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INVITED REVIEW

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Our research path toward the restoration of natural sensations in hand prostheses

Silvestro Micera[1,2] | **Solaiman Shokur**[1,2]

[1]Bertarelli Foundation Chair in Translational Neuroengineering, Neuro-X Institute, School of Engineering, Ecole Polytechnique Federale de Lausanne (EPFL), Lausanne, Switzerland

[2]The BioRobotics Institute, Interdisciplinary Health Center, and Department of Excellence in Robotics and AI Scuola Superiore Sant'Anna, Pisa, Italy

Correspondence
Silvestro Micera, Bertarelli Foundation Chair in Translational Neuroengineering, Neuro-X Institute, School of Engineering, Ecole Polytechnique Federale de Lausanne (EPFL), Lausanne, Switzerland.
Email: silvestro.micera@epfl.ch

Abstract

The human hand, with its intricate sensory capabilities, plays a pivotal role in our daily interactions with the world. This remarkable organ possesses a wide range of natural sensors that enrich our experiences, enabling us to perceive touch, position, and temperature. These natural sensors work in concert to provide us with a rich sensory experience, enabling us to distinguish between various textures, gauge the force of our grip, determine the position of our fingers without needing to see them, perceive the temperature of objects we come into contact with or detect if a cloth is wet or dry. This complex sensory system is fundamental to our ability to manipulate objects, explore our surroundings, and interact with the world and people around us. In this article, we summarize the research performed in our laboratories over the years and our findings to restore both touch, position, and temperature modalities. The combination of intraneural stimulation, sensory substitution, and wearable technology opens new possibilities for enhancing sensory feedback in prosthetic hands, promising improved functionality and a closer approximation to natural sensory experiences for individuals with limb differences.

KEYWORDS

bionics, hand prostheses, peripheral nerve, sensory feedback

1 | INTRODUCTION

The human hand is a remarkable organ that we use every day to interact with the external world. In particular, the hand is equipped with a remarkable array of natural sensors that enable us to perceive touch, position, and temperature, allowing us to interact with our environment in a sophisticated and nuanced way.

1. Touch Sensation: Our skin is equipped with various touch receptors. Meissner's corpuscles, located in fingertips and palms, detect light touch and vibrations. Merkel cells and discs in the upper skin layers discern sustained pressure and object textures. Pacinian corpuscles, deeper within the skin, respond to deep pressure, and intensity of touch. Ruffini endings, in deep skin layers, detect skin stretch.

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2. Position and Proprioception: Proprioceptors, scattered in muscles, tendons, and joints of the hand, relay information about hand position, movement, and muscle tension. This sense of proprioception allows us to perform intricate tasks by understanding joint angles and muscle engagement.
3. Temperature Perception: Thermoreceptors, found throughout the hand's skin, detect temperature changes. Cold receptors respond to temperature decreases, helping us sense cold objects or conditions, while warm receptors respond to temperature increases, allowing us to perceive warmth or hot objects.

The development of an artificial hand capable of mimicking the intricate capabilities of the human hand represents a remarkable stride in the field of prosthetics and robotics. By emulating the human hand's versatility, this device should not "only" restore lost functionality but also offer individuals with limb differences an opportunity to regain a sense of normalcy and autonomy in their daily lives, redefining the boundaries of what is achievable in the realm of human-machine interfaces.

Specifically, in response to end-user requests,[1] extensive efforts have been dedicated to addressing the challenge of restoring the flow of sensory information between hand prostheses and the human brain. In the next Sections, we are going to provide information about the results achieved by our group to restore all the human hand sensory modalities.

2 | RESTORATION OF TOUCH SENSATION USING TIME ELECTRODES

The challenge of restoring touch has been addressed both with non-invasive and invasive approaches.[2-10] Notably, considerable emphasis has been placed on the development of peripheral interfaces, which, when implanted within residual arm nerves, have demonstrated the ability to elicit sensations.[4,5,8,9-14]

In our laboratory, following numerous attempts, several years ago, we identified intraneural electrodes, specifically TIME electrodes,[15] as a viable solution for providing sensory feedback to amputees through the stimulation of the peripheral nervous system (PNS). After conducting initial short-term biocompatibility assessments and comparing these electrodes with other neural interfaces,[16] we made the decision to embark on the first short-term (30 days) implantation in collaboration with Prof. Paolo Maria Rossini in Rome, Italy, involving a trans-radial amputee. This pivotal clinical trial marked the first instance[17] where the restoration of sensory feedback through a prosthesis via peripheral nerve stimulation was demonstrated as a feasible endeavor. Specifically, we illustrated that by adjusting the electric current's charge injected through TIME electrodes in both the median and ulnar nerves of a person with hand amputation, using a proportional relationship with the feedback from force sensors integrated into a hand prosthesis, it became possible to restore the sensation of the applied force on a grasped object. Remarkably, the subject also displayed an effective ability to differentiate between objects based on their shape and stiffness, employing a strategy that closely resembled natural sensory perception.

Then, starting in November 2015, we conducted a series of three implants in trans-radial amputees, each participating in a 6-month trial. Throughout this trial, which spanned for each subject, we meticulously documented the sensations arising from electric current stimulation delivered through four TIME electrodes strategically implanted in the median and ulnar nerves. Our data collection involved weekly assessments over a span of up to 80 days post-implantation, focusing on characterizing the type, location, extent, and intensity of the sensations experienced over the missing (phantom) hand (as illustrated in Figure 1A,B, Petrini et al.[18]).

Moreover, we not only corroborated but also expanded upon the outcomes attained during the initial 1-month experiment. For instance, we demonstrated the profound potential of combining virtual therapy and neurostimulation (VTNS) in engendering a sense of "embodiment" in the patients, who additionally reported an enhanced perception of the forearm, an effect often referred to as the "telescopic" effect (as depicted in Figure 1C, Rognini et al.[19]). In the concluding phases of the clinical trials, participants began wearing all the control and stimulation electronics, conveniently housed in a backpack, enabling them to utilize the bidirectional prosthesis beyond the confines of the laboratory. This transition facilitated an evaluation of the technology's usability in less controlled, real-life scenarios. Impressively, all participants successfully performed a range of real-life tasks such as driving, underscoring the robustness, and user-friendliness of our setup even in these more challenging, real-world conditions.

Finally, we also showed[20] that it is possible to combine frequency and amplitude modulation strategies to increase the naturalness and efficacy of the stimulation.[21] This result shows even more the potential of our approach but at the same time clearly indicates that better results could be achieved in the future with hand prostheses with better and more "biomimetic" sensors.

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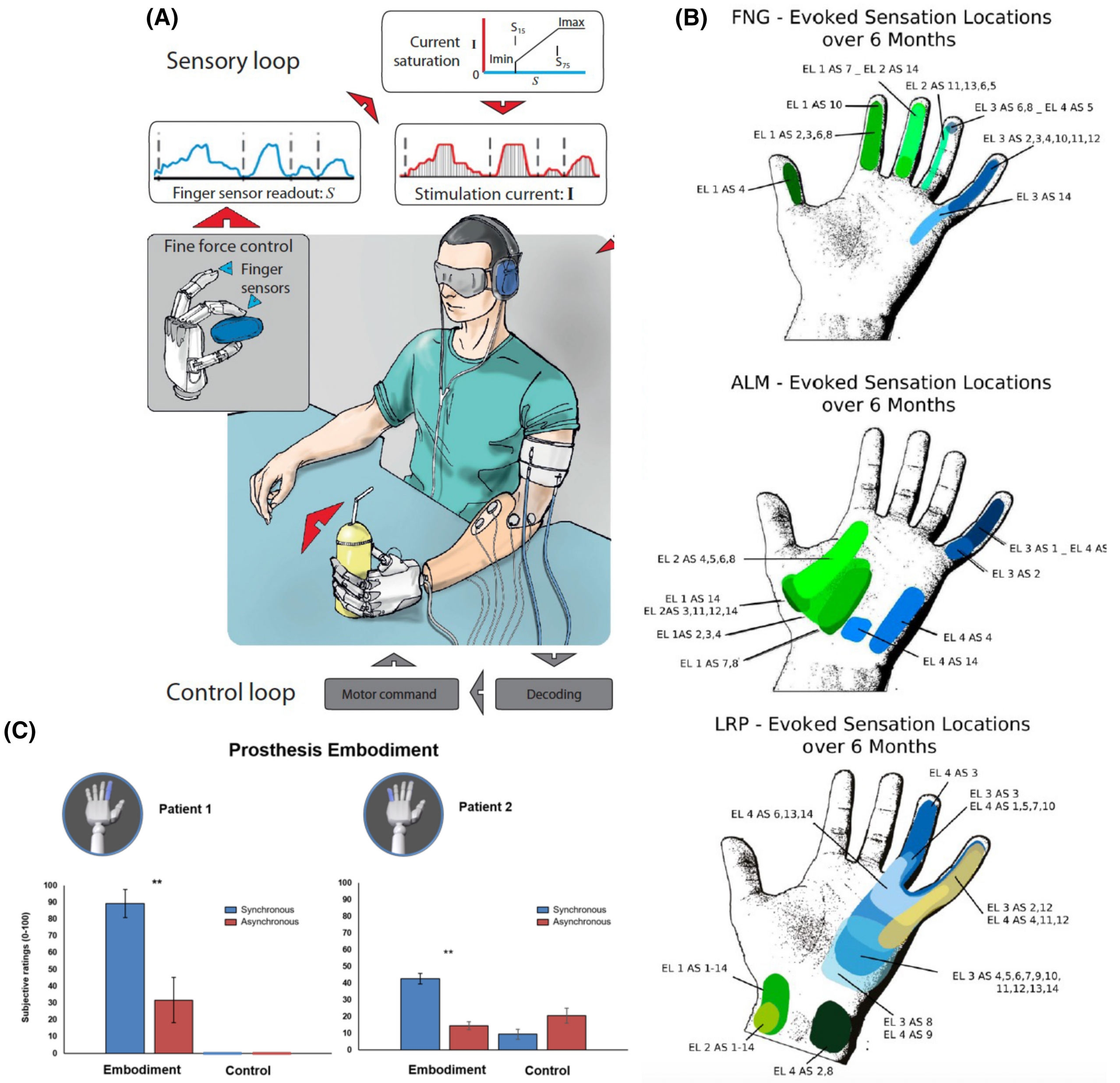

FIGURE 1 (A) The experimental setup used to verify the performance of our TIME-based tactile sensory feedback.[17,18] (B) The tactile sensations induced in three subjects.[18] The telescopic effect achieved by visual and tactile stimulation.[19] (C) Perceived phantom forearm length induced by the stimulation. [Color figure can be viewed at wileyonlinelibrary.com]

3 | RESTORATION OF POSITION INFORMATION USING RE-MAPPING STRATEGIES

Information about the position of the fingers in space is crucial to perform everyday activities. Unfortunately, direct nerve stimulation is rarely able to provide finger position information to the users. Proprioception, a critical aspect of limb control, relies in part on signals from type Ia and type II sensory afferents originating from muscle spindles. The close proximity of these proprioceptive afferents and motor neurons in nerves poses challenges, as activating proprioceptive pathways often leads to unintended muscle twitches. It has been observed that microstimulation of proprioceptive afferents alone does not result in perceptual responses unless accompanied by muscle activity, making it difficult to achieve selective and homologous proprioceptive feedback with current neural stimulation approaches, especially in transradial amputees. Instead, we recently explored the potential of sensory substitution or remapping, a concept widely used to restore various sensory modalities.[22] We adopted a hybrid approach for transradial amputees, where finger position information, referred to as remapped proprioception, was conveyed through sensory substitution using peripheral intraneural stimulation. Simultaneously, tactile information, termed somatotopic tactile feedback, was restored with a somatotopic approach, ensuring that sensations were correctly perceived on the fingers and palm, as demonstrated previously. Specifically, joint angle data was provided via intraneural stimulation of spared neural afferent pathways. To compare results, we also implemented the same sensory substitution approach using noninvasive electrotactile feedback with one participant. We allowed two transradial amputees to achieve remarkably high and near-natural proprioceptive accuracy, with a median joint angle reproduction precision of 9.1° and a median threshold for detecting passive movements of 9.5°, similar to results seen in healthy individuals. Moreover, by combining this proprioceptive feedback with somatotopic tactile feedback, the amputees demonstrated the ability to discriminate the size and compliance of objects with an impressive success rate of 75.5%. These findings show that re-mapping and re-learning can also be used in combination with directly induced sensations when necessary.

4 | RESTORATION OF THERMAL INFORMATION USING A WEARABLE SYSTEM

The reduced size of the thermal sensory nerves makes very challenging to selectively active only these neural endings with electrical neuromodulation. For this reason, temperature has been considered for several years, the most difficult sensation to restore in hand prostheses. This situation pushed us to identify alternative solutions to tackle this very important problem.

In our recent research, as documented in Iberite et al.,[23] we made a noteworthy discovery regarding thermal phantom sensations among upper limb amputees. Our findings revealed that alterations in temperature applied to specific regions of the residual arm elicited thermal illusions in the phantom hand of these amputees (see Figure 2). Importantly, we observed that these thermal phantom sensations displayed remarkable stability over time (up to 130 days in one case), paving the way for their potential use in restoring thermal feedback for prosthetic users. To translate this breakthrough into practical application, we developed the MiniTouch system. This technology facilitates the restoration of natural temperature sensations in upper limb amputees through non-invasive means. The system relies on a temperature sensor embedded in the prosthetic hand's finger, with the temperature information relayed to the user through a thermal display worn on the skin. The thermal display comprises a thermoelectric module affixed to a heatsink, while an ingenious custom sensor, known as the Active Thermal Skin (ATS) sensor, was designed to replicate the sensory capabilities of human skin. The ATS sensor is a thin Polyimide film encompassing two Platinum tracks arranged in an intricate pattern across its surface. Employing this method, we successfully induced thermal phantom sensations in the study participants. Remarkably, the amputees exhibited high precision and consistency in distinguishing various thermal stimuli. When integrated with current technologies, the restoration of thermal sensation promises to significantly enhance the overall prosthetic experience, ultimately bringing users closer to a sensation that closely mirrors the natural experience.

In an ongoing study, currently under revision, we have explored the feasibility of seamlessly integrating the MiniTouch system into the socket of existing prosthetic hands. In a pilot test involving a transradial amputee, we successfully demonstrated our ability to enhance commercially available prosthetics, enabling users to perceive thermal sensations in their phantom

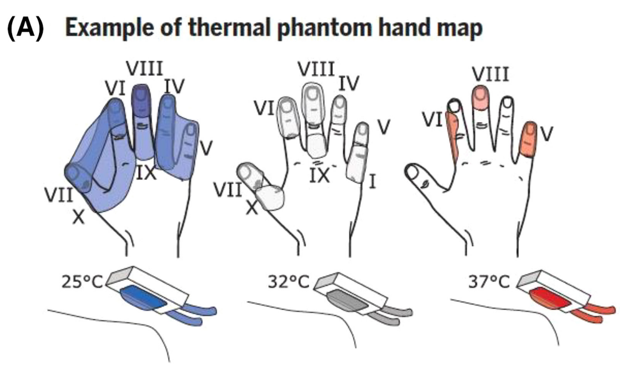

FIGURE 2 (A) Reported projection on the phantom hand for stimulations performed on the residual arm with the thermode set at 25°, 32°, or 37°C. The color corresponds to the participants' response, using a thermal visual analog scale, that ranges from very cold (dark blue) to very hot (dark red). (B) Example of three thermal phantom spots.[23] [Color figure can be viewed at wileyonlinelibrary.com]

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hand.[24] These developments mark a significant step forward in the quest to provide enhanced sensory feedback and functionality to amputees through cutting-edge technology.

5 | CONCLUSION

The current results of our development showcase the potential of our approach and, in doing so, open up exciting new avenues for the restoration of all hand sensory functions. The strides we have made in this field represent a significant leap forward in the realm of prosthetics and neurotechnology. Our research and innovations promise to enhance the quality of life for individuals with limb differences and potentially revolutionize the broader landscape of human–machine interfaces. These achievements reflect our progress and signal a promising future where individuals can regain a sense of touch and control over their prosthetic hands, ultimately reshaping the way we think about human augmentation and sensory restoration.

AUTHOR CONTRIBUTIONS

SM and SS wrote together the paper.

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Dr. Micera holds shares of Sensars Neurotechnology, a NEWCO developing a medical device for pain relief using intraneural stimulation.

CONFLICT OF INTEREST STATEMENT

SM is a shareholder of Sensars Neuroprosthetics which is developing neuroprosthetic solutions to reduce pain in people with limb amputation.

ORCID

Silvestro Micera https://orcid.org/0000-0003-4396-8217

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