribution of early-stage components, the regions of the corresponding somatosensory associated cortex have higher evoked potential. Then in the middle-stage, the activated regions of the cortex move forward, and the

Finger		Component	N20		N50		P80		N100		P200		N200		P300	
			t	Am	t	Am	t	Am	t	Am	t	Am	t	Am	t	Am
Amputee	Thumb	R	-	-	34	-5.06	111	2.19	131	1.01	147	1.85	163	0.65	186	4.32
		L	-	-	28	-2.68	135	2.89	159	0.77	178	1.52	190	1.27	256	4.33
	Index	R	-	-	24	-3.81	73	4.01	94	0.80	141	4.50	166	1.32	226	6.24
		L	18	-1.68	48	-1.48	76	5.08	126	0.24	170	5.27	190	3.69	239	13.30
	Middle	R	16	-2.24	52	-1.21	75	1.17	95	-0.02	134	3.47	185	0.34	213	3.96
		L	-	-	44	-4.65	75	5.98	122	-0.12	158	5.55	193	4.26	242	7.98
	Ring	R	18	-2.32	48	-1.99	79	2.88	97	2.16	132	3.35	155	1.37	216	6.15
		L	-	-	41	-7.17	73	1.65	95	-1.66	158	3.73	185	1.14	219	7.97
	Little	R	-	-	28	-1.92	77	2.69	101	1.20	142	3.83	184	3.11	239	5.89
		L	15	-2.10	46	-5.70	72	4.24	116	2.65	168	5.58	190	2.25	240	7.71
H1	Index	R	-	-	42	-1.73	67	0.09	98	-2.12	229	7.59	281	3.80	316	5.34
		L	-	-	44	-4.64	69	-2.14	111	-8.11	225	12.93	276	7.95	295	8.37
H2	Index	R	-	-	54	-2.66	67	-2.06	100	-8.80	217	14.22	285	3.29	330	6.75
		L	15	-0.29	54	0.03	71	1.22	102	-3.96	231	8.00	330	0.89	354	1.68
H3	Index	R	20	-0.94	63	-2.79	68	-2.75	99	-7.40	154	1.69	163	1.59	213	3.17
		L	25	0.15	69	-1.71	87	-0.79	116	-3.85	205	2.64	216	2.56	237	3.16

Fig. 5. Latency and amplitude of each ERP component for four subjects. R is short for the right and L is short for left. t denotes the latency of the ERP peak and its unit is millisecond. Am denotes the amplitude of the ERP peak and its unit is μV.

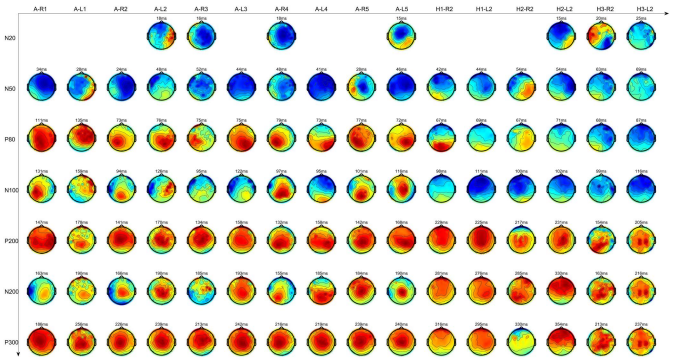


Fig. 6. Grand-averaged brain electrical activity mapping. A deeper red color represents a higher evoked potential, and a deeper blue color represents a lower evoked potential.

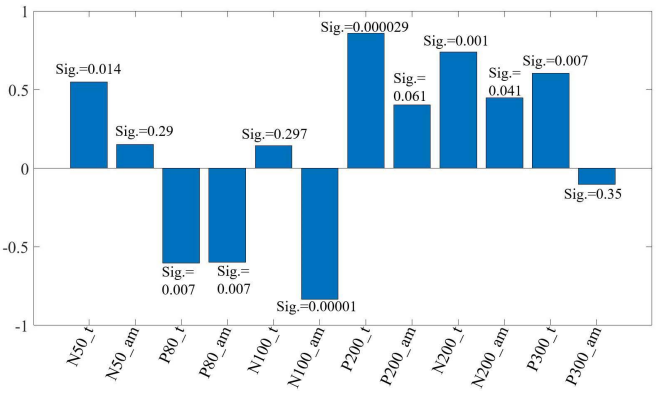


Fig. 7. Correlation analysis of the latency and amplitude of each ERP component between three groups.

corresponding regions of the primary somatosensory cortex are activated. In the later-stage, the grand cortex is activated.

To analyze the influence on the components of ERP waveforms, we performed a correlation analysis among the three stimulation conditions. The results of the analysis are shown in Fig. 7. The analysis focus on six components. In Fig. 7, the subscript with t denotes the correlation analysis of the latency of the component; the subscript with am denotes the correlation analysis of the amplitude of the component. Based on the results shown in Fig. 7, the mean latency and mean amplitude of each ERP component among three groups are listed in Table I.

TABLE I
MEAN LATENCY AND MEAN AMPLITUDE OF EACH ERP COMPONENT AMONG THREE GROUPS

Class	Component	Group PA	Group NA	Group NH
Mean latency (unit:ms)	N20	17±1.41	16.5±2.12	20±5
	N50	37.2±12.3	41.4± 7.92	54.33±10.48
	P80	83±15.81	86.2±27.32	71.5±7.74
	N100	103.6±15.55	123.6± 23.11	104.3±7.39
	P200	139.2±6.14	166.4± 8.53	210.17±29.11
	N200	170.6±13.31	189.6±2.88	258.5±59.25
	P300	216±19.61	239.2±13.22	290.83±55.01
Mean amplitude (unit: μV)	N20	-2.28±0.06	1.89±0.3	-0.36±0.55
	N50	-2.8±1.59	-4.34 ± 2.29	-2.25 ± 1.55
	P80	2.59 ± 1.04	3.97 ± 1.72	-1.07 ± 1.52
	N100	1.03 ± 0.79	0.37 ± 1.56	-5.7 ± 2.74
	P200	3.4 ± 0.98	4.33 ± 1.75	7.84 ± 5.13
	N200	1.36±1.07	2.52±1.41	3.34±2.5
	P300	5.31±1.09	8.26±3.21	4.75±2.52

1) N20: The component of N20, similar to N10 in some other research, is one of the rare ERP components [37], [38]. As shown in Fig. 5, the component of N20 appears in all three groups. However, since the N20 wave is considered as a subcortical component and hard to observe, the component of N20 was not found in each finger. Hence, the correlation analysis of N20 was not performed. The N20 wave is observed at 10∼25 ms

2) N50: The N50 component reflects the action potentials when the peripheral nerve stimulus reaches the cortical region [24], and is then observed at approximately 50 ms. In Fig. 4 ∼ Fig. 6, the N50 wave is the first common component in each finger among the three groups.

3) P80: The P80 waveform appears at about 80 ms following the N50 waveform, and it is the first typical positive potential that responds to the somatosensory stimulus. Fig. 6 shows that the P80 component is activated in the regions of the somatosensory associated cortex. The P80 amplitude of the amputee is much higher than that of the healthy able-bodied subjects. For P80, the brain activity mappings of the amputee have significant symmetry for the right and left stimulus.

4) N100: In the experimental results, the N100 component is observed around 94 ∼ 159 ms. As mentioned above, the amputee has a higher potential for the P80 component than healthy subjects, and meanwhile, the P80 potential of the amputee depolarizes more slowly than that of healthy subjects. Therefore, as shown in Fig. 6, the color of the brain activity mappings of the amputee is much deeper red.

5) P200: Together with N100 and P200, these two components are called the vertex potential [37]. As shown in Fig. 6, the primary somatosensory cortex which locates in the parietal lobe region is activated in three groups.

6) N200: The stage of N200 and P300 is usually considered as the stage of cognition. In this experiment, the N200 component is not a typical N2 [37] waveform as it has a much higher potential. In previous research, N2 potential responses to the focusing of spatial attention on the target location [39], [40]. In each block of the experiments, the stimulation location was fixed. Subjects did not need to pay too much attention to spatial attention to identify the stimulation position, and therefore the amplitude of N200 following P200 did not decrease quickly.

7) P300: P300 component is usually elicited by unpredictable and infrequent task-relevant shifts [33]. In this experiment, four subjects successfully elicited P300 waveforms. In Fig. 5, the brain activity mappings of P300 show that the entire cortex of each subject is activated.

IV. DISCUSSIONS

The phenomenon that the distal skin in the stump of some forearm amputees has preserved the sensation of the missing finger has been reported for many years [28], [41]. However, the cognition mechanism of sensory sensation of this phenomenon is still unclear. This section will in two aspects, delivering sensory sensation from the skin to the cortex and processing sensory sensation in the cortex, to discuss the somatotopy and homology of tactile sensation between projected fingers in residual limb and natural fingers in intact limb to understand the underlying mechanism of this phenomenon.

A. Delivering Sensory Sensation From the Skin to the Cortex

Delivering pathway of sensory sensation for the natural finger in the intact limb has been well investigated [42]. For the natural finger, there are several kinds of receptors [2] corresponding to the somatosensation modalities of touch, thermoreception, nociception, and proprioception. Cutaneous mechanoreceptors play an important role in transducing the external stimuli of touch to neural impulse information. Generally, the afferent fibers associated with the mechanoreceptors embedded in the skin convey the sensory information about mechanical contact in a fixed delivering pathway. These afferent fibers bundle in fascicles to form afferent nerves. Sensory information ascends from peripheral nerves through the spinal cord, to the brainstem, thalamic, and cortical areas. Somatosensory ERP is the response corresponding to the event of external stimuli.

However, studies on the delivery pathway of the sensory sensation for the projected finger on the stump are rare. Compared between the natural finger and the projected finger, since both will convey the sensory information through the peripheral nerves of the upper limb, the difference in the delivery pathway between them may be related to the delivery pathway between the natural finger's skin surface and the projected finger's skin surface to the peripheral nerves. This difference is the difference in the neurophysiological structure, which is hard to observe directly. Since the neurophysiological structure from the skin to the peripheral nerve encodes the external stimuli into the specific neural impulse information, it can use the known external stimuli (input signal) and the recorded early-stage ERP (output signal) to infer the character of the neurophysiological structure from the skin to

the peripheral nerve. The underlying principle is that sensory receptors are specialized neurons that respond to specific types of stimuli, and the specific kind of neural impulse will be conveyed in the fixed delivery pathway.

In this experiment, external stimuli are the encoded electrical stimuli that only evoke the tactile sensation pattern of touch, without pain or other patterns of tactile sensation. In the ERP recording results during the first 100 ms, the ERP of the early-stage is directly related to the external stimuli. In the early-stage, the brain cortex participates in processing the sensory information limited, and thus the ERP of the early-stage can objectively and directly represent the delivering feature from the skin through the peripheral nerve to the cortex. As shown in Fig. 4 and Fig. 5, all three groups contain the ERP components of N20, N50, and P80. These results are also in agreement with previous research [36], [43], in which both electrical stimulations in the natural finger and the median nerve of the wrist evoke the same ERP components as our experimental results. Electrical stimulations in the natural finger, projected finger, and median nerve all evoke tactile sensation and generate the same ERP components, and therefore it is reasonable to infer that three kinds of electrical stimulation encode similar sensory information. Further, the generation mechanism of tactile sensation of the projected finger may be similar to that of the natural finger or the stimulation of the median nerve. For these similarity and uncertainty, we will discuss these in more detail in the following.

The experimental results in this paper and other research are the basic and evidence to understand the delivery pathway between the projected finger skin surface to the peripheral nerves. Research has discovered that the whole five natural fingers are dominated by the median nerve and the ulnar nerve, where the median nerve dominates from the thumb finger to the half of the ring finger and the ulnar nerve dominates the rest half of the ring finger and the little finger [42]. As well known, both the median nerve and the ulnar nerve divaricate when the peripheral nerves pass through the wrist into the hand. In contrast, the evoked sensory information via the natural fingers will convey through the peripheral nerves including the median nerve and the ulnar nerve in the wrist to the spinal cord. Therefore, researchers have adopted two direct approaches to evoke the tactile sensation of the finger. First, on the skin surface of the wrist, researchers place the electrodes of electrical stimulation to the median nerve or ulnar nerve closely, and then the stimulation can evoke some patterns of tactile sensation of fingers [17]. Second, researchers also plant the electrodes under the skin surface and the electrodes are fixed together with the peripheral nerves, and similarly, the stimulation realizes the function of evoking kinds of tactile sensation [15]. However, in normal conditions, for the skin surfaces of the wrist of the intact limb of the able-bodied and the distal stump of an amputee who does not have the projected fingers, obviously, there is a common consensus that the mechanical press and slide on these skin surfaces are not able to evoke the tactile sensation of the finger. This consensus also exists in our previous research, where external stimuli on the skin surface of NPFM (non-PFM) for amputees who have projected fingers are unable to evoke the tactile sensation of the finger [29].

In this experiment, the amputee who has projected fingers successfully evokes the tactile sensation of the finger in parts of PFM and fails to evoke the tactile sensation of the finger in parts of NPFM with almost the same stimulation parameters, where NPFM closely adjoins PFM. This experimental result infers that the PFM and the peripheral nerve (median nerve and ulnar nerve) have rebuilt a fixed delivery pathway. The underlying mechanism of this delivery pathway is different than the previous mentioned electrical stimulation in the skin surface of the wrist. For electrical stimulation on the skin surface of the wrist to evoke the tactile sensation of the finger, the stimulation electrode is very close to the peripheral nerve, and the distance between the electrode and the nerve is very short. As shown in Fig. 1, different projected fingers are distributed in the different parts of the skin surface of the stump distal, and the corresponding different parts are separated in the physical space. This distribution feature of physical space for the projected fingers is different than the direct electrical stimulation in the skin surface of the wrist, whereas it accords with the physical space of the nature fingers. Therefore, based on the previous analysis, we infer that the delivering pathway of the projected finger may be more similar to that of the natural finger. In other words, the median nerve and the ulnar nerve of the peripheral nerve may divaricate new pathways, and these pathways would have been linked to the PFM [44].

Further, during the screening, the projected fingers in the PFM have a similar response of tactile sensation as the natural fingers. We have used two kinds of tactile sensation to screen the PFM: mechanical press by using a hard object to press the skin surface of the PFM and mechanical slide by using a hard object slide along the surface of the PFM. The projected fingers have both responses to these two kinds of tactile sensation. This result may infer that the new pathways between the PFM and the perpheal nerves were like the afferent fibers which linked the mechanoreceptor to the peripheral nerves tightly just as the natural fingers, and the new pathways owned the function to encode the external stimuli into the neuro impulse of tactile sensation just as the natural fingers. The justification of the inference is based on the following facts. First, after the nerve of the amputee has been severed, the proximal nerve can regenerate but usually grow haphazardly in all directions [49]. Second, targeted sensory reinnervation (TSR) has shown that the amputated afferent peripheral nerves successfully rerouted to the skin in the residual limb [50] and the reinnervated sites can activate the phantom hand [51], where it shows that a re-direction between the cutaneous receptor and the peripheral nerves could build a stable sensory site of the amputee's phantom hand on the skin surface of the stump. Therefore, we are inferring that regeneration and re-direction play an important role in the phenomenon of PFM.

In conclusion, based on the above analysis, it may infer that the delivery pathway of the projected finger was similar to that of the natural finger. And this inference may explain that the ERP components of the early-stage are similar for

both the stimulation in the projected fingers and the natural fingers.

B. Processing Sensory Sensation in the Cortex

The above has analyzed the similarity of the somatosensory neuro singles evoked by between the projected fingers and the natural fingers in the aspect of the delivery pathway of sensory sensation. The brain cortex is also working as a sophisticated mechanism, and it also satisfies the principle that the same type of neuro single is processed in the specific cortical areas and the fixed processing network. Therefore, we would like to analyze the similarity in more detail.

When the sensory information delivered from the peripheral nerve in the upper limb reaches the level of the cortex, the primary somatosensory cortex and secondary somatosensory cortex will participate in the processing of the sensory sensation [42]. In the aspect of psychology, the ERP components generated in the processing can be divided into three parts, where the first part is the sensation that is corresponding to the ERP components of the early stage, the second part is the perception that is corresponding to the ERP components of the middle stage, and the third part is cognition (narrow sense in this paper) that is corresponding to the ERP components of the later stage [45]. In the part of sensation, the P80 component is the typical component. As shown in Fig. 6, compared with two P80 mappings of the corresponding left natural finger and the right projected finger of the amputee, both the mappings show the activated areas are located in the paracentral lobule posterior gyrus with bilateral symmetry. N100 is the typical component of the part of perception. The P200 component follows the N100 component, and Fig. 6 shows that the activated area of P200 is located in the postcentral gyrus of the parietal lobe for all groups. The part of cognition includes the components of N200 and P300. In Fig. 6, it shows the activated area spreads forward from the parietal lobe to the prefrontal lobe, where the prefrontal lobe is the major area to process cognition for human beings. For the change and distribution in the mappings shown in Fig. 6, the results are consistent with previous research [21], [46], and the results also meet the request for bilateral symmetry. Based on this analysis, it can be concluded that the somatosensory cortical singles evoked by the stimuli in the projected fingers and the natural fingers have similar processing features of spatial distribution. Because cortical areas and networks are specialized to respond to specific types of stimuli, we could infer that the somatosensory cortical singles evoked by the stimuli in the projected fingers and the natural finger are similar.

Further, the following will analyze the difference of latency and amplitude, where the aim is to find a reasonable explanation for the difference and prove the similarity further.

According to neurophysiology, the nerve pathway is shorter and the neural impulse information reaches the cortex faster [43]. Therefore, as shown in Fig. 7, to the latency of the N50 component in which the cortex participates in the processing limited, the latency of Group PA is faster than that of Group NA. For the result that the latency of Group NA is faster than that of Group NH, the reason may be that the amputee subject uses the natural fingers more frequently than the able-bodied subjects, which leads to the skin sensibility of the amputee subject being higher than that of the able-bodied subjects.

The P80 component is the first major positive waveform in the ERP results and is considered as the typical component to represent the sensation. In Fig. 7, the latency of the P80 component is shown as a negative correlation between the three groups (Sig. $=$ 0.007). This means that Group PA has the longest latency of the P80 component, Group NH has the shortest latency of the P80 component, and the latency of the P80 component of Group NA is in the middle. According to psychology, the latency of the component of sensation is shorter and the sensibility of sensation is higher [45], [52]. Therefore, it can infer that the sensibility of sensation for Group PA is lowest, for Group NH is highest, and for Group NA is in the middle. Considering that the subjects in Group NH are much younger than the subject in Group NA, this is the reason that the sensibility of sensation of Group NH is higher than that of Group NA. Hence, we have found a reasonable explanation for the difference in the P80 component. Meanwhile, in Fig. 7, the amplitude of P80 is shown as a negative correlation between three groups (Sig. $=$ 0.007), where Group PA has the highest amplitude and Group NH has the lowest amplitude. As shown in Fig. 3, the stimulation current amplitude is largest for Group PA and smallest for Group NH. Since the P80 component is as the component of sensation, the relation between the amplitude of the P80 component and the stimulation current amplitude is a positive correlation [45], [53], and thus the P80 component has the corresponding difference in amplitude.

The N100 component follows the P80 component and is the typical component of perception. For the amplitude of the N100 component, as shown in Fig. 7, the relation of the amplitude of the N100 component is a negative correlation (correlation coefficient $=$ -0.834, Sig. $=$ 0.00001). It shows that the amplitude of the N100 component of Group PA is highest, the amplitude of the N100 component of Group PA is in middle, and the amplitude of the N100 component of Group NH is lowest. Considering the relation of the amplitude of the stimulation current, it shows that the amplitude of the N100 component and the amplitude of the stimulation current has no positive correlation. According to psychology, the amplitude of the component of the perception is higher, and the difficulty of perception is higher [45], [54]. It can infer that Group PA has the highest difficulty in perception, and Group NH has the lowest difficulty in perception. This inference also accords with general knowledge.

For the components of the part of cognition, the typical component is the P300 component. In Fig. 7, the latency of the P300 component is shown as the positive correlation between the three groups, whereas this positive correlation does not mean that the cost of cognition of Group PA is the lowest. For cognition latency, the interval latency between the P200 and P300 components is the valid latency. The mean interval latency between the P200 and P300 of Group PA is 76.8 ms, and the mean interval latency between the P200 and P300

of Group NA is 72.8 ms. The reason that Group PA has the smallest latency is the latency between the N100 and P200 of Group PA is the shortest among the three groups. The latency between the N100 and P200 is 35.6 ms, 42.8 ms, and 105.8 ms for Group PA, Group NA, and Group NH, respectively. Group PA has the shortest latency between the N100 and P200, and it means that the perception evoked by the electrical stimulation in the PFM maintain in the shortest time. In Fig. 4(a) ∼ (e), for the ERP recording results which are later than P300 components, it shows that the amplitude for the stimulation in the natural finger is much higher than the amplitude for the stimulation in the projected finger, where it means that tactile sensation evoked by natural finger has more ability to maintain sensory information than that evoked by projected finger [55], [56]. Further, we may infer that the tactile sensation evoked by the natural finger could deal with more complex sensory information in the physical world.

In conclusion, we have analyzed and found the underlying reasonable explanation for the difference in sensory sensation in the cortex between the three groups. It shows that the processing of sensory sensation in the cortex of the three groups is similar, and thus we can infer that the somatosensory evoked by external stimuli is also similar.

V. Conclusion

In this paper, one amputee subject and three able-bodied subjects are recruited. The somatosensory ERPs evoked by the stimulations on the projected fingers and the natural fingers are recorded. The somatosensory ERPs offer the opportunity to study delivering and processing of task-relevant stimuli from the skins of the projected/natural fingers through peripheral nerves to the cortex. The first finding of the study is that, since the ERP components of the early-stage are similar for both the stimulation in the projected fingers and the natural fingers, it can infer that the delivery pathway of the projected finger was similar to that of the natural finger. In other words, the median nerve and the ulnar nerve of the peripheral nerve may divaricate new pathways, and these pathways would have been linked to the PFM. The second finding of the study is that, as the processing of sensory sensation in the cortex of the three groups is similar, it can also infer that the somatosensory evoked by the external stimuli are also similar. Based on these two findings, we show the uniformity of the somatotopy and the homology of tactile sensation between the projected fingers in the residual limb and the natural fingers in the intact limb.

To the best of our knowledge, this paper is the first study to compare the somatosensory response of the entire five projected fingers and natural fingers. However, the present study had several limitations. First, the samples in this paper are limited, where only one amputee subject and three able-bodied subjects are recruited. Further study will recruit more subjects. Second, for the able-bodied subjects, only the ERPs related to the index fingers were recorded. Stimulations on the index fingers could evoke the response related to the peripheral nerve partially. For integrity, further study should record the ERP related to the entire five natural fingers of the able-bodied subjects.

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