Science Translational Medicine

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RESEARCH ARTICLE | BIOENGINEERING

Restoring Natural Sensory Feedback in Real-Time Bidirectional Hand Prostheses

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- **First author**: the one that provided the most relevant original contribution and did the practical work for the study
- **Last author**: the source of the funding for the project, came-up with the main idea behind the project, provided guidance
- Corresponding author: the primary point of contact, responsible for handling communication with the journal editors, reviewers, and readers
- Others - generally - in order of importance
- Co-authorship is more and more common

How to read a paper

A first quick read

1. Read the title
2. Read the abstract carefully
3. Check the Figures + captions

More in deep

4. Read Introduction (▶motivation)
5. Read the figures + results text (▶ contribution)
6. If something is not clear - > check the methods
   - If still not clear -> check the supplementary materials
7. Discussion (▶ Interpretation of the results, consequence for the field, limitations)

BIOENGINEERING

Restoring Natural Sensory Feedback in Real-Time Bidirectional Hand Prostheses

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Hand loss is a highly disabling event that markedly affects the quality of life. To achieve a close to natural replacement for the lost hand, the user should be provided with the rich sensations that we naturally perceive when grasping or manipulating an object. Ideal bidirectional hand prostheses should involve both a reliable decoding of the user's intentions and the delivery of nearly "natural" sensory feedback through remnant afferent pathways, simultaneously and in real time. However, current hand prostheses fail to achieve these requirements, particularly because they lack any sensory feedback. We show that by stimulating the median and ulnar nerve fascicles using transversal multi-channel intrafascicular electrodes, according to the information provided by the artificial sensors from a hand prosthesis, physiologically appropriate (near-natural) sensory information can be provided to an amputee during the real-time decoding of different grasping tasks to control a dexterous hand prosthesis. This feedback enabled the participant to effectively modulate the grasping force of the prosthesis with no visual or auditory feedback. Three different force levels were distinguished and consistently used by the subject. The results also demonstrate that a high complexity of perception can be obtained, allowing the subject to identify the stiffness and shape of three different objects by exploiting different characteristics of the elicited sensations. This approach could improve the efficacy and "life-like" quality of hand prostheses, resulting in a keystone strategy for the near-natural replacement of missing hands.

Intro

Pivot

Methods & Results

Conclusion & outlook

Fig. 1. Bidirectional control of hand prosthesis and characterization of neural stimulation

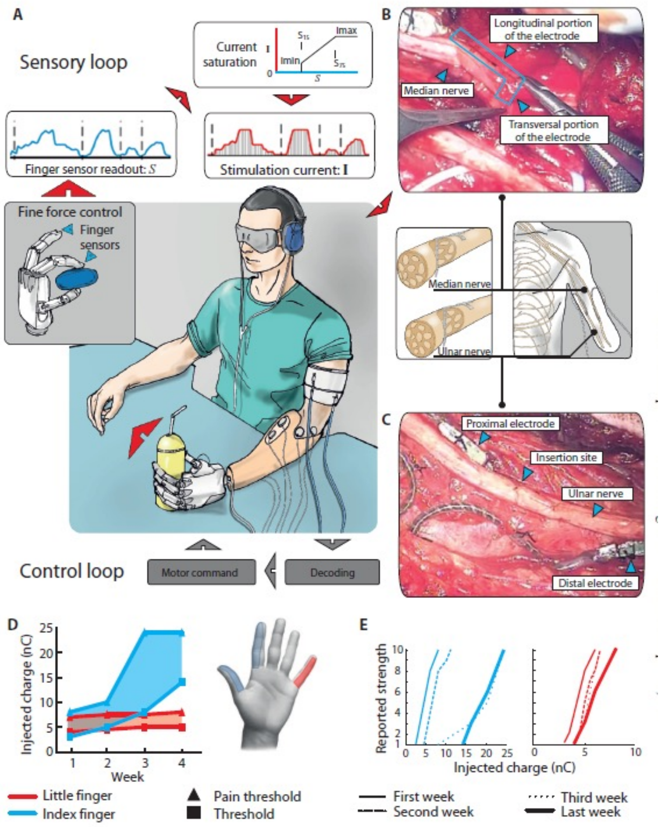


Fig. 1. Bidirectional control of hand prosthesis and characterization of neural stimulation. During experiments, the participant was blindfolded and acoustically shielded. The real-time bidirectional multiple-grasp control of the hand prosthesis involved both a reliable decoding of the user's motor command—immediately converted into hand motion (control loop)—and a simultaneous readout from prosthesis sensors fed back to the user through intrafascicular nerve stimulation (sensory loop). The decoding was performed by processing sEMG signals, whereas the encoding was simultaneously achieved by intrafascicular stimulation of the median and ulnar nerves using TIMEs. (A) The current was delivered as a function of the prosthetic hand sensor readouts. S15 and S75 are 15 and 75% of the range of sensor values, respectively. (B) Photograph of the surgical insertion of a TIME electrode in the median nerve of the participant. (C) Depiction of the subject's ulnar nerve with the two implanted electrodes. (D) Time course of the reported threshold and saturation of sensation over 4 weeks in the little and index fingers. The sensation threshold corresponded to the minimal sensation of touch reported, whereas saturation ("pain threshold") was defined as the charge that elicited a nearly painful touch as reported by the subject. (E) Sensation strength for each finger [color-coded as in (D)] reported on a scale from 1 to 10 for each of the 4 weeks.

Fig. 2. Fine force control

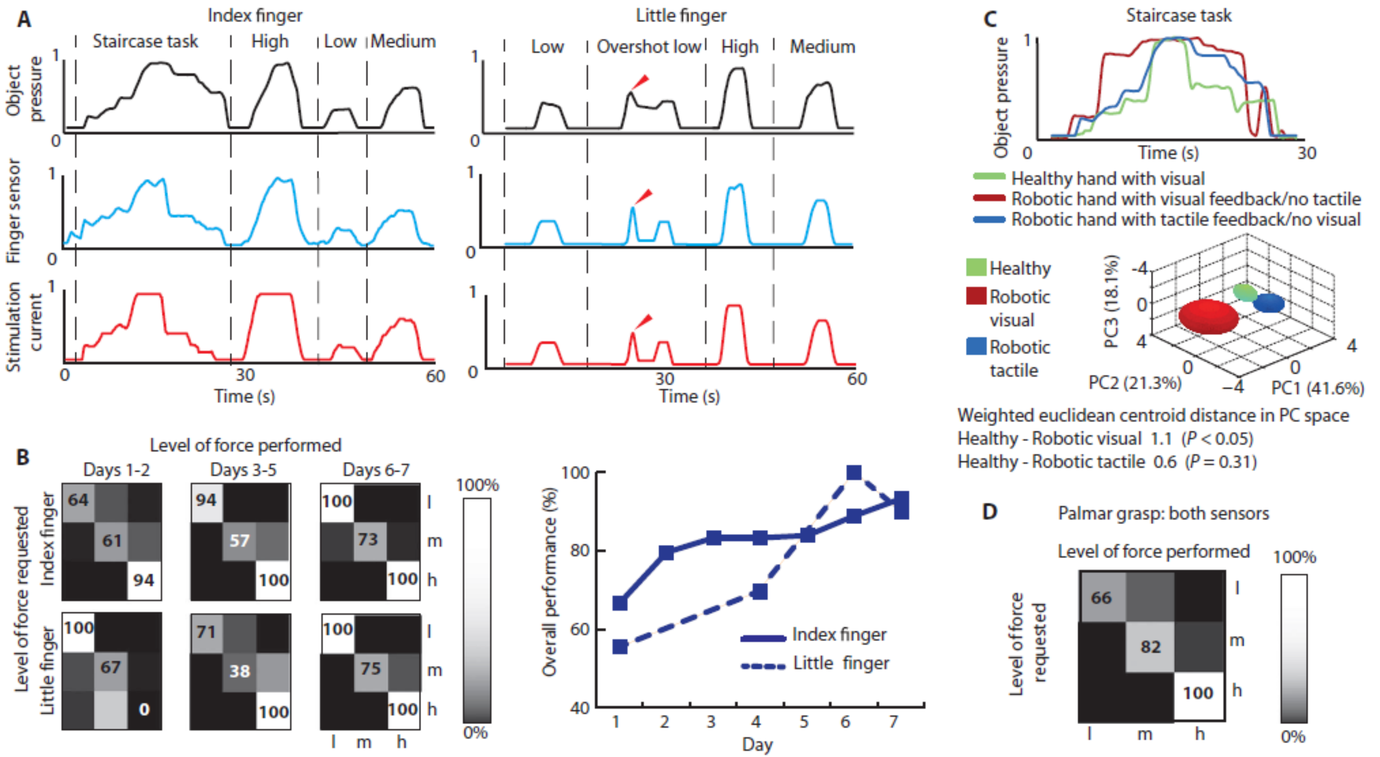
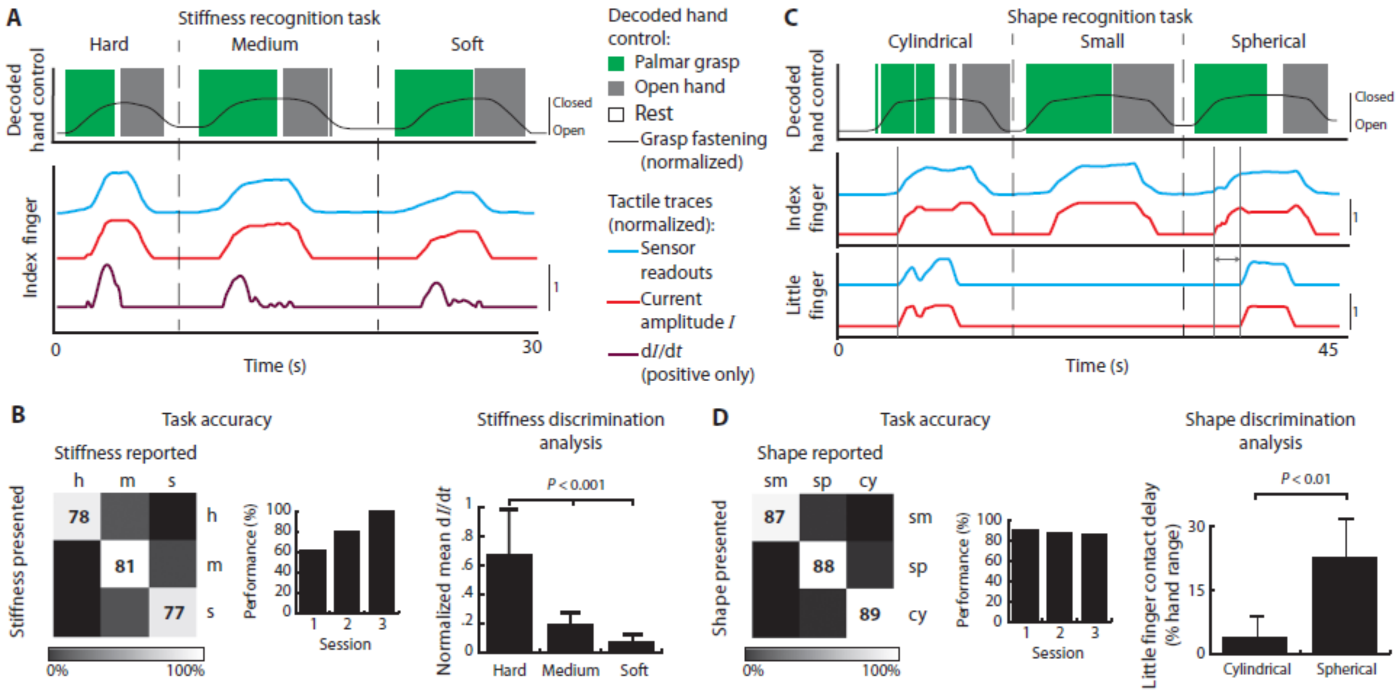


Fig. 5. Object stiffness and shape recognition.



What we want you to do

- **Motivation**

What was the rationale of this research?

- **Contribution**

Key findings? What was new compared to existing literature?

- **Discussion and outlook (2pt)**

Consequences for the field? Future applications?

Limitations?

Clinical motivation

Technical/scientific gap

INTRODUCTION

Sophisticated hand control is a peculiar characteristic of higher primates. Dexterous manipulation is achieved through a complex relationship between motor commands, executed movements, and sensory feedback during hand activities. Hand loss causes severe physical debilitation and often distress because skillful object grasping and manipulation are compromised, thus depriving the person of the most immediate and important source of tactile sensing in the body. For these reasons, replacing a lost hand and its precise functionalities is a major unmet clinical need that is receiving attention from engineers, neurophysiologists, and clinicians. An ideal hand prosthesis should reproduce the bidirectional link between the user's nervous system and the peri-personal environment by exploiting the post-amputation persistence of the central and peripheral neural networks and pathways devoted to hand motor control (*1*) and sensing (*2–5*). In particular, real-time and natural feedback from the hand prosthesis to the user is essential to enhance the control and the functional impact of prosthetic hands in daily activities, prompting their full acceptance by users within an appropriate "body scheme" that does not require continuous visual monitoring, as with current artificial hands (*6, 7*).

Recent notable advances in the field of hand prostheses have included designing devices with multiple degrees of freedom and equipped with different sensors (*8–10*). These developments have made the need for more effective bidirectional control even more compelling. A promising solution is represented by targeted muscle reinnervation (TMR), which consists of rerouting the residual nerves of the amputees over the chest muscles (*11, 12*). Individuals with arm or hand amputations can chronically use TMR-based prostheses, which could theoretically allow for a certain amount of sensory feedback (*13, 14*). However, because the superficial electromyogram (sEMG), used as a control signal, is recorded from the same body region (that is, the chest) that must be mechanically stimulated to provide feedback, real-time bidirectional control could be difficult to achieve. In this scenario, TMR subjects must contract muscles and simultaneously perceive a touch sensation on the skin overlying the same muscles, therefore possibly producing the so-called neurophysiological "sensory gating" (*15*).

In parallel, the rapid development of neural interfaces for the peripheral nervous system (*16*) has provided potential for new tools through which bidirectional communication with nerves in the stump could be potentially restored. Initial feasibility demonstrations of the induction of some sensations (*17*) and preliminary trials of the sporadic control of nonattached prostheses (*18–20*) have recently been performed. However, to date, no evidence has been gathered for the real-time use of these neural interfaces for the effective bidirectional control of dexterous prosthetic hands performing different grasping tasks.

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Limitation

because of the homology and real-time properties of this neural coding. The participant's ability to control different levels of grasping force, execute functional manipulations, and identify some simple object properties as three levels of compliance and three different shapes provides powerful evidence of the impact that this approach could have in real-life applications.

However, this study was conducted on one participant over a limited amount of time, and future studies will show on larger populations of amputees accurately the performance and limits of this artificially induced sensory feedback integration into the control of prosthesis. The other limitation is the fact that the tests were conducted continuously over the course of 1 week, so it is not clear whether the user would retain or even improve performances over a longer period of not being used. Moreover, many other sensations, or more sophisticated perceptions that might be elicited with this implants, were not tested.

Restoring sensory feedback is necessary to improve the usability of a hand prosthesis in daily life activities, where regaining control of the force output or being able to recognize object properties would increase the quality of life of people who suffer from hand amputation. The concept of this closed-loop bidirectional control, using a stimulating neural interface, could also be extended to enable the stimulation of a larger number of sites on the nerve implants. By coupling these locations for stimulation with the readouts of as many sensors embedded in the hand prosthesis, a wider variety of sensations could be delivered to the user, in terms of both position (for example, palm sensing) and type of sensation (for example, proprioception). To translate this technology to common clinical practice and even everyday use, several goals have to be achieved. First, the equipment used for stimulation should be miniaturized and fully implantable. The control unit for decoding of motor intention from sEMG signals and encoding of sensation by stimulation should be programmed on-chip and introduced in the socket of the prosthetic hand. Overall, this approach opens up new possibilities for hand prosthesis users, paving the way for the development of natural, dexterous, and effective bidirectional control of these devices.

fore, trials were interrupted when the subject asked it. Data were considered outliers when they exceeded 2 SDs from the mean.

Subject recruitment

All procedures were approved by the Institutional Ethics Committees of Policlinic A. Gemelli at Catholic University, where the surgery was performed, IRCCS San Raffaele Pisana (Rome), where the experiments took place, and Campus Bio-Medico University, whose clinical personnel collaborated during the experiments. The protocol was also approved by the Italian Ministry of Health. One male participant (D.A.S.), age 36 years, was selected for the experiments from a group of 31 candidates with hand amputation because of the stump characteristics (transradial amputation and sufficient number of remnant muscles) and his psychophysical abilities (expert user of EMG-driven hand prostheses). He suffered a transradial left arm amputation 10 years ago, as a consequence of a traumatic event.

Bidirectional prosthesis and real-time control

The surgical procedure for implanting TIMEs is described in the Supplementary Materials and Methods. The bidirectional prosthesis comprised a set of commercial devices (Prensilia IH2 Azzurra robotic hand, 2 GRASS QP511 analogical amplifiers, Multichannel System STG4008 stimulator) and the TIMEs developed in the homonymous EU project. The artificial hand was connected to the stump of the volunteer by a custom-made socket (Ortopedia Italia). The artificial hand and the stimulator were controlled by custom-developed software in LabVIEW (National Instruments). The prosthetic hand was equipped with tension sensors measuring the force exerted by the index and the little fingers.

The users' residuum sEMG signals were used to decode the intended grasp. Decoded hand motion was driven in terms of progressive position control, resulting in a gradual opening or closing of the hand. The sensors embedded in the hand were used as inputs for the delivery of the afferent neural stimulation. Current-controlled stimulation was delivered through the TIME active sites (1 in the median nerve and 1 in the ulnar nerve, with overall 56 active stimulating and 8 ground sites), eliciting a sensory perception reliably localized within the territories of the stimulated median or ulnar sensory fascicles. The stimulation was provided at fixed frequency and width of a biphasic train of pulses, whereas the cur-

What we want you to do

Motivation

Sensory feedback is important

- for motor tasks
- Body schema
- To not rely on visual feedback

No Study has shown bidirectional prosthetic usage

Contribution

- The authors used intrafascicular stimulation of two nerves of the arm to provide tactile sensation in the phantom hand.
- The participant could control the grasp force in real-time
- He could recognize objects’ proprieties, such as stiffness and shape

Discussion and outlook

The authors have shown a stable natural sensation in closed-loop.

Opens up to new prosthetics with sensory feedback

Limitation: only 1 subject, stability beyond a few days? Portability? Other sensory modalities, such as proprioception