Somatotopically Evoked Tactile Sensation via Transcutaneous Electrical Nerve Stimulation Improves Prosthetic Sensorimotor Performance

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***Abstract*— Sensory feedback provides critical interactive information for the effective use of hand prostheses. Non-invasive neural interfaces allow convenient access to the sensory system, but they communicate a limited amount of sensory information. This study examined a novel approach that leverages a direct and natural sensory afferent pathway, and enables an evoked tactile sensation (ETS) of multiple digits in the projected finger map (PFM) of participants with forearm amputation non-invasively. A bidirectional prosthetic interface was constructed by integrating the non-invasive ETS-based feedback system into a commercial prosthetic hand. The pressure information of five fingers was encoded linearly by the pulse width modulation range of the buzz sensation. We showed that simultaneous perception of multiple digits allowed participants with forearm amputation to identify object length and compliance by using information about contact patterns and force intensity. The ETS enhanced the grasp-and-transport performance of participants with and without prior experience of prosthetic use. The functional test of transport-and-identification further revealed improved execution in classifying object size and compliance using ETS-based feedback. Results demonstrated that the ETS is capable of communicating somatotopically compatible information to participants efficiently, and improves sensory discrimination and closed-loop prosthetic control. This non-invasive sensory interface may establish a viable way to restore sensory ability for prosthetic users who experience the phenomenon of PFM.**

***Index Terms*— Non-invasive sensory feedback, somatosensory compatibility, evoked tactile sensation (ETS), transcutaneous electrical nerve stimulation (TENS), prosthetic hand.**

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I. Introduction

RESEARCH to improve sensorimotor functions for prosthetic hands has been proliferating rapidly over the past decade. A variety of invasive and non-invasive neural techniques have been explored for communicating tactile and proprioceptive sensory information [1], [2], [3], [4], [5], [6], [7], [8], [9]. Invasive techniques can convey sensory information via direct stimulation of sensory nerves along the afferent pathway at the periphery, spinal cord, and primary somatosensory cortex [10], [11], [12], [13], [14]. Surface electrotactile stimulation presents a convenient way to access the sensory nerves but with less intuitive perception and functionality [6], [15], [16], [17]. Somatotopic and quality-matched sensory information may be achieved through mechanical stimulation in specific areas of the stump skin [18], transcutaneous electrical nerve stimulation (TENS) [19], [20] or a cutaneous interface via target reinnervation surgery [21]. However, a somatotopically compatible and reliable non-invasive technique for users of bionic hands is still lacking.

TABLE I
CLINICAL INFORMATION FOR AMPUTEE SUBJECTS

Subject	Age	Sex	Amputation level and side	Cause	Year since amputation	Own prosthesis	Utility frequency (Day)	Dominant hand	Myoelectric prosthesis experience
S1	58	M	Right distal third of forearm	Trauma	11	Functionality	> 6 hours	R	Yes
S2	50	M	Right distal third of forearm	Trauma	5	Functionality	> 6 hours	R	Yes
S3	59	M	At right wrist	Trauma	44	Functionality	< 2 hour	R	Yes
S4	65	M	Right distal third of forearm	Trauma	37	Cosmetic	None	R	None
S5	69	M	Left distal third of forearm	Trauma	46	Cosmetic	None	R	None
S6	69	M	Left distal third of forearm	Trauma	16	Cosmetic	None	R	None

The unique phenomenon of projected finger map (PFM) occurs naturally in the stump of certain individuals with forearm amputation. This has been explored to provide a non-invasive way for somatosensory tactile feedback [22], [23]. It is initially identified via mechanical stimulation [24] that conveys a somatotopic sensation. Our previous studies show that transcutaneous electrical nerve stimulation (TENS) in the PFM area of stump skin can also induce digit-specific sensation, referred to as evoked tactile sensation (ETS) [23]. The somatotopic ETS is demonstrated to be conveyed from periphery sensory nerves to the area of the primary somatosensory cortex that corresponds to the missing hand via a direct afferent neural pathway [25]. Additionally, the direct activation of sensory nerves of different modalities via TENS endows ETS with multiple sensory qualities [26], [27], which allows the ETS to encode multi-modality somatosensory information [28]. In addition, its somatosensory threshold is stable over a period of more than 10 months [23], [29]. These features offer a potential way for long-term restoration of reliable and intuitive non-invasive tactile sensory feedback for the population of amputees with PFM (see Discussion and Table Sup 2).

Nevertheless, the effectiveness of this technique is yet to be verified to augment prosthetic sensorimotor functions. The goal of this study was to evaluate what functional benefits the ETS may bring to amputees using a hand prosthesis. Here we investigated the efficacy of ETS-based feedback for enhancing sensorimotor performance with the bidirectional prosthetic hand. We tested two fundamental hypotheses regarding the functional roles of ETS-based tactile feedback. First, it is hypothesized that the multi-digit ETS may supply multi-dimensional tactile information for participants with forearm amputation to detect the physical parameters of objects grasped. Second, the ETS may provide dynamic sensory information to aid sensorimotor control of the prosthetic hand. Four sets of experiments in the closed loop were designed to test these two hypotheses in participants with forearm amputation. Two basic identification tasks were carried out with the sensorized Bebionic hand off the stumps of participants to prevent any alternative sensory feedback from being informative. Two functional control and sensory tasks were performed with the prosthetic hand worn by participants with amputation to mimic the complex scenarios in daily life. Test results supported the two hypotheses, and the findings consistently showed that ETS-based feedback significantly enhanced overall sensorimotor performance across all participants. This study confirmed the essential roles of ETS-based tactile feedback in effectively and simultaneously communicating natural and intuitive sensory information to multiple digits.

II. METHODOLOGY

A. Participant Recruitment

Six male participants with forearm amputation were recruited for this study. They were selected for having an intact PFM of all five fingers (Fig. Sup 2). The detailed clinical information is listed in Table I. None of the participants had a history of neurological disease or significant cognitive impairment. They were informed about experimental protocols and signed a consent form before the experiment. They were divided into two groups: one with prior experience using a prosthetic hand (EXP, S1, S2, and S3), and one without any prior use of a prosthetic hand (IEXP, S4, S5, and S6). This study was approved by the Institutional Review Board for Human Research Protections, Shanghai Jiao Tong University.

B. Integration of Bidirectional Prosthetic Hand

The non-invasive multi-channel electrical sensory feedback system was integrated into the commercial Bebionic hand (Ottobock, Germany). The anti-artifact module utilized a combination of hardware blanking and software filtering to remove the artifact of electrical stimulus (Fig. 1A) [30]. The difference between filtered surface Electromyography (sEMG) envelopes collected from the extensor and flexor carpi muscles was used to linearly control the moving speed of this prosthetic hand.

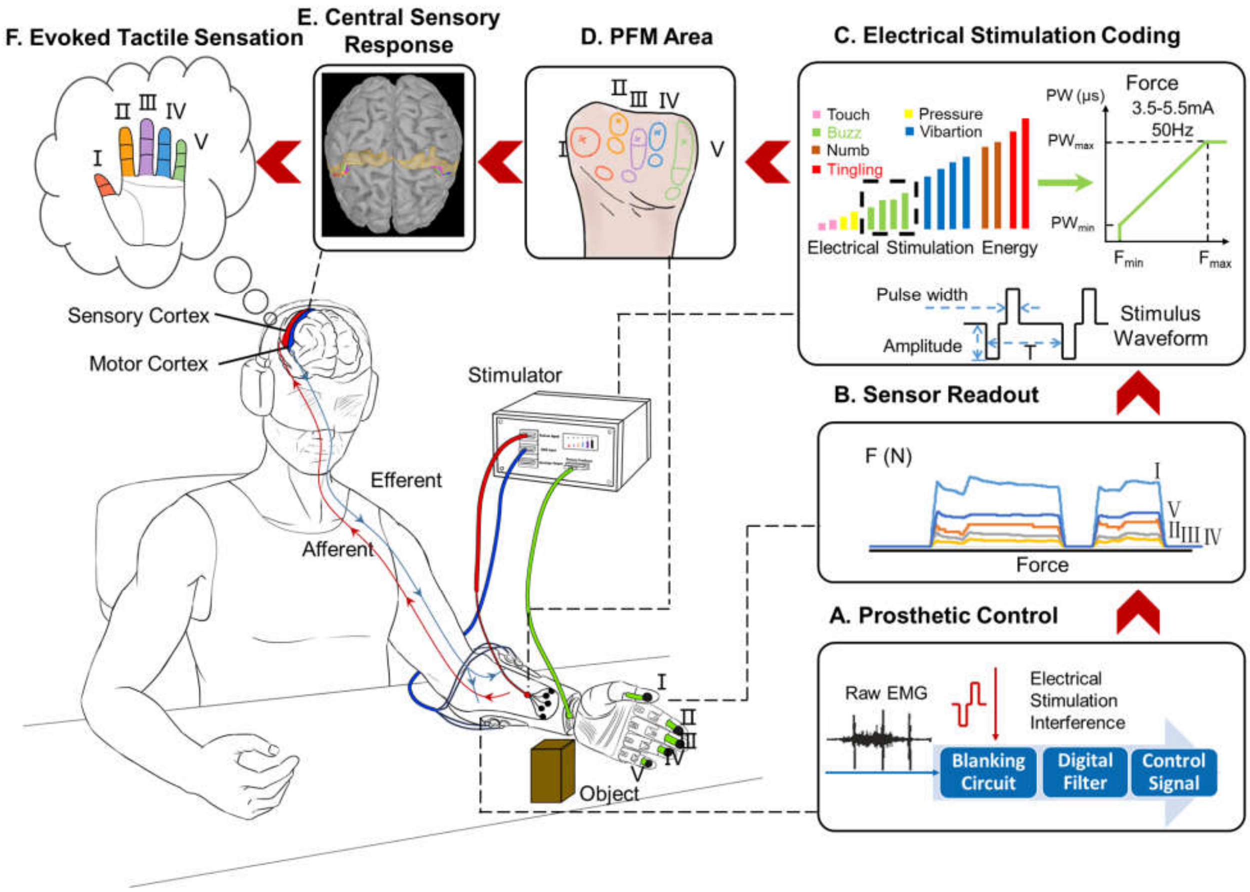

Fig. 1. Overview of the bidirectional prosthetic hand. An individual with transradial amputation controlled an integrated prosthetic hand equipped with the evoked tactile sensation (ETS) feedback system to grasp an object. The seamless bidirectional sensory-motor communication was realized in this prosthetic hand. (A). Control signals were adopted from two-channel surface electromyography signals filtered by the blanking circuit and digital filters. (B) Force sensors delivered pressure signals to the multiple-channel electrical stimulator for encoding. (C) Buzz sensation was chosen to encode the physical contact pressure information with a linear pulse-width coding strategy (fixed amplitude range 3.5∼5.5 mA for tactile feedback, fixed frequency 50Hz). The current stimulus was a biphasic, charge-balanced, cathode-first pulse train with 10 μs inter-pulse interval, and was delivered to the projected finger map areas as shown in (D) to inform subjects of somatotopic tactile information. (E) The primary somatosensory cortex is activated by the tactile information through the afferent pathway (adapted from the previous study [22] with permission), which caused the discrete sensation of each digit of the missing hand (F).

The contact pressure collected by force sensors (Flexiforce, Tekscan Inc, United States) on five fingertips (Fig. 1B) was encoded into biphasic, charge-balanced, cathode-first pulse trains using a linear pulse-width strategy [29] (Fig. 1C). The somatotopic multi-digit sensory stimulation was delivered to the PFM area (Fig. 1D and Sup 1) through surface custom electrodes [29]. Non-invasive stimulation at the PFM activated corresponding hand areas in the primary somatosensory cortex [25] (Fig. 1E), which ultimately induced the sensation of discrete fingers (Fig. 1F).

C. Tactile Feedback Based on ETS

TENS were applied to the five most sensitive points (marked with a cross) on finger-specific PFM areas (Fig. 1D and Sup 2) with stable Ag/AgCl powder sintered electrodes of 10 mm diameter [29]. The hydrogel patch of 11 mm in diameter was used to attach the stimulation electrodes to the skin surface. The reference square nonwoven electrode (40 mm × 40 mm) (Yancheng Dalun Medical Equipment Co. Ltd, China) was placed near the elbow of the ipsilateral arm.

Previous studies showed that multiple perceptual qualities of ETS appeared in a consistent order: touch, pressure, buzz, vibration, numb, tingling [23], [28] (Fig. 1C). Among these sensory qualities, the buzz sensation elicited at 50 Hz was chosen to encode contact pressure information due to its wide pulse width range and high sensitivity [28]. For each stimulation site, its pulse width modulation range was obtained with a consistent calibration protocol [28]. The fixed amplitude was chosen as the first value at which the buzz sensation was perceived with a fixed frequency (50 Hz) and pulse width (200 μs). The perceptual threshold ($PW_{perceptual}$) was identified as the pulse width values at which the buzz sensation appeared. Then, the pulse width increased with a step of 20 μs every 5 s. The value before buzz sensation changed into another perceptual quality was set as the upper threshold (PW_{upper}). The upper threshold of contact pressure (F_{upper}) in each task was identified as the maximum force that could be generated by the user to control the grip of the prosthetic hand. The intensity of buzz sensation on each finger increased directly in relation to the increase in contact pressure between the corresponding prosthetic fingertip and the object.

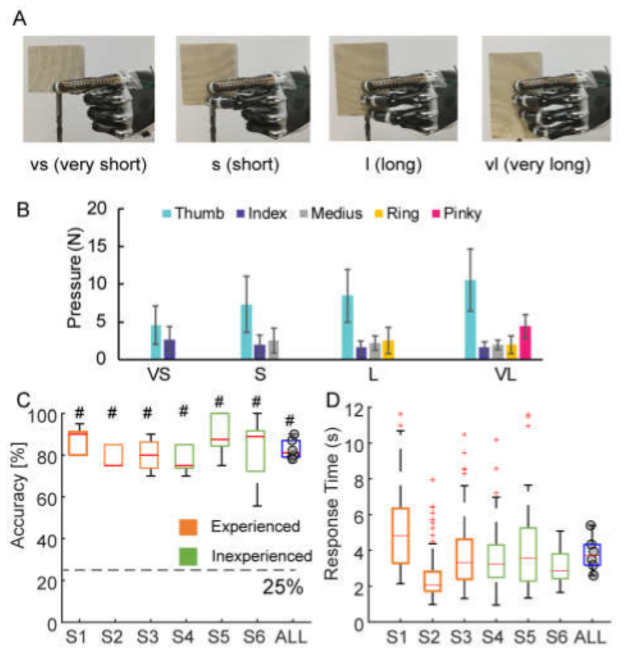

Fig. 2. Basic length identification task. (A) Four objects with different lengths and same size used in this task and their labels. (B) The pattern of contact pressure of five fingers from all subjects when grasping objects of four different lengths. (C) and (D) show the accuracy and response time of six amputee subjects and overall performance for all subjects. '#' identifies the level that is above the chance level ($p < 0.05$).

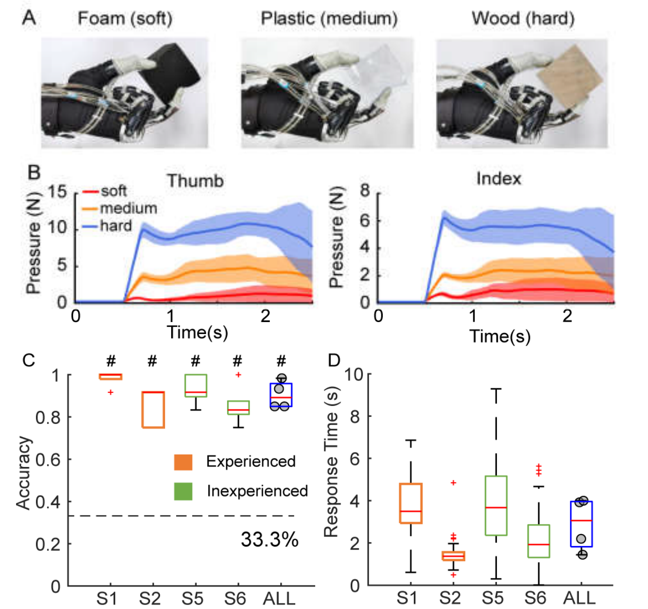

Fig. 3. Basic compliance identification task. (A) Foam (soft), plastic (medium) and wood (hard) blocks with different compliance levels and same size used in this task. (B) The diagram of contact pressure information (mean ± std) of thumb and index fingers for three objects during grasping of S1. (C) and (D) show the identification accuracy and response time for four individual subjects and all subjects. The gray dashed line indicates the chance level. '#' identifies the level that is significantly higher than the chance level ($p < 0.05$).

Thus, the contact pressure was encoded using a linear pulse width modulation strategy designed to related electrical intensity to measured force as follows:

$$\mathrm{PW} = \frac{(PW_{upper} - PW_{perceptual})}{F_{upper} - F_{low}} * (F - F_{low}) + PW_{perceptual} \tag{1}$$

where PW is pulse width output and F is force sensor readout. F_{low} is set as 0. If F is higher than F_{upper}, PW is equal to PW_{upper}.

D. Basic Length and Compliance Identification Tasks

The basic feature identification task was designed to assess the efficacy of contact finger pattern and force intensity provided by ETS-based tactile feedback on discriminating object length or compliance. During these tasks, participants wore noise-canceling headphones and were blindfolded. They sat comfortably in a chair with the prosthetic hand off-body and mounted on a table. This setup was critical to eliminate any incidental feedback, such as vibrations from the motor. Consequently, participants were unable to make the recognition without tactile feedback. Therefore, both tasks were conducted only with ETS-based tactile feedback to evaluate its effectiveness in providing discernible cues for object features.

In the length identification, four blocks with the same width and different lengths (6 cm (very short), 8 cm (short), 10 cm (long), and 12 cm (very long)) (Fig. 2A) were used. They were placed between the thumb and the other four fingers of the prosthetic hand. The contact finger pattern differed between objects with different lengths (Fig. 2A). Before the test, each object was presented to the participant with visual feedback. This pre-test lasted for 5 minutes, allowing the participants to familiarize themselves with the experimental setup. Participants were asked to close the prosthetic hand while one of the four objects was placed in its grip and report the length of the grasped block. Concurrently, they pressed the trigger bar, a specific mechanism integrated into the experimental setup to record the timing of their response. Each object was presented 25 times for S1-S4, while there were 10 repetitions of each object for S5 and S6.

The compliance identification task was performed in the same manner as the object length identification task described above. Here, there were 3 kinds of objects of different compliance levels (foam ("soft"), plastic ("medium"), and wood ("hard") blocks) and the same size (Fig. 3A). They were placed between the thumb and index fingers of the prosthetic hand. Each object was presented 20 times for all participants. S3 and S4 were unable to participate in this task due to personal scheduling conflicts.

In both tasks, the experimenter did not guide or influence the identification strategy of participants. The reported results and real blocks presented to participants for identification were recorded. The response time was identified as the duration from contacting the block to pressing the trigger bar.

E. Functional Modified Box and Block Task

The modified box and block task was adapted from the block-foraging stiffness discrimination task (Fig. 4A) [31]. Here, there were four types of blocks with two different

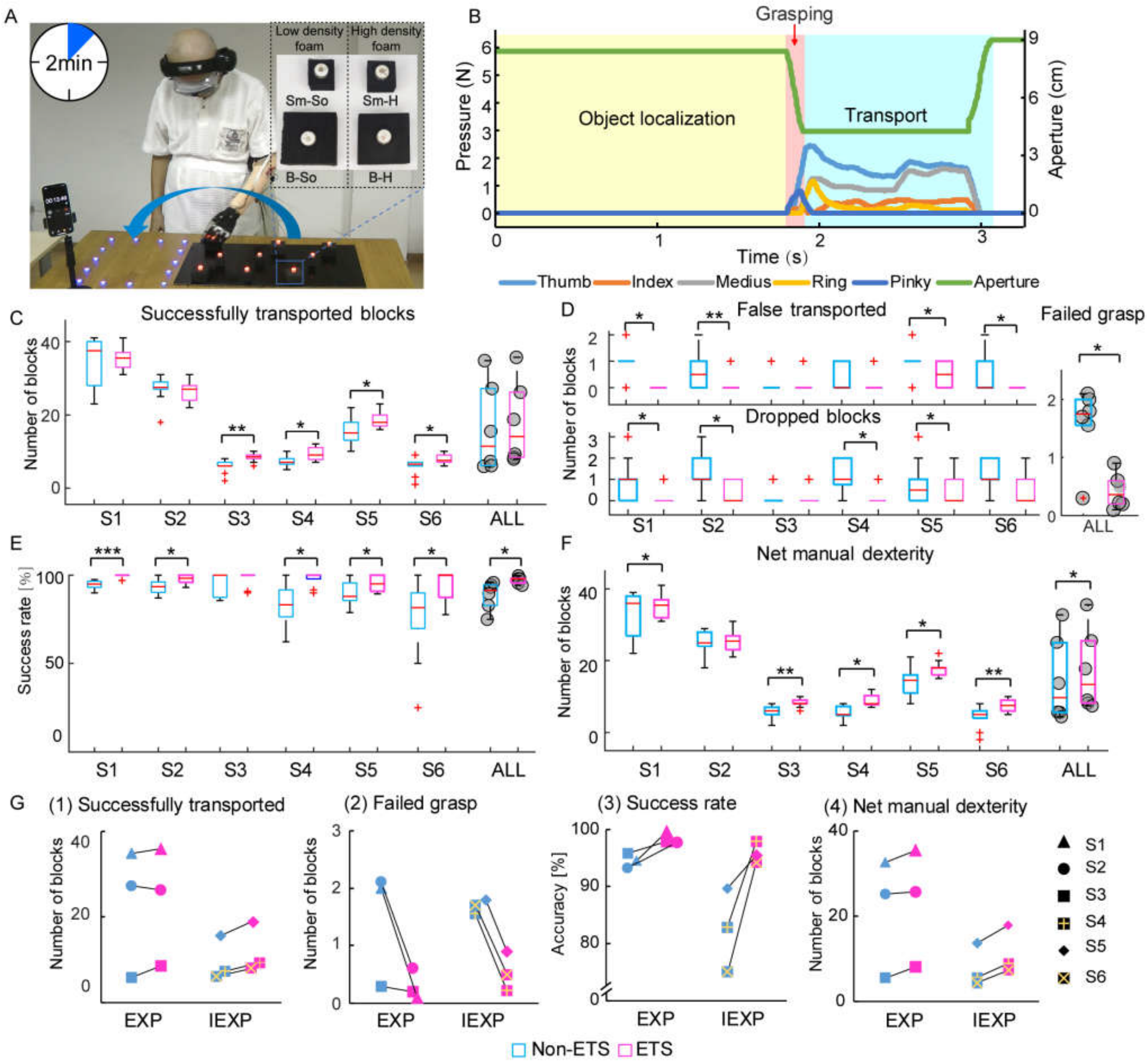

Fig. 4. Functional modified box and block Task. (A) Experimental setup. Blocks with two sizes and two compliance levels were randomly presented on the metal platform. The subject was asked to transport as many as possible blocks from the metal platform to the target area which was marked by blue lights. (B) Representative contact pressure and aperture information obtained during this task. (C) The individual and performance of successfully transported blocks for six amputee subjects. (D) The number of false transported and dropped blocks for six subjects and performance of failed grasp. (E) and (F) illustrate success rate and net manual dexterity for all subjects. (G) Results of four evaluation criteria for EXP and IEXP group with or without ETS feedback. * ($p < 0.05$), ** ($p < 0.005$), *** ($p < 0.001$).

compliance levels ("soft" block made of 0.03g/cm3 polyurethane foam, "hard" block made of 60 HSC ethylene-vinyl acetate copolymer) and two different sizes ("small" block of 2.5 × 2.5 × 3 cm3, "big" block of 5 × 5 × 3 cm3), allowing a total of four kinds of objects. They were placed on a 45 × 34 × 0.5 cm3 metal platform located on the amputated side. All blocks were attached to the platform with a small circular neodymium magnet (0.8 cm in height and 1 cm in diameter). The position of blocks and target area (25 × 34 cm2) were indicated by the red and blue LED lights respectively. Yellow light was attached between the thumb and index finger on the back of the prosthetic hand.

In this task, participants wore noise-canceling headphones and special custom goggles with a blackout sticker that only allowed visual cues from the LED lights. Before this task, participants wore the prosthetic hand with their custom sockets to familiarize themselves with the experimental setup for 10 minutes. In this task, they were asked to utilize this prosthetic hand to transport as many blocks as possible from the metal platform to the target area in 2 minutes. There were a total of 10 trials for each participant. All six participants took part in this task. The task was performed under two different feedback conditions: (1) with ETS-based tactile feedback (ETS-based), and (2) without ETS-based feedback (non-ETS),

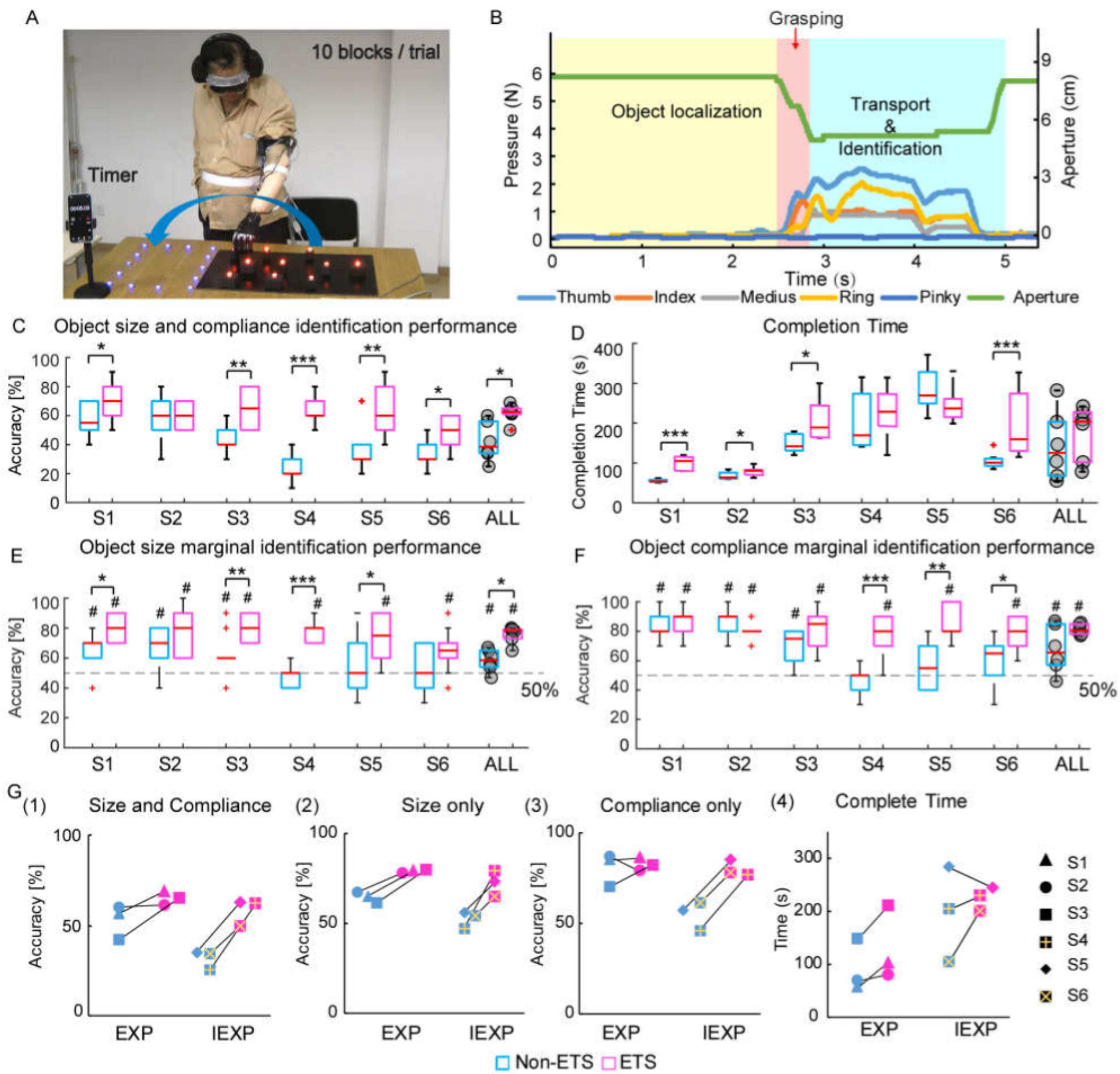

Fig. 5. Functional identification and transport task. (A) Experimental setup. The subject wore the bidirectional prosthetic hand to identify the size and compliance of 10 blocks and transport them to the target area. (B) Representative trace of contact pressure and aperture information for the process of identifying and transport a block. (C) and (D) illustrate the individual and performance of overall accuracy and completion time for six amputee subjects. (E) and (F) show the performance of identifying only size or compliance with or without ETS feedback. The gray dashed line indicates the chance level. '#' signifies the level that is significantly higher than the chance level ($p < 0.05$). (G) The performance of four evaluation criteria for EXP and IEXP groups in different conditions. * ($p < 0.05$), ** ($p < 0.005$), *** ($p < 0.001$).

indicating the absence of real-time electrical stimulation signals.

This task was divided into three phases: object localization, object grasp, and object transfer. Four criteria were adapted to evaluate the performance efficacy. The performance of successfully transported blocks and dropped blocks were measured as the number of blocks successfully transported and dropped in any phase respectively. The criterion of false transported blocks was measured by the number of trials where the participant attempted to grasp an object but failed, resulting in the transportation of an empty prosthesis. The criterion of net manual dexterity [32] was measured as the number of successfully transported blocks minus the number of failed grasps (dropped blocks plus false transported blocks).

F. Functional Block Identification and Transport Task

To further evaluate the impact of ETS-based feedback on the sensory function in a functional task, participants were asked to identify the size and compliance of each block before transporting it to the target area (Fig. 5B) using the same experimental setup as described in section II-E. In each trial, 10 random blocks were given. The participant was asked to locate, identify, and transport these blocks as quickly and accurately as possible. Each trial ended when the participant had transported all 10 blocks. A session consisted of 2 trials, with a total of 20 blocks, comprising 5 blocks of each type. All six participants took part in this task.

This task was conducted with and without ETS-based feedback with random but not in a cross order. The contact force, aperture signal, identification results, and completion time of each trial were recorded. The marginal identification criterion was analyzed to evaluate the performance in identifying particular object features (compliance or size).

G. Evaluation of Embodiment, Willingness and Confidence

The subjective assessment of the embodiment, willingness to use the prosthetic hand, and confidence in completing tasks was further conducted in different feedback conditions. The embodiment questionnaire consisted of seven items and was adapted from previous studies [33], [34], [35] (Table Sup 1). The last four statements were control items designed to avoid suggestibility and the first three (Non-control items) were used to evaluate the embodiment level. Participants reported how much they agreed with the statement in each item from −3 (disagree strongly) to 3 (agree strongly). This questionnaire was conducted before and during the basic identification tasks, as well as under different conditions of functional tasks.

The willingness to use the prosthetic hand with or without ETS-based tactile feedback in daily life was evaluated after the embodiment questionnaire with the same rating scale. The assessment of confidence for completing functional tasks in different feedback conditions was also evaluated with a questionnaire using the same seven-point scale (Table Sup 1).

H. Statistical Analysis

All data were analyzed using Statistical Product and Service Solutions (IBM SPSS Statistics 26.0). Since the recognition result (right or wrong) followed a binominal distribution, the identification accuracy was compared against the possibility of chance level (the probability of an event occurring at random) with the Binominal test for individual or all participants. The one-sample Kolmogorov-Smirnov test was used to test if the dataset was normally distributed. Since none of the datasets passed the test, the nonparametric Kruskall-Wallis test was used to assess the effect of feedback type on the performance of participants or overall performance in functional tasks. The performance of individual participants in the overall analysis and different participant groups is expressed as the mean value for all trials in each feedback condition. For analyses within the EXP or IEXP groups, we first organized and paired the data with or without ETS-based tactile feedback for each individual in ascending order. Subsequently, the Wilcoxon paired signed rank test was conducted to analyze all paired data. The distribution of all performance was reported by the median and interquartile range (IQR).

III. Results

A. Length Recognition via Contact Pattern With Multiple Digit ETS

The use of finger-specific somatotopic information provided by the ETS-based feedback to identify object length was first characterized. The average pressure during identification of different blocks for all participants was shown in Fig. 2B. The contact pattern of fingers (combination of contact finger spatial sites) was related to the length (or size) of objects for all participants (Fig. Sup 3).

The overall performance of all participants was 82.7%, specifically 87% for S1, 79% for S2, 80% for S3, 78% for S4, 90% for S5, and 82.2% for S6 (Fig. 2C); which were all above the chance level (25%) evaluated with Binominal test ($p < 0.05$; Fig. 2C). This indicated that finger-specific spatial information provided by ETS could be efficiently utilized in feature recognition by different populations of participants without training or any other sensory cue. The median response time for all participants was 3.70s {1.57} (Fig. 2D). Results showed that all participants irrespective of experience in using a hand prosthesis could identify the object length quickly with a high accuracy. Questionnaire results on embodiment, willingness and confidence were presented in the Supplementary Materials collectively (Fig. Sup 1).

B. Perception of Force Intensity Information in ETS

The intensity of contact force is another critical dimension of information to perceive the external environment by four participants with amputation (S1, S2, S5, and S6). The contact force of thumb and index while identifying objects of three compliance levels for S1 was presented in Fig. 3B and for all participants in Fig. Sup 4.

The overall performance of compliance identification was 90.4%, specifically, 98.3% for S1, 85% for S2, 93.3% for S5, and 85% for S6 (Fig 3C). The correct identifications for all participants were above the chance level of 33.3% ($p < 0.05$). Results indicated that all participants were able to utilize force intensity information in ETS to identify object compliance efficiently. The median response time in compliance identification varied from 1.44s to 3.97s, with a median of 3.06 s {2.35} for all four participants (Fig. 3D). The time required to identify the compliance in the EXP group and IEXP group was 2.19 s {2.30} and 3.6 s {2.32}, respectively.

C. Enhanced Motor Control Ability by ETS-Based Tactile Feedback

To further investigate the impact of ETS-based tactile feedback on the motor control function of a prosthetic hand, a modified box and block test was designed. Completion of the task consisted of three phases, object locating, grasping and transporting (Fig. 4B).

The median number of successfully transported blocks by the six participants was 14.0 blocks {20.3}, which was significantly higher than that without tactile feedback (11.4 blocks {23.1}) ($p < 0.05$; Fig. 4C). The total number of successfully transported blocks varied widely among participants with or without experience in using prosthetic hands (Fig. 4C). Among the participants, S3, S4, S5 and S6 showed significantly greater number of successful transports with ETS-based feedback than that without tactile feedback. With ETS-based tactile feedback, the number of false transported by S1, S2, S5, and S6 decreased, while S1, S2, S4, and S5 dropped fewer blocks (Fig. 4D). The median failed grasp with ETS-based feedback (0.36 block {0.5}) was significantly lowered than that without ETS-based feedback (1.75 blocks {0.78}) ($p < 0.05$; Fig. 4D). The success rate gave a clearer picture of ETS's impact on task performance, in which the total success rate was 97.21 % with ETS and 88.4 % without (Fig. 4E). All participants except for S3 achieved a significantly higher success rate with ETS-based tactile feedback (Fig. 4E). All participants except for S1 and S2 scored significantly higher in the net manual dexterity when they were provided with ETS-based tactile feedback (Fig. 4F). The overall success rate and net manual dexterity were significantly better with ETS ($p < 0.05$). These results established the positive role of ETS in controlling prosthetic motor functions by participants. Fig. 4G illustrates the average performance of different participant groups with or without ETS-based tactile feedback. Results consistently showed the enhancement of ETS-based tactile feedback on the fewer errors, higher success rate, and net manual dexterity for all participants with or without experience in using a prosthetic hand (Fig. 4G (2), (3) &(4)).

D. Enhanced Sensory Identification Ability With ETS Tactile Feedback

The functional performance with ETS-based feedback was further evaluated in a transport and identification task similar to daily life activities. The functional task consisted of three phases, object locating, grasping, transport, and identifying (Fig. 5B).

Fig. 5C-5G summarize the results of this test. All participants except for S2 performed with higher accuracy in Combined size and compliance identification with ETS-based tactile feedback (Fig. 5C). The accuracy of all participants with ETS-based feedback was 61.7%, significantly higher than that without ETS (42%) ($p < 0.05$; Fig. 5C). In particular, S1, S2, S3 and S6 used more time to complete the transport and identification of 10 blocks with ETS than without ($p < 0.05$; Fig. 5D). Overall completion time was 203.9 s {135.3} with ETS and 125.5 s {158.6} without ETS (Fig. 5D). Due to the inconsistent performance trends among participants under different feedback conditions, there was no significant difference in the overall completion time. For identifying size only, the accuracy for all participants was 75.7% with ETS, significantly higher than 58.3% without ETS feedback ($p < 0.05$; Fig 5E). S1, S3, S4, and S5 identified sizes significantly better with ETS than that without ETS. Participants with prior hand prosthesis experience (S1, S2, and S3) surpassed the chance level in size identification across both sensory feedback conditions. Conversely, participants without prior experience (S4, S5, and S6) exceeded the chance level (50%) only when provided with ETS-based tactile feedback (Fig. 5E). For marginal identification of only compliance, overall accuracy was 81.2% with ETS-based feedback, and 67.7% without tactile feedback (Fig.5F). Only participants without prior experience in hand prosthesis (S4, S5, and S6) displayed better performance when provided with tactile feedback. The marginal compliance identification performance was consistent with marginal size identification. Only participants without prior experience showed no significant difference from chance level (50%) in compliance identification when no tactile feedback was provided (Fig. 5F). The effect of ETS-based tactile feedback on the average performance of individual participants is presented more clearly in Fig. 5G. The improvement of accuracy in identifying combined features or single features was achieved for participants without experience (Fig. 5 (1), (2) & (3)), which is not consistent for participants in EXP group (Fig. 5G (1), (3) &(4)).

E. Subjective Sense of Embodiment, Willingness and Confidence

In basic perception tasks, the survey of the embodiment questionnaire showed that Q1, Q2, Q3, and Q5 received higher scores with ETS compared to those without ($p < 0.001$; Fig. Sup1A). Non-control items in the embodiment questionnaire also received higher scores with ETS than none ($p < 0.001$; Fig. Sup1A). Non-control items (Q1-Q3) were significantly agreed as opposed to control items (Q4-Q7) when provided with ETS-based feedback ($p < 0.001$; Fig. Sup1A), implying that participants were not susceptible to suggestion.

In functional tasks, Q1, Q2, and Q5 collected higher scores with ETS feedback (Fig. Sup1C). Participants agreed more about the non-control items (Q1-Q3) with the ETS-based feedback than without ($p < 0.001$; Fig. Sup1C), implying that participants were not suggestible ($p < 0.001$). Results confirmed that the ETS-based feedback brought about the improvement of sense of embodiment in participants. The willingness to use the closed-loop prosthetic hand was significantly improved ($p < 0.001$; Fig. Sup1B & D). The confidence level in functional tasks was also elevated by the presence of ETS ($p < 0.01$; Fig. Sup1D).

IV. Discussion

Although extensive research is aimed at providing sensory feedback for prosthetic hands [1], [2], [3], [7], [8], [9], [36], [37], there is still a paucity of non-invasive neural interfaces for stable and reliable sensory feedback. In this study, the novel ETS technique via TENS is evaluated in participants with forearm amputation for its functionality in a closed loop. Previous studies have elucidated its ability to elicit stable and intuitive finger-specific sensation through a regenerated reliable afferent pathway with a variety of sensory percepts [23], [25], [28]. Here, we provide further evidence to support the two hypotheses regarding their essential roles in augmenting prosthetic sensorimotor performance. First, all participants demonstrated an improved ability to perceive object length and compliance when supplied with ETS information (Fig. 2 & 3). This suggests that the information in finger contact patterns and force intensity in the ETS can be effectively conveyed to and utilized by the participants to discriminate these physical properties. Second, the ETS-based feedback boosts sensorimotor functions of all participants in the two functional tasks that required grasp, transport, and identification (Fig. 4 & 5). Although six participants were tested in this study, results confirm that the ETS-based technique is promising as a long-term, stable, reliable, and efficacious way of non-invasive sensory feedback for the population of people with forearm amputation who experience PFM.

The first hypothesis in this study is that participants with forearm amputation can effectively integrate contact pattern and intensity information provided by the somatotopic ETS-based tactile feedback for discriminating physical features. Results show that all participants could identify object size or compliance with accuracy that significantly surpassed the level of random chance. In basic tests for length (size) recognition, the high identification success rate signifies that the tactile sensation of specific fingers can be integrated to yield an intuitive perception of size. This sensory ability is not influenced by prior experience of using prosthetic hands (Fig. 2D). The performance in the identification of four different lengths (82.7%) is comparable with that of four different sizes (78%) with invasive peripheral neural interfaces [11]. The intensity information in the ETS could be effectively processed by the participants with forearm amputation to recognize compliance of objects regardless of their prior use of a prosthetic hand. The accuracy of participants with ETS-based feedback (90.4%) (Fig. 3D) is comparable with the performance for identification of three different compliance levels with peripheral nerve stimulation at 78.7% [13], transcutaneous electrical nerve stimulation at 60% [20] and spinal cord stimulation at 46% [38]. The median response time of the six participants was 2.37 s, much shorter than 7.91 s observed in identifying two objects of different compliance levels via peripheral nerve stimulation [14]. This suggests that ETS information is more natural and intuitive, and therefore requires less cognitive processing. These results indicate that the dual-dimensional tactile information provided by ETS about the object size and force strength can be perceived and utilized by all the participants effectively. In the design of basic tasks, visual and auditory cues are cut off to underscore the dependency on ETS-based tactile feedback. Consequently, participants cannot perceive any information without tactile feedback and the control condition was not conducted for these tasks.

The second hypothesis here is that the ETS could enhance prosthetic control by participants with amputation effectively. The functional modified box and block test clearly shows that the presence of ETS increases the accuracy of task performance, and lowers failure grasps, suggesting the positive effectiveness of ETS information on motor control (Fig. 4C, 4D, 4E & 4F). This may be due to the existence of ETS-based feedback to form a closed sensory-control loop of the prosthetic hand. During the object localization phase, tactile feedback allows individuals to determine whether they have successfully grasped an object more rapidly than visual cues can, following an attempt to pick up the object. During the grasping and transport phases, the contact force can be modulated in real-time with closed-loop control. This ability is reflected in the reduction of failed grasps and improvement of success rate and net manual dexterity (Fig. 4D, 4E & 4F). Interestingly, prior use of prostheses shows a strong effect on the performance of participants. This skill not only allowed the EXP group to manipulate the hand prosthesis efficiently, but also enabled them to utilize the incidental feedback (e.g. motor vibration) to access its spatial position (Fig. 4G) [39]. For inexperienced participants, the improvement by the ETS in motor control is reflected in all four criteria (Fig. 4). Other studies also observed that the impact of sensory feedback on experienced participants is not as notable as that on the IEXP participants [15]. However, the limited number of participants in this study only shows a preliminary trend. Further study of the effects of experience will require the recruitment of more participants. Nevertheless, the presence of ETS-based tactile feedback allows all participants, regardless of their prior experience, to enhance their grasp control in functional scenarios.

The ETS contains dual dimensional information in the contact pattern and intensity of multiple fingers, which improves both transport and feature discrimination in the sensorimotor functional task (Fig. 5A, 5B & 5C). The significant improvement of performance in identifying combined size and compliance shows that the spatial contact finger and force intensity information can be utilized efficiently in a functional scenario (Fig. 5C, 5E & 5F). However, the presence of ETS-based perceptual feedback does not result in a significant increase in completion time (Fig. 5D). This may be due to the combined effect of ETS-based tactile feedback on prosthetic hand manipulation and perception of object properties. The performance in identifying object size margins is significantly enhanced with ETS-based tactile feedback, whereas the overall perception of object compliance did not display a significant difference under both feedback conditions (Fig. 5E &5F). This indicates the positive role of natural finger sensations in augmenting the perceptual abilities of participants with forearm amputation, which is consistent with previous studies [24]. The marginal identification of experienced participants is consistently above the chance level with or without ETS-based feedback, while the performance of inexperienced (Fig. 5E &5F) participants is better only when ETS-based feedback is present. The experienced participants may form an internal model about the operation of a prosthetic hand from the long-term use in activities of daily life [40], [41], [42]. This also reveals the interesting point that the experience of using the hand prosthesis may influence the integration of ETS-based tactile feedback in sensorimotor functionality (Fig. 5G). Nevertheless, adding ETS-based feedback yields an overall improvement in sensorimotor performance, implying the general effectiveness of ETS-based feedback for participants with forearm amputation in hand prostheses.

The post-test survey discloses that the subjective embodiment, willingness, and confidence are all boosted with ETS-based sensory feedback (Fig. Sup1). The score of the embodiment questionnaire is increased by ETS-based feedback in both basic and functional tasks (Fig. Sup1A & Sup1C), indicating that ETS-based feedback enables participants to feel ownership of the prosthetic hand as a part of their body. Since lack of embodiment is an important reason to reject a hand prosthesis [43], it is reasonable to expect that ETS may motivate the willingness of participants with amputation to use hand prostheses in daily life (Fig. Sup1B & Sup1D). The ETS further bolsters their confidence to execute functional tasks. This is consistent with findings in the literature that sensory feedback enriches the sense of embodiment [33], [34],

[35], [44]. Thus, it is possible for ETS-based feedback to raise the acceptance rate of prosthetic hands by users.

The limitation of the ETS-based feedback technique, however, is the restricted amputee population who may benefit from it. A survey of 68 participants with upper limb amputation examined from multiple rehabilitation centers in China revealed that about 42.6 % of them developed PFM perception, while 19.1 % of them experienced PFM for five digits (Table Sup 2). In practice, the tactile sensation of two or three fingers may still satisfy the need for sensory feedback in most grip tasks [14], [45], [46]. Thus, more than 40% of individuals with forearm amputation can utilize this sensory feedback without having to undergo surgical interventions. For those without any PFM, the option to recreate PFM is available using targeted sensory re-innervation (TSR) [47], [48], [49].

In conclusion, this study examines the integrative sensorimotor performance of ETS-based feedback in both basic and functional scenarios. The high-quality spatial and intensity information in the ETS-based feedback enables participants with forearm amputation to detect multiple physical parameters of objects effectively. The presence of ETS-based feedback improves the closed-loop sensorimotor performance of forearm amputees. These enhancements in sensorimotor functions underscore the premise that the ETS-based feedback is efficacious for either conventional or next-generation prosthetic hands [7], [50]. Furthermore, the ETS-based sensory feedback allows participants with forearm amputation to perform a range of daily activities that require control of contact force or bimanual manipulation (Fig. Sup 5 & Movie Sup 2). The outcome of this study strongly supports deploying the ETS-based technique of sensory feedback to home use for those with a compatible limb condition.

Supplementary Materials

Fig. Sup 1. Performance of questionnaires in basic and functional tasks.

Fig. Sup 2. Projected finger map of six participants with forearm amputation.

Fig. Sup 3. The pattern of contact pressure for blocks with different lengths in six participants.

Fig. Sup 4 Contact pressure of thumb and index finger during identification of three different sizes in S2, S5, and S6.

Fig. Sup 5. Performance of daily activities.

Table Sup 1. Questionnaires for embodiment, willingness and confidence.

Table Sup 2. Evaluation data of evoked tactile sensation (ETS) in 68 participants with amputation.

Movie Sup 1 (.mp4 format). Performance of the functional identification and transport task.

Movie Sup 2 (.mp4 format). Activities of daily living with the bidirectional prosthetic hand.

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