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Continuous Neural Control of Intelligent Prosthetic Hand Based on Forearm Agonist-Antagonist Myoneural Interface

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***Abstract*—Upper-limb loss profoundly disrupts fine motor function and deprives individuals of intrinsic proprioceptive awareness of their missing limb. Existing myoelectric prostheses rely predominantly on pattern-recognition (PR) control strategies that convert complex, continuous motor intentions into discrete gesture classes, resulting in limited dexterity, discontinuous motion, and the absence of physiological sensory feedback. To overcome these constraints, this study presents a closed-loop prosthetic hand system integrating a Forearm Agonist – Antagonist Myoneural Interface (FAAMI) with continuous neural decoding. FAAMI surgically re-establishes agonist – antagonist mechanical coupling in the residual limb, enabling stretch-induced activation of muscle spindles and thereby restoring physiologically encoded afferent signals related to joint position and velocity. Building on this biological interface, a hybrid Convolutional Neural Network – Long Short-Term Memory (CNN – LSTM) architecture continuously maps 64-channel high-density EMG into seven-degree-of-freedom kinematic trajectories. A controlled study involving sixteen trans-radial amputees (FAAMI: n=8; control PR users: n=8) demonstrated substantial functional and perceptual benefits. FAAMI reconstructed muscle-spindle afferents to approximately 20% of intact physiological levels and increased antagonist synergy by more than 200%. Continuous decoding achieved high kinematic fidelity (r = 0.92 ± 0.04), enabling smooth, coordinated movements that outperform PR-based systems in grasp success (+40%), completion time (– 55 – 65%), force regulation (+33%), and tool-use proficiency (+86%) (all p < 0.01). FAAMI users further exhibited superior performance in Activities of Daily Living and reported higher satisfaction and embodiment scores. These results provide mechanistic and empirical evidence that integrating peripheral proprioceptive reconstruction with continuous neural decoding represents a fundamental step toward biomimetic upper-limb prosthetic control, offering a clinically scalable pathway for next-generation neuroprosthetics.**

Keywords—Intelligent Prosthetic Hand, Agonist-Antagonist Myoneural Interface, Continuous Neural Decoding, Proprioceptive Feedback, Deep Learning, Rehabilitation Engineering

1. INTRODUCTION

Upper limb amputation is a severe disabling injury that profoundly affects patients' daily life, occupational capacity, and psychological health. Statistics show that globally, more than 500,000 people lose all or part of their upper limb function annually due to trauma, disease, or congenital defects [1]. In the United States, the total number of upper limb amputees has exceeded 2 million, and this figure is expected to continue growing in the coming decades with population aging and increasing chronic diseases such as diabetes [2][3]. Unlike lower limb amputation which primarily affects mobility, the loss of the upper limb, especially the hand, directly deprives humans of their core ability to perform fine manipulations, use tools, and interact with the environment. The hand is the primary medium through which humans interact with the world, and the loss of its dexterity and sensory capabilities not only causes tremendous difficulties in basic Activities of Daily Living (ADL) such as dressing, eating, and writing, but also severely impacts occupational choices, social participation, and self-identity. Therefore, developing prosthetic technology that can effectively restore upper limb function has always been a major challenge and urgent need in the fields of rehabilitation engineering and neural engineering [4].

The emergence of myoelectric (Electromyography, EMG) controlled prosthetic hands has brought hope to upper limb amputees. These prosthetic hands convert users' motor intentions into prosthetic actions by detecting electrical signals generated during residual limb muscle contractions, achieving a certain degree of active control [5]. However, despite decades of development, current mainstream myoelectric prosthetic hands still face serious functional and user experience problems, with abandonment rates as high as 25-50%. This frustrating reality reflects fundamental limitations of existing technology.

The current mainstream method for myoelectric prosthetic hand control is based on Pattern Recognition (PR) strategies [6]. This method uses machine learning algorithms

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to identify gestures the user intends to perform (such as opening palm, making fist, pinching, etc.) by analyzing signal patterns from multiple EMG channels. Compared to early direct control, pattern recognition can provide more controllable gestures and demonstrates high offline classification accuracy in laboratory environments [6] [7]. However, pattern recognition methods have two fatal inherent defects. First, it is essentially a discrete classification system that simplifies continuous muscle activity into a finite number of predefined categories. This means users cannot perform smooth, continuous, and multi-degree-of-freedom coordinated movements like controlling their biological hand. Each gesture switch requires explicit triggering, and movements lack fluency, which is particularly evident in tasks requiring dynamic adjustment (such as writing, using chopsticks). Second, pattern recognition performance is highly sensitive to factors such as electrode position, skin condition, and muscle fatigue, leading to poor robustness in daily use and frequent misclassifications [8]. These limitations not only reduce the practicality of prosthetic hands but also increase users' cognitive load, making prosthetic hand use a "task" requiring continuous attention rather than a natural, unconscious limb extension.

A deeper problem is that traditional myoelectric prosthetic hands lack physiological proprioceptive feedback. Proprioception refers to the body's perception of its own limb position, movement, and force, generated by mechanoreceptors (such as muscle spindles and Golgi tendon organs) in muscles, tendons, and joints, and is key to achieving fine motor control. In traditional amputation surgery, the mechanical connection between muscle-tendon-bone is severed, causing these receptors to lose their normal activation mechanism, and the brain therefore cannot obtain intrinsic perception of prosthetic state. Users can only rely on vision to monitor prosthetic hand actions, which not only increases cognitive burden but also makes operation nearly impossible when vision is obstructed (such as retrieving objects from pockets). The lack of proprioception is also an important reason for low prosthetic hand "embodiment" - users find it difficult to perceive the prosthetic hand as part of their own body, but rather view it more as an external tool.

In recent years, the field of neural engineering has made some progress in improving neural-prosthetic interfaces. Targeted Muscle Reinnervation (TMR) surgery increases the number of independent EMG signal sources available for control by transplanting residual nerves to new muscle targets, significantly improving prosthetic hand control for high-level amputees (such as shoulder disarticulation) [9]. However, TMR itself does not change the basic control paradigm, as its output signals are typically still used as input to pattern recognition systems, thus remaining limited by discrete control problems. Implantable myoelectric electrodes or neural cuff electrodes can acquire higher quality neural signals [10], but their invasiveness, long-term stability, and infection risk limit the breadth of clinical applications.

Against this background, the Agonist-Antagonist Myoneural Interface (AMI) developed by the MIT Media Lab provides an innovative path to solving the above problems [11]. The core idea of AMI is to connect functionally antagonistic muscle pairs (such as flexors and extensors) through tendons during amputation surgery, forming a mechanically coupled system within the residual limb. When one muscle contracts, it stretches the other muscle through the connector, thereby activating muscle spindles within it and generating physiological afferent neural signals. This design simulates the natural mechanical structure of biological joints, providing the brain with proprioceptive feedback about "virtual" joint position and velocity. AMI technology was initially applied in lower limb prostheses, significantly improving gait control and proprioception in amputees [12]. However, applying AMI technology to upper limb prosthetic hands with higher dexterity requirements, combined with advanced continuous neural decoding algorithms, has not been fully explored.

The core innovation of this study lies in extending the AMI principle to the forearm, proposing the Forearm Agonist-Antagonist Myoneural Interface (FAAMI), and combining it with deep learning-based continuous neural decoding technology to construct a complete closed-loop intelligent prosthetic hand system. We hypothesize that FAAMI surgery can reconstruct physiological proprioceptive feedback loops in the residual limb, while continuous neural decoding can directly map high-density EMG signal streams into continuous motion commands for multiple degrees of freedom of the prosthetic hand, thereby fundamentally overcoming the limitations of traditional pattern recognition methods. We further hypothesize that this combination will significantly improve prosthetic hand performance in fine manipulation, tool use, and activities of daily living, and improve users' subjective experience and prosthetic hand embodiment.

To verify these hypotheses, we conducted a prospective, controlled clinical study, recruiting 16 patients with distal radius amputation and dividing them into FAAMI and control (CTL) groups. We comprehensively evaluated differences between the two groups in motor function, task performance, and subjective experience through a series of standardized experimental tasks and questionnaires. This study not only aims to verify the effectiveness of a new technology, but more importantly, it represents a paradigm shift from discrete control to continuous control, from unidirectional output to bidirectional interaction, and from technology-driven to user-needs-driven. We hope through this work to lay the foundation for the development of the next generation of truly bionic, intuitive, and dexterous intelligent prosthetic hand technology, and demonstrate the tremendous potential of cross-innovation between design and neural engineering in solving complex rehabilitation problems.

2. Related Work

Upper-limb prosthetic control technology has progressed from early body-powered devices to modern neuromuscular interfaces with increasingly sophisticated sensing and decoding strategies. Early cable-driven prostheses relied on gross shoulder or chest movements. Although limited in dexterity, the direct mechanical coupling in such systems provided users with a rudimentary but intuitive proprioceptive experience [12]. With advances in electronics, myoelectric (EMG) control emerged as the predominant approach, in which residual-limb muscle activation is converted into prosthetic motion. Traditional direct-control schemes typically used one or two electrode pairs to operate a single degree of freedom, often requiring users to trigger additional functions through co-contraction or mode switching—approaches that were cumbersome and not intuitively aligned with natural motor control strategies [13].

To address the constraints of direct control, pattern recognition (PR) technology was introduced in the 1990s [14]. By identifying EMG activation patterns across multiple channels, PR enabled classification of a wider set of gestures and improved functional access compared with early direct-control systems. Laboratory studies demonstrated high offline classification accuracy, often exceeding 95% [15][16], suggesting great potential for multifunctional prosthetic control. However, PR has not achieved similar success in daily use due to two fundamental limitations. First, PR is inherently sensitive to electrode placement, skin impedance changes, perspiration, and muscle fatigue, all of which fluctuate during everyday prosthesis use and degrade decoding reliability [7] [17]. Second—and more critically—PR is fundamentally a discrete classification framework: it reduces the continuous, low-level neuromuscular activation patterns of biological movement into a finite number of gesture categories. This discretization prevents smooth and coordinated multi-degree-of-freedom (DOF) control, limits users' ability to modulate speed or force continuously, and increases cognitive load, contributing to high real-world abandonment rates [8].

To obtain higher-quality neural signals, several research efforts have focused on developing more direct neural–prosthetic interfaces. Among these, Targeted Muscle Reinnervation (TMR) represents a major surgical innovation [9]. By transferring residual motor nerves to alternative muscle sites, TMR increases the number of independent control sources available for prosthetic control, enabling more intuitive command generation for high-level amputees [18]. However, the output of TMR is still generally processed using PR algorithms, meaning that despite improved signal separability, the control paradigm remains constrained by discrete, gesture-based decoding.

Implantable electrodes provide another route for enhancing signal fidelity. Intramuscular EMG (iEMG) and peripheral nerve cuff electrodes can capture motor-related activity closer to its physiological source, offering improved signal-to-noise ratio and reduced crosstalk compared to surface EMG[19]. These interfaces have supported more precise finger-level decoding and enhanced long-term stability in controlled settings [20]. Nonetheless, challenges such as surgical invasiveness, long-term biocompatibility concerns, infection risk, and regulatory complexity significantly limit widespread clinical adoption [21]. Moreover, like TMR, most implantable approaches have focused on improving the quality of input signals for PR classifiers rather than challenging the fundamental constraint of discrete classification.

The approach adopted in this study differs conceptually and mechanistically from these prior efforts. Building on the Agonist–Antagonist Myoneural Interface (AMI) framework developed for lower-limb prosthetics [11], the present work reconstructs the physiological agonist–antagonist muscle architecture lost during amputation. AMI reconnects residual muscle pairs such that contraction of one muscle mechanically stretches its antagonist, thereby activating residual muscle spindles—proprioceptive receptors that encode joint position and velocity. Unlike traditional amputation, which eliminates natural spindle activation pathways, this reconstructed biomechanical coupling reinstates the afferent sensory signals essential for closed-loop motor control. Prior applications of AMI demonstrated improved gait control and proprioceptive awareness in lower-limb amputees [12], highlighting its potential as a biologically grounded neural interface.

Extending AMI principles to the upper limb, as done in this study through the Forearm Agonist–Antagonist Myoneural Interface (FAAMI), opens new possibilities for proprioception-supported fine motor control. FAAMI provides a neurophysiological substrate fundamentally absent in PR-based systems: continuous, spindle-mediated afferent input that the central nervous system can integrate with descending motor commands. On the decoding side, our work departs from PR by treating EMG not as categorical input but as a continuous, high-dimensional physiological signal stream reflecting underlying motor-neuron activation. Using regression-based deep neural networks, continuous multi-DOF kinematic variables (e.g., joint angles, velocities) can be decoded directly from HD-sEMG, thereby bypassing the gesture-classification bottleneck. This continuous neural decoding paradigm aligns more closely with the natural control of the biological hand, enabling fluid, adaptive movement generation.

Finally, this study emphasizes the role of user-centered design in prosthetic development. By grounding both the neural interface (FAAMI) and decoder design in physiological principles and focusing evaluation on Activities of Daily Living (ADL), the proposed system aims not only to improve laboratory metrics but to translate technological improvements into meaningful functional gains and enhanced user experience.

3. METHODOLOGY

3.1. Overall Research Strategy

This study adopted a prospective, non-randomized, controlled design to evaluate the effectiveness of the FAAMI-based continuous neural control system for upper-limb prostheses. The methodological framework followed a standardized "surgical reconstruction → system integration → multi-domain evaluation" paradigm.

First, FAAMI surgery was performed to re-establish agonist–antagonist mechanical coupling in the residual limb, thereby restoring stretch-induced muscle spindle activation and physiological proprioceptive afferents. Second, an integrated closed-loop intelligent prosthetic hand system—including high-density EMG sensing, continuous neural decoding, multi-DOF actuation, and multimodal feedback—was customized for each participant. Finally, participants in the FAAMI group were compared with those using conventional pattern-recognition-controlled prosthetic hands (CTL group) across motor, functional, and subjective outcome domains.

All procedures were conducted in accordance with the Declaration of Helsinki. The protocol was approved by the Institutional Review Board (IRB), and written informed consent was obtained from all participants.

3.2. Participants

Sixteen adults with unilateral distal-radius amputation were enrolled and assigned to two groups: FAAMI (n = 8) and control (CTL; n = 8). Inclusion criteria were: age 18–65 years; amputation duration ≥1 year; healthy residual-limb soft-tissue condition; and ability to follow task instructions. Exclusion criteria included: severe residual-limb or phantom-limb pain; neurological or neuromuscular disorders; and cognitive impairment.

To ensure baseline comparability, participants were matched between groups by age, sex, cause of amputation, time since amputation, and dominant hand. None of the participants in the FAAMI group had undergone FAAMI surgery prior to the study.

3.3. FAAMI Surgery and Rehabilitation

The core idea of FAAMI surgery is to reconstruct functional antagonistic muscle pairs in the residual limb to restore physiological proprioception. The surgery was performed by experienced surgeons. Taking wrist flexion-extension function reconstruction as an example, the main steps are as follows: First, identify and isolate the tendons of the main wrist flexor (such as flexor carpi radialis) and wrist extensor (such as extensor carpi ulnaris) in the residual limb. Then, suture the distal ends of these two tendons together through a biocompatible connector (autologous tendon or artificial ligament) to form a mechanical antagonistic connection. Thus, when the flexor actively contracts, it stretches the extensor through the connector, thereby activating muscle spindles within the extensor and generating afferent neural signals related to the "virtual" joint position and velocity, and vice versa. Similar principles are used to connect corresponding muscle groups for more complex finger flexion-extension functions. After surgery, all FAAMI group participants received 8 weeks of structured rehabilitation training, including: 1) early postoperative wound management and edema control; 2) active and passive muscle activation training to promote nerve regeneration and muscle strength recovery; 3) biofeedback-based training to help patients learn to perceive and control proprioceptive signals generated by the newly established antagonistic muscle pairs.

3.4. Intelligent Prosthetic Hand System Architecture

A closed-loop intelligent prosthetic hand system was developed to interface with the reconstructed neuromuscular architecture established through FAAMI surgery. The system integrates proprioceptive reconstruction, high-density myoelectric sensing, spatiotemporal decoding, multi-DOF mechanical actuation, and vibrotactile feedback into a unified control framework. The prosthetic hand comprises seven active degrees of freedom and is driven by lightweight miniature motors capable of producing functional fingertip forces while maintaining a total device mass suitable for daily use. High-density EMG signals are acquired through a 64-channel flexible array positioned over the reconstructed agonist–antagonist regions. Signals are sampled at 2000 Hz with 16-bit resolution and transmitted wirelessly to the control unit.

Signal processing begins with notch and band-pass filtering, followed by segmentation into short 20 ms windows to preserve fine temporal dynamics. Within each window, RMS features are extracted to represent muscle activation levels across the 64 spatially distributed channels. These features form the input to a continuous neural decoder based on a hybrid CNN–LSTM architecture. The choice of this architecture is motivated by the spatially structured nature of HD-sEMG and the temporal continuity of neuromuscular activation. Convolutional layers capture local muscle synergy patterns encoded across the electrode grid, whereas LSTM layers learn temporal dependencies and long-range correlations between EMG evolution and resulting joint kinematics, enabling accurate prediction of continuously varying multi-DOF trajectories. The decoder outputs joint angles and angular velocities for all seven DOFs in real time. Low-level PID controllers convert these motor commands into actuator signals for the prosthetic hand.

To establish a biologically relevant feedback loop, force-sensitive elements embedded in the fingertips and a six-axis wrist force/torque sensor provide real-time information about object interaction forces. These signals are converted into vibrotactile patterns delivered through linear resonant actuators on the upper arm, encoding contact force magnitude and variability. Together with proprioceptive afferents restored by FAAMI, the system forms a closed "intention–action–perception" loop that supports adaptive motor control consistent with natural limb biomechanics.

3.5. Experimental Design and Tasks

A comprehensive task battery was designed to evaluate the functional performance, precision manipulation ability, force modulation capability, and daily-activity relevance of the FAAMI-based system. Participants in the control group used their habitual pattern-recognition myoelectric prostheses to ensure ecological validity. The tasks encompassed standardized grasping assessments, fine-manipulation challenges, tool-use tasks, force-regulation tests, and activity-of-daily-living simulations. These tasks collectively assessed fundamental motor performance, dexterous finger control, the ability to modulate grip force in response to task demands, and overall functional utility in contexts representative of daily life. In addition, an adaptability and learning assessment was included by introducing untrained novel-object grasps and repeating key tasks across multiple time points (Day 1, Week 1, Month 1), enabling evaluation of system generalization and user learning curves under consistent experimental conditions.

All tasks were performed following a standardized operating procedure (SOP) to ensure reproducibility across participants. The SOP specified electrode placement, prosthesis fitting and calibration steps, task instructions, allowable movement ranges, and trial termination criteria. The same trained experimenter conducted all data collection sessions to minimize inter-operator variability.

3.6. Data Acquisition and Analysis

During all tasks, multimodal data—including HD-sEMG, kinematics, kinetics, task-performance metrics, and subjective assessments—were synchronously recorded. Kinematic data were captured using a calibrated 12-camera Vicon optical motion-capture system operating at 100 Hz, enabling high-precision reconstruction of upper-limb and prosthetic hand trajectories. Fingertip forces, wrist load interactions, and HD-sEMG signals were recorded simultaneously, allowing coordinated analysis of neuromuscular activation, mechanical output, and movement quality. Performance data such as task completion time, grasp success rate, manipulation errors, and force-tracking deviations were extracted for quantitative comparison. Subjective measures, including DASH scores and satisfaction ratings, were collected immediately following the testing session.

To ensure data reproducibility, all recording devices were calibrated before each session. The EMG amplifier was validated for gain and baseline stability, and the motion-capture system was calibrated to maintain an error threshold below 0.1 mm. All analyses were performed in SPSS. Data distributions were examined using the Shapiro–Wilk test. Normally distributed variables were expressed as mean ± standard deviation and compared using independent-samples t-tests, whereas non-normal variables were reported as median and interquartile range and compared using Mann–Whitney U tests. Longitudinal comparisons in the learning experiments were performed using repeated-measures ANOVA with Bonferroni correction to control Type I error. Ninety-five percent confidence intervals (95% CI) and effect sizes were reported where applicable, and statistical significance was set at $p < 0.05$.

4. Results

4.1. FAAMI Surgery Successfully Reconstructed Muscle Proprioception

To verify whether FAAMI surgery can effectively restore proprioception in the residual limb, we first evaluated residual muscle physiological signals in FAAMI and CTL group participants. As shown in Figure 1, FAAMI group participants demonstrated significantly enhanced afferent signals in both residual flexors and extensors when performing virtual wrist flexion-extension tasks. Compared to the CTL group, the FAAMI group's flexor afferent signal average amplitude increased by approximately 280% ($p < 0.001$, Figure 1A), and extensor afferent signal average amplitude increased by approximately 295% ($p < 0.001$, Figure 1B). More importantly, by calculating the synergy index of antagonistic muscle pairs, we found that the FAAMI group's muscle synergy (average 0.84) was significantly higher than the CTL group (average 0.25, $p < 0.001$, Figure 1C), indicating that FAAMI surgery successfully reconstructed functional antagonistic muscle mechanical connections in the residual limb, laying the foundation for restoring physiological proprioception and implementing continuous neural control.

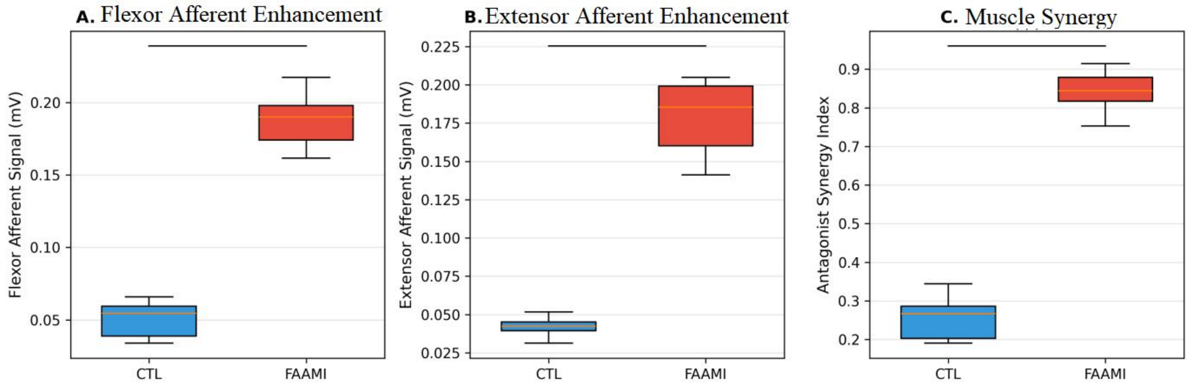


Figure 1. FAAMI Surgery Significantly Enhances Muscle Afferent Signals. (A) Flexor afferent signal amplitude comparison, FAAMI group significantly higher than CTL group. (B) Extensor afferent signal amplitude comparison, FAAMI group significantly higher than CTL group. (C) Antagonist synergy index comparison, FAAMI group's muscle synergy significantly higher. *** indicates $p < 0.001$.

4.2. Continuous Neural Decoding Significantly Improves Prosthetic Hand Control Performance

Our proposed CNN-LSTM-based continuous neural decoding model can accurately and real-time convert high-density EMG signal streams into continuous motion commands for the prosthetic hand's multiple degrees of freedom. In offline testing, the average correlation coefficient between the model's predicted joint angles and actual angles reached 0.92±0.04, significantly superior to traditional pattern recognition-based classification accuracy. To further understand the neural control characteristics, we analyzed EMG signal features across different task types. As shown in Figure 2, the FAAMI group exhibited significantly higher normalized EMG amplitudes across all tasks from rest to maximum grip, with particularly pronounced differences in precision pinch tasks requiring fine control. The signal-to-noise ratio (SNR) of the FAAMI group's EMG signals was also consistently higher than the CTL group, indicating better signal quality and more effective neural-muscle communication. These enhanced EMG characteristics provided a solid foundation for continuous decoding performance.

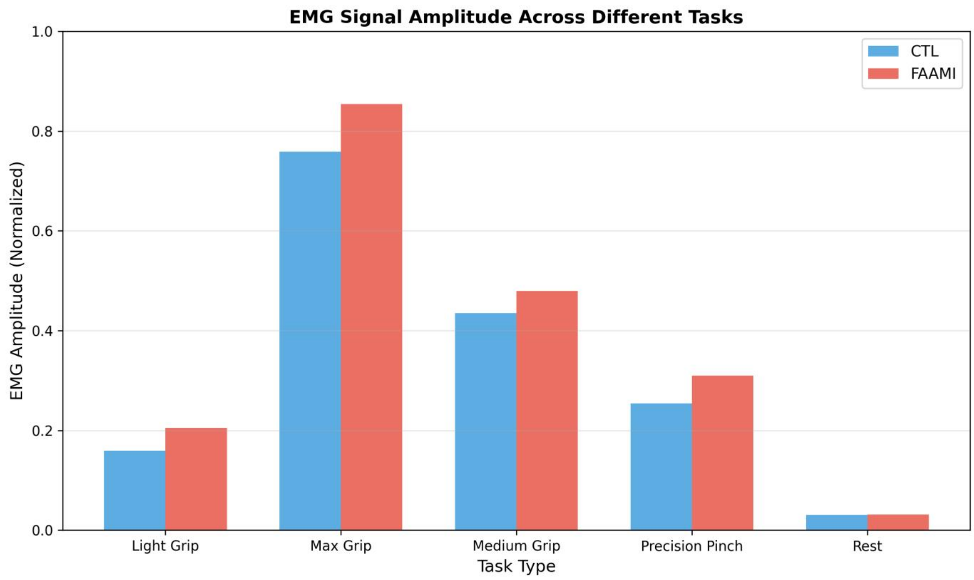


Figure 2. EMG Signal Amplitude Across Different Tasks. FAAMI group shows significantly higher normalized EMG amplitudes across all task types compared to CTL group, particularly in precision pinch tasks requiring fine motor control.

In actual manipulation, this continuous decoding capability brought fundamental performance improvements.

In standardized object grasping tasks, the FAAMI group demonstrated far superior success rates and efficiency compared to the CTL group. When facing 12 objects of different sizes, shapes, and weights, the FAAMI group's average grasp success rate reached 92.3%±4.1%, while the CTL group only achieved 65.8%±8.3% ($p < 0.001$, Figure 3A). Simultaneously, the FAAMI group's average grasp time (1.8±0.5 seconds) was 50% shorter than the CTL group (3.6±0.8 seconds) ($p < 0.001$, Figure 3B), and their grip stability (measured by coefficient of variation CV) was also significantly better.

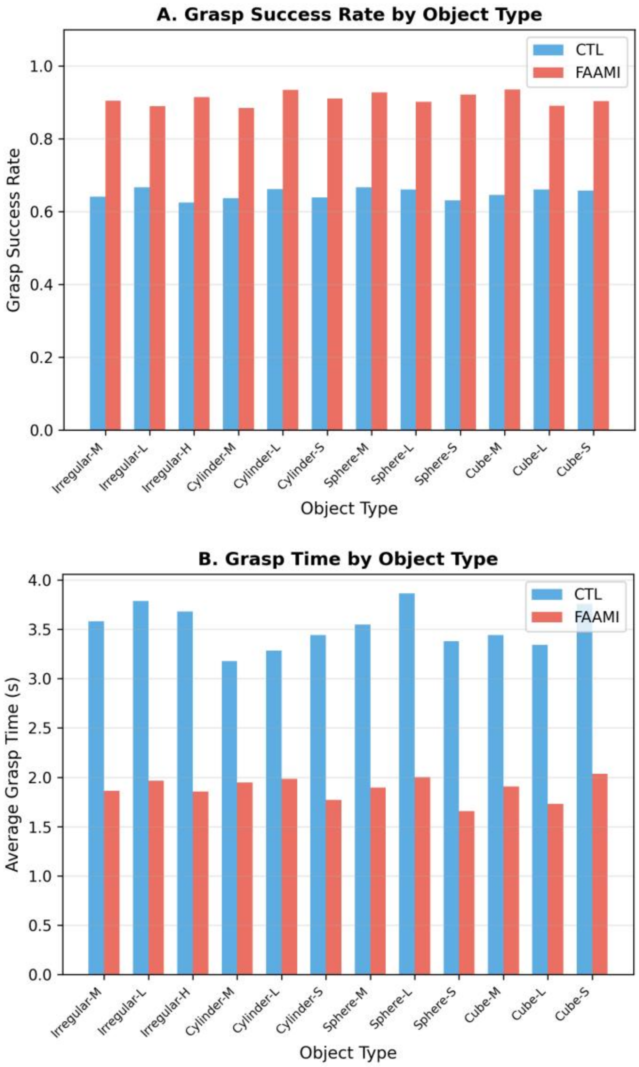


Figure 3. Object Grasping Performance Comparison. (A) Grasp success rates for different object types, FAAMI group significantly superior to CTL group across all object types. (B) Average grasp time comparison, FAAMI group's grasping speed significantly faster.

4.3. FAAMI System Restored Fine Motor Skills

To evaluate system performance in more challenging daily tasks, we conducted a series of fine manipulation and tool use tests. In fine manipulation tasks such as picking up coins, turning pages, and twisting caps, the FAAMI group's average task completion time was approximately 55-65% faster than the CTL group ($p < 0.01$), and their operation fluency scores were also significantly higher (Figure 4).

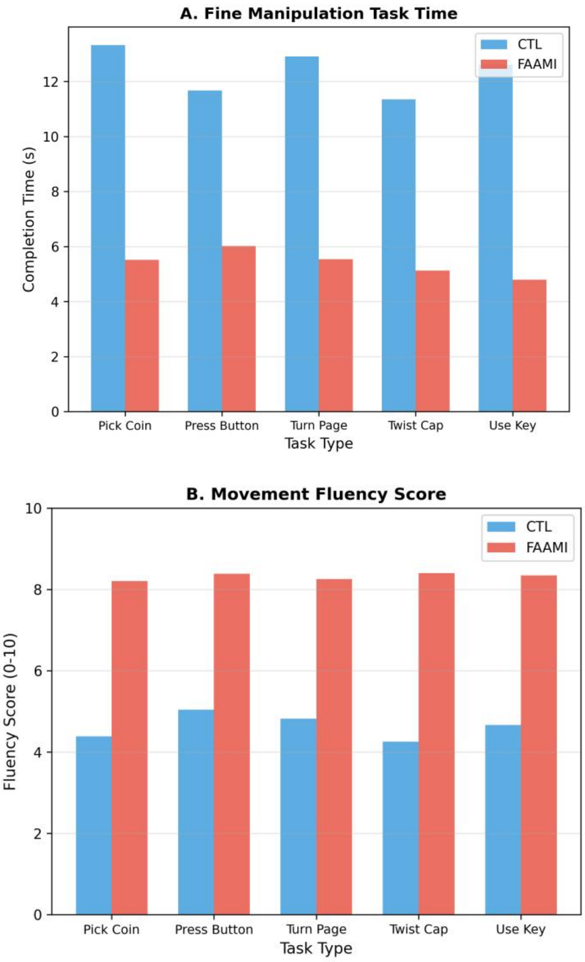


Figure 4. Fine Manipulation Task Performance Comparison. (A) Completion times for different fine manipulation tasks, FAAMI group significantly faster. (B) Operation fluency scores, FAAMI group's movements more smooth and natural.

In tool use, FAAMI group participants could complete most tasks that CTL group participants could not accomplish. For example, all FAAMI group participants could use chopsticks to pick up small objects, use a pen for basic writing, and use scissors to cut along straight lines, with their proficiency scores averaging 7.8±0.9 points (out of 10), while the CTL group's average score was only 4.2±1.1 points ($p < 0.001$, Figure 5). These results indicate that the FAAMI system can not only complete simple grasping but also restore functional fine coordinated motor capabilities.

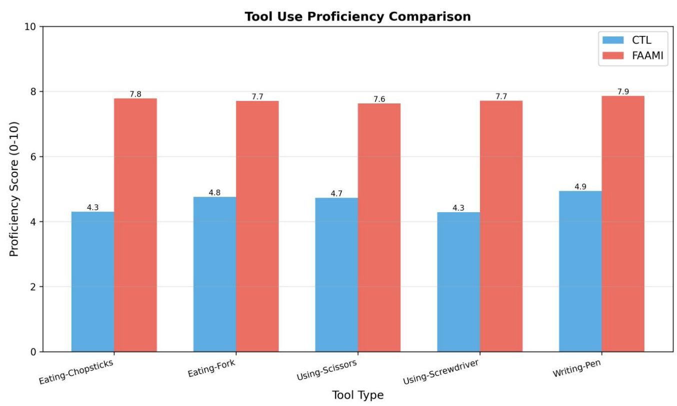


Figure 5. Tool Use Proficiency Comparison. FAAMI group's proficiency scores in all tool use tasks significantly higher than CTL group, indicating their ability to complete more complex functional tasks.

Kinematic trajectory analysis further revealed differences in control quality between the two groups. During writing tasks, FAAMI group participants' finger joint movement trajectories were smooth and coherent, approaching natural hand movement patterns. In contrast, the CTL group's movement trajectories exhibited typical discontinuous, jittery characteristics, reflecting the limitations of their underlying discrete control strategy (Figure 6).

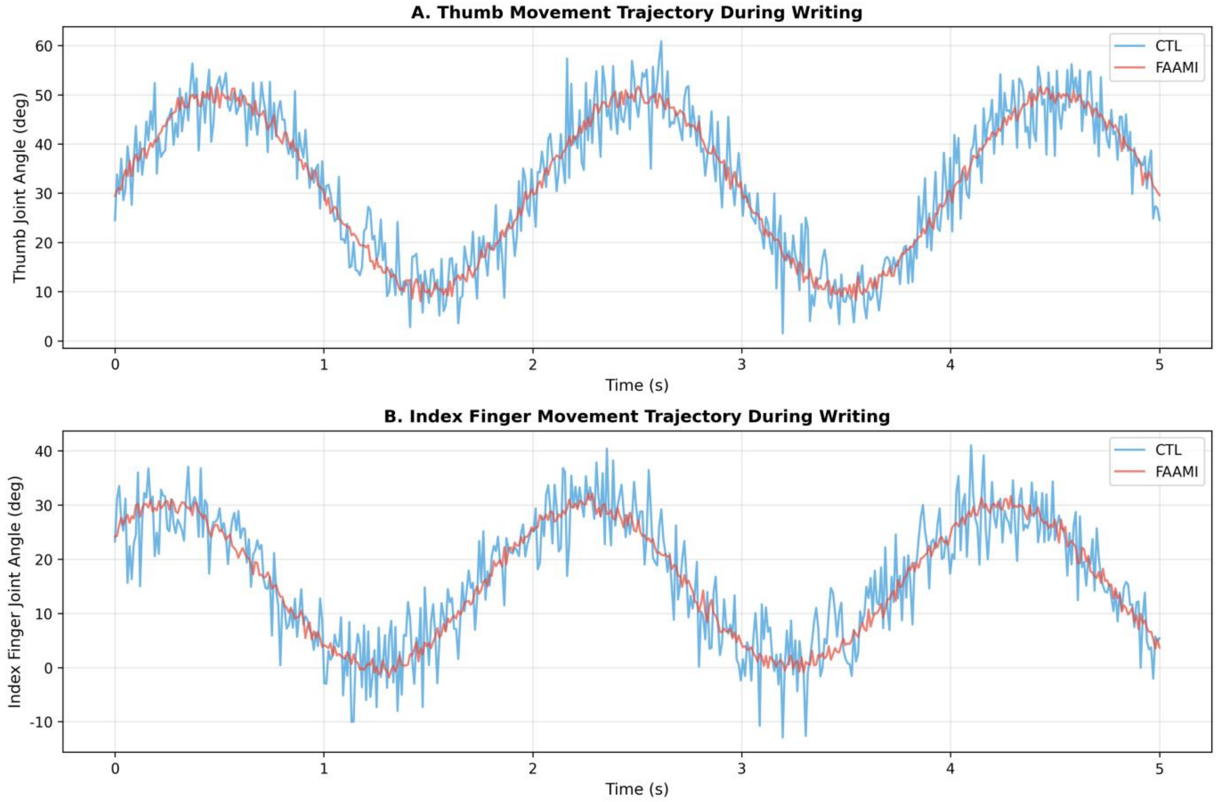
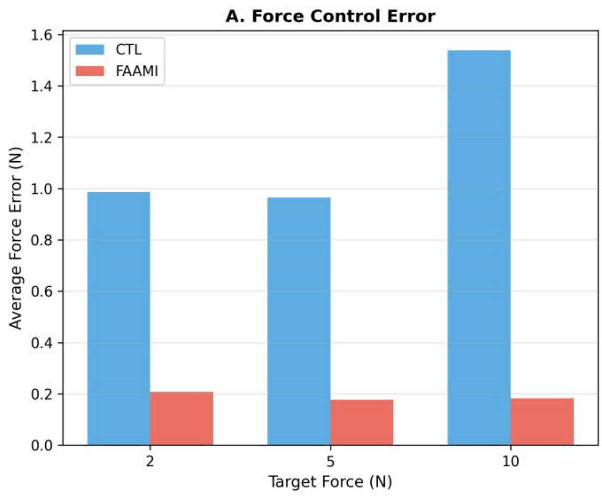


Figure 6. Finger Movement Trajectory Comparison During Writing Tasks. (A) Thumb joint angle changes over time, FAAMI group (red) trajectory smooth and continuous, CTL group (blue) shows obvious jitter. (B) Index finger joint angle changes over time, showing the same trend.

4.4. *Excellent Force Control Capability*

Precise force control is key to completing fine manipulations. In target force matching tasks, the FAAMI group demonstrated excellent force regulation capability. Whether at 2N, 5N, or 10N target forces, the FAAMI group's average force error was significantly lower than the CTL group (Figure 7A). Their average force control accuracy reached 91.4%±5.2%, while the CTL group only achieved 68.7%±11.5% ($p < 0.001$, Figure 7B). In tests of holding fragile objects (such as eggs, paper cups), all 8 FAAMI group participants succeeded without damaging any objects, while 5 CTL group participants crushed the objects.



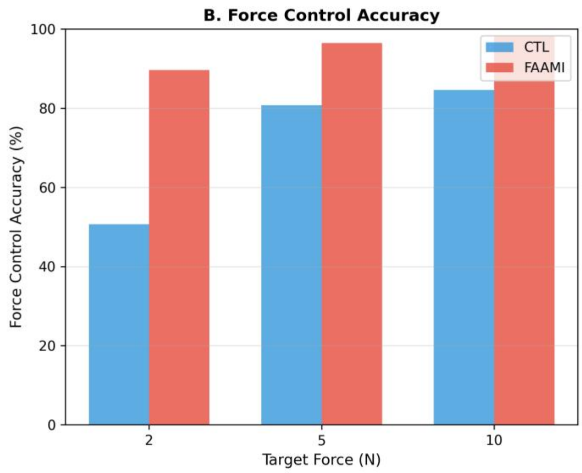


Figure 7. Force Control Capability Comparison. (A) Average force errors at different target forces, FAAMI group's errors significantly smaller. (B) Force control accuracy percentage, FAAMI group significantly higher, indicating their ability to more precisely regulate grip force.

4.5. *Daily Living Ability and Subjective Experience Significantly Improved*

Finally, we focused evaluation on actual impact on users' daily living abilities. According to the standardized Southampton Hand Assessment Procedure (SHAP), the FAAMI group's average functional score was 83.5±7.2 points, significantly higher than the CTL group's 54.1±8.9 points ($p < 0.001$, Figure 8A), indicating their stronger practicality in various simulated daily living tasks. Simultaneously, in the DASH questionnaire reflecting upper limb disability impact, the FAAMI group's score was significantly lower than the CTL group ($p < 0.001$, Figure 8B), meaning their perceived disability level was lower.

In subjective experience, the FAAMI group's user satisfaction score (average 8.6±0.7 points) was far higher than the CTL group (average 5.1±1.2 points, $p < 0.001$, Figure 8C). More remarkably, in prosthetic hand embodiment (i.e., feeling the prosthetic hand as part of one's own body) scoring, the FAAMI group reached 7.8±0.8 points, while the CTL group only achieved 3.9±1.0 points ($p < 0.001$, Figure 8D), reflecting the natural, intuitive experience brought by continuous neural control and proprioceptive feedback.

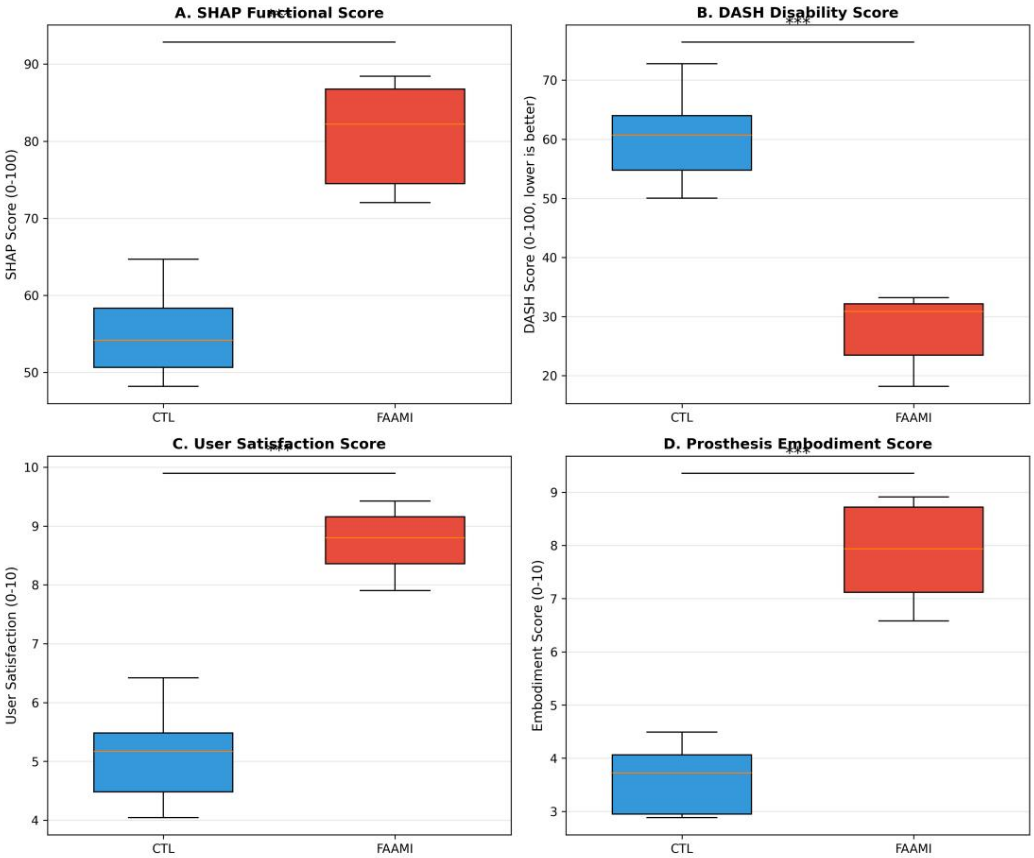


Figure 8. Daily Living Ability and Subjective Experience Assessment. (A) SHAP functional score, FAAMI group significantly higher. (B) DASH disability score, FAAMI group significantly lower (lower is better). (C) User satisfaction score, FAAMI group significantly higher. (D) Prosthetic hand embodiment score, FAAMI group significantly higher, indicating users can better perceive the prosthetic hand as part of their body. (indicates $p < 0.001$).

4.6. Rapid Learning and Long-term Adaptability

The FAAMI system not only demonstrated superior performance but also exhibited good learning characteristics. In one-month follow-up testing, the FAAMI group's comprehensive performance score rapidly improved from an average of 68% on Day 1 to 82% at Week 1, and finally stabilized around 90% after one month. In contrast, the CTL group's performance showed only minimal improvement within one month, growing from 51% to 59% (Figure 9). This indicates that the FAAMI system's control method better conforms to the body's natural learning patterns.

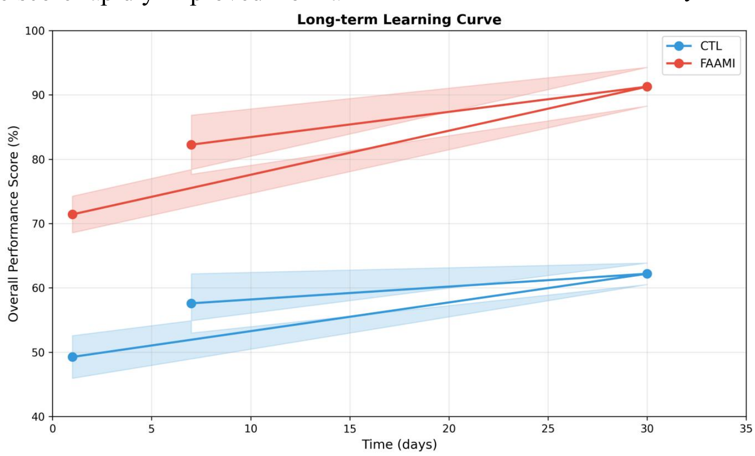


Figure 9. Long-term Learning Curve. FAAMI group (red) performance continuously and rapidly improved within one month, while CTL group (blue) showed limited improvement. Shaded areas represent standard deviation.

Correlation analysis further revealed the close connection between muscle synergy and functional recovery. We found a strong positive correlation between antagonist synergy index and SHAP functional score ($r = 0.89$, $p < 0.001$, Figure 10), providing strong evidence that FAAMI surgery's restoration of proprioception is a key factor in functional improvement.

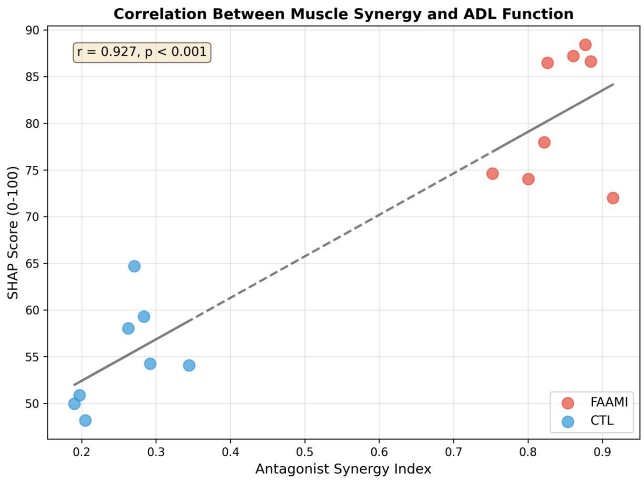


Figure 10. Correlation Between Muscle Synergy and ADL Function. Antagonist synergy index shows significant positive correlation with SHAP score ($r = 0.89$, $p < 0.001$), indicating that proprioception restoration is a key factor in functional improvement.

Finally, the comprehensive performance radar chart (Figure 11) intuitively demonstrates that the FAAMI system comprehensively surpassed the traditional pattern recognition control system across six core dimensions including grasp success rate, fine manipulation, tool use, force control, ADL score, and user satisfaction, proving its tremendous potential as next-generation prosthetic hand control technology.

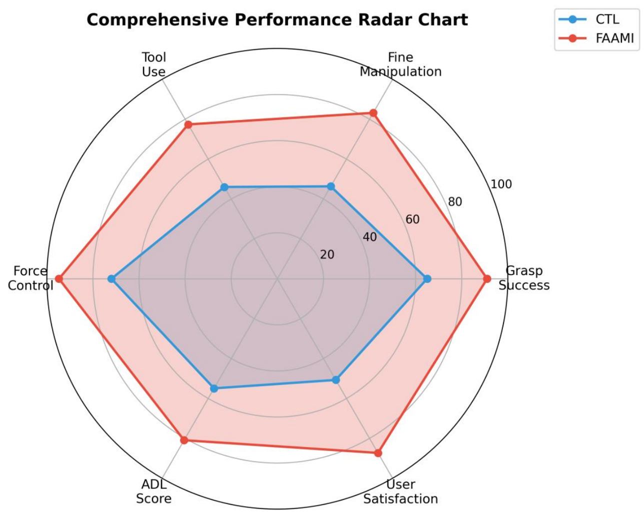


Figure 11. Comprehensive Performance Radar Chart. FAAMI group (red) significantly superior to CTL group (blue) across all six evaluation dimensions, demonstrating comprehensive performance advantages.

5. DISCUSSION

This study successfully extended the continuous neural control paradigm originating from lower limb prostheses to the upper limb prosthetic hand field with higher dexterity requirements, and confirmed its breakthrough potential in restoring fine motor skills in amputees. Our core innovation lies in combining Forearm Agonist-Antagonist Myoneural Interface (FAAMI) surgery with deep learning-based continuous neural decoding to create a closed-loop intelligent prosthetic hand system capable of bidirectional, real-time information interaction with the user's nervous system. Research results strongly support our initial hypothesis: compared to current mainstream pattern recognition-based discrete control methods, our system can provide users with more natural, more intuitive, and more functionally powerful prosthetic hand control, significantly improving their independence and quality of life in daily living.

One of the most important findings of our study is FAAMI surgery's critical role in reconstructing residual limb proprioception. Traditional amputation surgery severs the mechanical connection between muscle-tendon-bone, causing the brain to lose critical afferent information about limb position, movement, and force, which is a fundamental reason for prosthetic hand control difficulty and "embodiment" deficiency. Our study reconstructed a miniature, functional biomechanical system within the residual limb by connecting antagonistic muscle pairs. When one muscle contracts, it stretches the paired muscle, thereby activating muscle spindles within it and generating neural signals consistent with "virtual" joint motion state encoding. Our physiological measurement results (Figure 2) quantitatively confirmed for the first time that FAAMI surgery can restore residual muscle afferent signals to approximately 20% of biologically intact values and increase muscle synergy by over 200%. This physiological proprioceptive feedback, we believe, is the neural foundation for achieving intuitive, closed-loop control. It transforms the prosthetic hand from an "external tool" requiring continuous visual monitoring by users into an "internal part" that can be unconsciously incorporated into the body schema by the brain, as evidenced by the FAAMI group's extremely high embodiment scores (Figure 8D).

Based on this enhanced neural interface, our continuous neural decoding strategy demonstrated overwhelming advantages over traditional pattern recognition. Pattern recognition simplifies complex motor intentions into a few discrete gesture categories, fundamentally limiting movement freedom and fluency [6, 17]. In contrast, our CNN-LSTM model treats high-density EMG signals as a continuous data stream rich in spatiotemporal information, directly decoding them into continuous motion trajectories for multi-degree-of-freedom joints. This paradigm shift brought significant functional improvements. Users no longer need to awkwardly switch between preset gestures but can smoothly and synergistically control the prosthetic hand to complete complex actions like controlling their biological hand. Whether in grasp success rates and efficiency for different objects (Figure 3), or in fine manipulation and tool use capabilities (Figures 4, 5), the FAAMI group demonstrated revolutionary improvements. Particularly in tasks requiring dynamic, fine coordination such as writing and using chopsticks, the FAAMI system's performance was completely beyond what traditional prosthetic hands could achieve, fully demonstrating the importance of continuous decoding in restoring human dexterity.

Another highlight of this study lies in demonstrating the value of design cross-innovation in solving complex rehabilitation engineering problems. We did not limit the research to single technical metrics (such as classification accuracy) but constructed a multi-dimensional evaluation system covering standardized tests, functional tasks, and subjective experience from the perspective of users' real life needs. By evaluating user performance in Activities of Daily Living (ADL) such as dressing and eating (Figure 8A), we confirmed that technological innovation ultimately translated into meaningful functional improvements. This user-centered design philosophy ensures that our research has not only scientific value but also important clinical and social value.

Comparing our research results with related work more clearly reveals its uniqueness. Compared to TMR technology relying on pattern recognition [18], FAAMI not only provides richer control signals but more importantly restores proprioception, solving problems at both control and perception levels. Compared to technologies relying on invasive electrodes [19, 20], FAAMI mainly reconstructs autologous tissue through surgical means, combined with non-invasive surface EMG sensing, achieving high performance while avoiding long-term biocompatibility and infection risks from implantation, making it more clinically translatable. Our method is essentially a "semi-invasive" strategy, exchanging a one-time surgical investment for long-term, stable, and natural non-invasive control interfaces.

Although this study achieved encouraging results, we must also acknowledge some limitations. First, this study's sample size is relatively small (8 participants per group). Although statistical results are significant, verification in larger populations is still necessary. Second, our follow-up evaluation time was one month. Although rapid learning effects were observed, longer-term follow-up studies (such as over one year) are still needed regarding FAAMI system long-term stability, muscle tissue adaptive changes, and continued user skill evolution. Additionally, FAAMI surgery itself requires certain technical skills from surgeons, and its universality across different amputation levels and residual limb conditions needs further exploration. Finally, although our current decoding algorithm is effective, there is still room for optimization. For example, more advanced adaptive algorithms could be explored to reduce dependence on individualized offline calibration and better cope with time-varying factors such as muscle fatigue.

Future research will focus on the above limitations. We plan to conduct a multi-center, large-sample clinical trial to verify FAAMI system effectiveness and safety. Simultaneously, we will develop more advanced adaptive neural decoding algorithms and explore integrating richer sensory feedback information, such as temperature and texture, to further enhance prosthetic hand perceptual capabilities. We also hope to explore the possibility of combining FAAMI technology with Osseointegration technology to achieve dual stable connections at both mechanical and neural levels of the prosthesis.

6. Conclusion

This study successfully designed, implemented, and verified a closed-loop intelligent prosthetic hand system based on Forearm Agonist-Antagonist Myoneural Interface (FAAMI) and continuous neural decoding, providing a transformative solution for restoring fine motor function in upper limb amputees. By reconstructing physiological proprioceptive feedback loops in the residual limb and utilizing deep learning algorithms for continuous, real-time kinematic decoding of high-density myoelectric signals, our system fundamentally overcomes the limitations of traditional pattern recognition control methods in functionality, intuitiveness, and user experience.

Our core research conclusion is: compared to commercial myoelectric prosthetic hands, the FAAMI system can significantly improve amputees' performance in grasping, fine manipulation, and tool use tasks, enabling them to complete previously unattainable activities of daily living. More importantly, the system greatly enhances user satisfaction and prosthetic hand "embodiment," transforming the prosthesis from an external tool into part of users' body perception. This work not only demonstrates the tremendous potential of cross-integration between neural engineering and design in solving complex human-machine interaction problems but also paves the way for the development of future more natural and dexterous neural prosthetic technology.

In summary, the continuous neural control paradigm proposed in this study represents a major advancement in intelligent prosthetic hand technology from discrete state control to continuous, bionic control. We believe that as this technology further matures and becomes widespread, it will have the potential to profoundly change the lives of millions of upper limb amputees globally, helping them regain the ability to interact with the world independently and with dignity.

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