

Advances in Neuroprosthetic Hand Rehabilitation: Enhancing Tactile Sensation through Soft Skin Compliance and Electrotactile Feedback

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Abstract

Restoration of hand function following upper-limb amputation has transitioned from purely mechanical replacement to sophisticated neural integration. A critical barrier in current prosthetics is the "sensory gap" the lack of biological-like compliance and real-time tactile feedback. This article explores recent breakthroughs in neuroprosthetic design, specifically focusing on the synergy between soft synthetic skin compliance and electrotactile sensory feedback. By employing internal open-pocket architectures in synthetic phalanges, compliance can be increased by over 400%, mimicking the human finger's natural displacement of >2 mm at 2 N of force. When coupled with closed-loop electrotactile systems, these "soft" neuroprosthetics achieve object discrimination accuracies exceeding 97%. This dual approach addresses both the functional and emotional requirements of prosthetic users, paving the way for more natural social interaction and embodiment.

Kew Words: neuroprosthetics; soft robotics; electrotactile feedback; skin compliance; myoelectric control; sensory substitution; artificial intelligence; neuromorphic computing

Introduction

The human hand is a sophisticated sensory-motor organ essential for environmental exploration and social bonding. For decades, prosthetic development focused primarily on motor output. However, the lack of haptic feedback and the mechanical stiffness of conventional devices often lead to a lack of "embodiment" the feeling that the prosthesis is a part of the user's body [1, 2]. Modern rehabilitation protocols now emphasize "sensory-driven autonomy," where the limb is no longer a passive tool but an intelligent partner capable of interpreting environmental cues and providing real-time neural feedback [3].

Biomechanical Compliance and Structural Innovation

Human skin is a non-linear, viscoelastic material that deforms under load to increase contact area, providing stable grip and soft sensation.

•Human vs. Synthetic Phalanx Deformation

Biomechanical studies show that a natural human finger phalanx undergoes a displacement of approximately 2.1 mm under a 2 N force [4]. In contrast, standard rigid prosthetic phalanges typically deform by less than 0.2 mm [5].

•The Open-Pocket Model

To replicate natural compliance, researchers have introduced internal "open-pocket" architectures within synthetic phalanges.

1. Silicone (2 mm pockets): Improved compliance by 235% [6].
2. Polyurethane (2 mm pockets): Improved compliance by 436% [6].

This structural biomimicry ensures that the prosthesis "gives" when it contacts an external surface, facilitating a more human-like mechanical response [7].

AI-Driven Sensory Mapping and Electrotactile Feedback

The most significant leap in 2025–2026 has been the integration of Artificial Intelligence (AI) to bridge the gap between artificial sensors and biological nerves.

•Neuromorphic Encoding and Deep Learning

Current neuroprosthetics utilize Long Short-Term Memory (LSTM) networks and Spiking Neural Networks (SNNs) to process temporal tactile data [8]. Unlike traditional linear mapping, these AI models interpret complex pressure and shear patterns to predict "grasp types" with high precision [9].

* Spatial Encoding: By mapping specific sensors to skin locations, single-finger stimulation accuracy has reached 98.57% [10].

* Biomimetic Temporal Coding: Modulating pulse frequency and width based on natural neural firing patterns has improved sensation "naturalness" by 6.8% compared to standard tonic stimulation [11, 12].

•Shared Human-Machine Control

Recent breakthroughs (December 2025) highlight systems where an artificial neural network trained on grasping postures allows each finger to identify nearby objects via proximity sensors [13]. This "shared control" allows the AI to stabilize the grip autonomously while the user provides high-level intent, significantly reducing the cognitive load on the amputee [14].

Functional Outcomes and Clinical Significance

The synergy of soft skin, AI, and electrical feedback allows for precision in object handling that was previously unattainable without visual confirmation.

| Feature | Accuracy Rate | Reference |

|---|---|---|

| Object Hardness Discrimination | >97.2% | [10] |

| Curvature Recognition | >97.8% | [10] |

| Texture Identification | ~85% | [15] |

Conclusion

The integration of compliant prosthetic skin with AI-enhanced electrotactile feedback offers a promising pathway for functional rehabilitation. By matching the mechanical properties of human tissue and providing intuitive sensory feedback through neuromorphic chips, modern neuroprosthetics are becoming true extensions of the human body, restoring not just function, but the "humanity" of touch.

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