Study on Prosthetic Hand Proprioception Feedback Based on Hybrid Vibro-Electrotactile Stimulation

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***Abstract*—Sensory substitution technologies represent a significant advancement in modern prosthetics, with hybrid tactile feedback approaches gaining increasing attention. However, limited studies have examined the role of hybrid tactile feedback in closed-loop prosthetic control, particularly in relation to varying visual conditions. This study employed a 2-factor mixed design involving 10 non-disabled participants and 3 transradial amputees. Three visual conditions–Optimal Vision, Limited Vision, and Blocked Vision were tested. Participants performed prosthetic wrist and hand position-matching tasks utilizing vibrotactile, electrotactile, and hybrid vibro-electrotactile (HyVE) feedback modes provided by a custom-developed prosthetic position feedback control system. Outcome measures included categorical analysis of task completion outcomes, control precision error (CPE), completion time (CT), and feedback preference. The HyVE feedback mode elevated success rates across all visual conditions, while effectively reducing the incidence of errors and confusion trials. Compared to electrotactile mode, HyVE yielded significantly lower CPE, and compared to vibrotactile mode, it enabled significantly shorter CT. Furthermore, 7 out of 13 participants (>50%) selected HyVE as their preferred feedback mode. The proposed HyVE tactile feedback method effectively combines the advantages of electrotactile and vibrotactile stimulation, mitigating their respective limitations. It enables accurate perception of prosthetic motion without the need for continuous visual monitoring, showing significant potential for enhancing everyday prosthetic functionality.**

***Index Terms*—Prosthesis, proprioception, sensory feedback, electrotactile, vibrotactile.**

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I. Introduction

THE global demand for prosthetic devices continues to rise significantly, driven by population aging, traffic accidents, and disease-related limb loss [1]. With approximately 130 million individuals worldwide affected by various disabilities, the number of upper-limb amputees has been steadily increasing [2]. As essential medical rehabilitation devices, prostheses play a crucial role in restoring limb functionality for these patients. However, despite remarkable mechanical advancements, many users face a persistent challenge: the lack of effective sensory feedback in prosthetic systems [3], [4]. Sensory feedback is vital for prosthetic operation, as it enhances control precision and flexibility while improving users' sense of embodiment and comfort [5]. Current sensory feedback technologies in prosthetics are broadly categorized into invasive and non-invasive approaches [6]. Invasive techniques restore sensation via direct neural stimulation and can provide highly realistic feedback, but their complexity limits practical implementation [7], [8]. Consequently, non-invasive sensory substitution methods–particularly those utilizing tactile stimulation to convey sensory information through alternative pathways—have garnered significant research attention [9].

Among non-invasive tactile feedback modalities, vibrotactile (VIB) and electrotactile (ELE) systems are the most widely adopted in modern prosthetics. VIB feedback is valued for its cost-effectiveness, energy efficiency, and ease of integration [10], relying on vibration motors to activate cutaneous mechanoreceptors. Studies have shown that VIB feedback improves sensorimotor performance by increasing grasping accuracy and reducing task error rates [9], [11], [12]. However, VIB feedback using eccentric mass motor actuators is limited by a relatively long rise time [13] and low spatial resolution [6], which constrain performance in high-precision tasks.

In contrast, ELE feedback, which delivers low-amplitude current pulses to the skin [14], offers faster response times and reduced energy consumption. It has demonstrated strong efficacy in conveying critical prosthetic state information, such as joint position and grip force [15], [16]. For instance, Martinu et al. found that ELE stimulation enhanced both operational flexibility and control precision [17]. Nonetheless, this method is associated with drawbacks, including unnatural sensations—often described as prickling or burning—and a high sensitivity to skin conditions and electrode positioning, which necessitate careful calibration [6], [10], [18].

To overcome the limitations of single-modality feedback systems, hybrid tactile feedback has emerged as a promising solution [19]. By integrating vibrotactile and electrotactile modalities, hybrid systems leverage the strengths of each approach to deliver more accurate, responsive, and multidimensional feedback [10]. Empirical studies have confirmed that hybrid feedback outperforms unimodal systems in information transmission and task performance. Vargas et al. demonstrated that hybrid feedback significantly improved the accuracy of object size and hardness perception [20]. Similarly, Takahashi et al. found that hybrid feedback offered superior performance in texture and stiffness discrimination, enhancing tactile perception [21]. Guémann et al. further demonstrated that combining vibrotactile and electrotactile feedback significantly enhanced task completion rates and reduced users' visual load during elbow joint control tasks [12].

The key strength of hybrid tactile feedback lies in its ability to convey multidimensional information without increasing the area of skin stimulation. This is exemplified by the HyVE (Hybrid Vibro-Electrotactile) interface [22], which concurrently transmits both vibrotactile and electrotactile signals to the same skin region, thereby enhancing information throughput without requiring additional skin surface [23]. This integration specifically addresses the limitations of unimodal systems: while electrotactile feedback offers excellent temporal resolution, it can induce discomfort and interfere with sEMG signals. vibrotactile feedback, although more comfortable, suffers from mechanical delays. The hybrid approach strategically combines short electrotactile pulses (to offset vibrotactile latency) with sustained vibration (to maintain comfort), thereby improving real-time responsiveness, minimizing discomfort, and enhancing control stability [10].

Despite the considerable potential of hybrid tactile feedback systems, several challenges hinder their widespread application in myoelectric prostheses. Chief among these is the complexity of the sensory feedback system [6], [24]. Existing research on hybrid feedback has primarily focused on tactile and force feedback in prosthetic hands [11], [12], [20], [21], [23], [25], with limited attention to proprioceptive feedback—i.e. the perception of motion and position— which is crucial for fine-tuning prosthetic posture in real-time [26]. It remains unclear whether hybrid tactile feedback can provide superior proprioceptive support compared to unimodal systems. This question is particularly relevant for closed-loop prosthetic control in fine motor tasks, such as trajectory tracking, where proprioceptive effectiveness depends not only on the tactile stimuli but also on sensorimotor integration [20], [27], [28], [29]. In daily activities, amputees primarily rely on visual input to control prosthetic devices. However, visual feedback alone is often insufficient for accurately estimating joint angles and movement speed [30], [31]. The integration of visual and tactile information is therefore essential for increasing control precision. According to sensory integration theory [32], the nervous system dynamically adjusts the weighting of visual and tactile inputs to optimize proprioceptive accuracy [33]. Given the variability in visual conditions during prosthetic use (e.g., poor lighting or occlusion), investigating how tactile feedback compensates for visual limitations is vital for advancing feedback technologies.

This study tests the hypothesis that hybrid tactile feedback can significantly improve prosthetic users' motion state perception and demonstrate superior adaptability across different visual conditions. To examine this, we designed a series of motion control tasks using three tactile feedback modalities: VIB, ELE, and hybrid (HyVE). Through comprehensive evaluation of task accuracy, efficiency, and user experience, we evaluated the impact of hybrid feedback on prosthetic performance. Our experimental design also systematically examines the interaction between visual and tactile feedback by introducing three visual conditions: optimal vision (OPT), limited vision (LIM), and blocked vision (BLC). Unlike previous studies that primarily centered on basic sensory discrimination tasks, this research integrates HyVE feedback directly into functional prosthetic control, better reflecting real-world use. Our findings not only support the potential of hybrid tactile feedback in multisensory integration but also offer valuable insights into optimizing real-time performance, precision, and user comfort. These results contribute to the ongoing development of intelligent prosthetic systems and pave the way for more intuitive, natural, and effective user experiences.

II. Material and Method

A. Participants

The experiment recruited 10 non-disabled participants (aged 20-26 years; 5 males and 5 females) and 3 transradial amputees (demographic details provided in Table I). All participants were recruited through clinical partners and had no prior experience using myoelectric prostheses or routine prosthetic devices. None reported a history of skin allergies or related dermatological conditions. The study protocol received ethical approval from the Institutional Review Board of Three Gorges Hospital affiliated with Chongqing University (Approval No. 2021-KY-24). Prior to the experiment, all participants provided written informed consent after receiving a detailed explanation of the experimental procedures from the research team.

B. Experimental Setup

As illustrated in Figure 1 (A), the experimental system comprises several modules: a prosthetic device with two degrees of freedom, a main module, a secondary module, and a

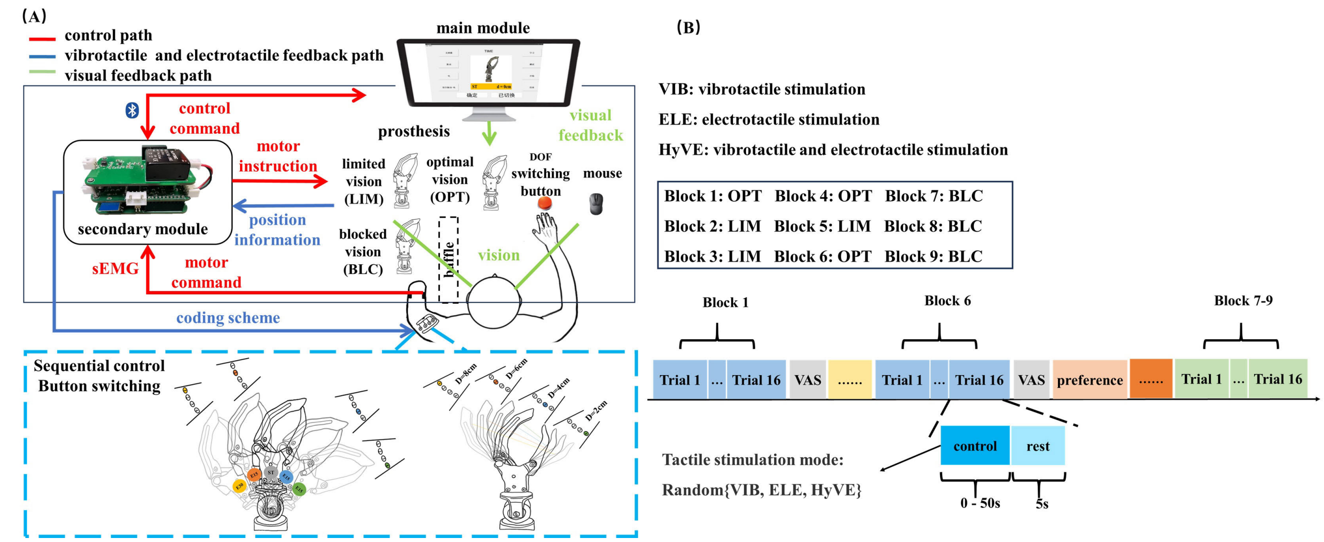


Fig. 1. Schematic of the experimental system and task design. (A) The system comprises four key components: (a) Prosthesis (2-DOF): Operates under three visual conditions– OPT, LIM and BLC; (b) Secondary Module: Outputs motor commands to the prosthesis based on received sEMG signals and adjusts the encoded tactile stimulation according to real-time prosthesis encoder output; (c) Main Module: Provides a PC interface with visual and textual cues and communicates with the Secondary Module via Bluetooth to issue commands and record data; (d) Stimulation Array: A 4-channel VIB and ELE array placed on the upper arm that delivers spatially encoded tactile stimuli. Spatial encoding is used to represent four wrist flexion/extension (FE) angles and four hand apertures using the same four stimulation sites. Sixteen target position combinations (hand movement followed by wrist movement) are presented in random order. (B) The formal experiment consists of nine blocks: three each for OPT, LIM, and BLC conditions. OPT and LIM blocks follow an ABBA counterbalancing design to diminish learning effects. Blocks 7-9 are carried out subsequently. Each block consists of 16 trials with randomized feedback types (VIB, ELE, HyVE), a control phase lasting 0-50s, and a 5s rest phase. After each block, participants complete a Visual Analog Scale (VAS) to assess fatigue and ensure data reliability.

TABLE I
DEMOGRAPHIC INFORMATION OF 3 AMPUTEES

Participants	Gender	Age	Amputee hand	Amputation years	Cause of amputation
A1	female	39	left	32	machine strangulation
A2	male	61	left	24	machine strangulation
A3	female	26	left	26	congenital disease

stimulation array. All system components were independently designed, fabricated, and assembled by the research team.

a) The prosthetic hand (Moel: SJS32, Danyang Prosthetics Factory, Jiangsu) was modified to include two DC stepper micromotors (FAULHABER 2224006SR) with IEH2-4096 magnetic encoders for wrist flexion/extension (FE) and hand aperture control. Two dry surface electromyography (sEMG) electrodes were used to collect signals from the user's forearm muscles. These myoelectric signals were processed using an envelope detection algorithm. The encoders provided continuous feedback on prosthetic motion to the secondary module, which then generated corresponding tactile stimuli in real-time based on predefined encoding protocols.

b) The main module operated on a PC platform (Intel®Core™i7-12700H processor, 2.30 GHz, 16.0 GB RAM) running Python-based control software. A 21-inch monitor displayed experimental instructions via a graphical user interface (GUI) developed using the tkinter library. This interface included interactive buttons for user input and recorded real-time prosthetic joint positions and task completion time (CT) in.csv format. Control commands were transmitted to the prosthesis through the pyserial library, which also received feedback on r angular position.

c) The secondary module was responsible for generating multi-channel tactile feedback and driving the prosthesis. It consisted of a major control board and associated sub-boards. The major control board featured: (I) an STM32F103RCT6 microcontroller for generating PWM signals, selecting stimulation channels (CH1-CH4), and issuing motor control signals; (II) a Bluetooth chip for communication with the PC; and (III) an interface for sEMG electrode input.

The sub-board primarily handled motor driving and tactile stimulation. Motor control was implemented through a high-current driver capable of operating two motors. The rotation direction was controlled by GPIO pin logic levels from the microcontroller unit (MCU). A double-pole double-throw (DPDT) switch allowed users to toggle between wrist FE angle and hand aperture control, enabling multi-DOF movement.

The tactile stimulation was implemented in two forms: (I) ELE stimulation: A custom H-bridge circuit and MCU-generated PWM signals produced biphasic square current pulses. A 70V power source and a constant current regulator ensured stable output. (II) VIB stimulation: vibration eccentric mass motor actuators were powered by a 3.3V DC source, with frequency and intensity modulated by adjusting PWM frequency and duty cycle. The major control board and sub-board were interconnected through board-to-board connectors. All components passed electrical safety tests for withstand voltage and leakage current in compliance with China GB9706 safety standards.

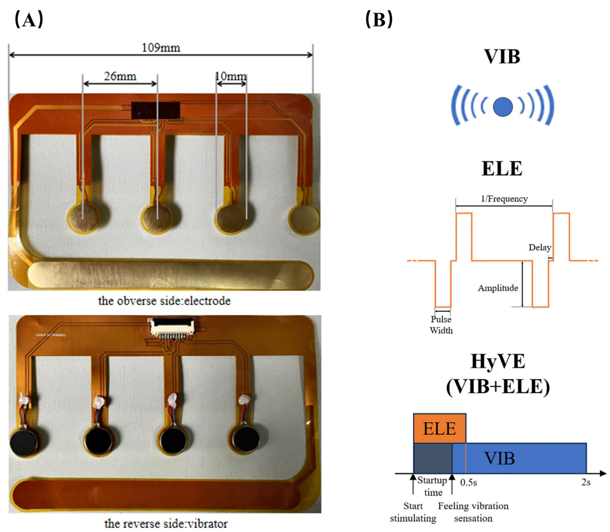


Fig. 2. (A) Stimulation array with FPC technology. Electrode array(obverse) and vibrator array(reverse). (B) Three kinds of feedback modes: VIB, ELE, and HyVE.

d) The stimulation array consisted of 4-channel circular ELE electrodes and 4-channel vibration eccentric mass motor actuators (Model: LCM1027A2445F). As shown in Figure 2 (A), the array employed flexible printed circuit (FPC) technology, with the eccentric mass motor actuators mounted on the reverse side of the ELE electrodes, creating a compact and space-efficient design. Each electrode had a diameter of 10 mm and an inter-electrode spacing of 26 mm, exceeding the minimum distinguishable stimulation distance [34], [35]). The entire array length was109 mm, suitable for typical upper arm circumference. The ELE current range was 0-8 mA per channel. The array was positioned on the participant's left upper arm and was certified by the Chongqing Medical Device Quality Inspection Center (Report No. HXWT-230018) for delivering reliable and perceptible tactile feedback.

C. Experimental Procedure/Protocol

1) Pre-Experimental Preparations: To eliminate the confounding effects of prosthetic weight, the device was mounted on a stationary stand and controlled via sEMG signals recorded from the left forearm's flexor and extensor muscles. The tactile interface was positioned on the left upper arm, near the shoulder, to minimize electrical interference with the sEMG electrodes. A DOF selection button was fixed on the table in front of the participant. Participants sat comfortably in a chair facing a laptop in a quiet environment.

As shown in Fig 3, the prosthetic wrist was adjusted to a neutral, straight position with the hand initially closed. Two sEMG electrodes were then placed on the flexor and extensor muscles using elastic straps. Signal amplification settings were adjusted to ensure smooth and reliable control. Each experimental trial required participants to perform a wrist FE task and a hand aperture control task. Participants could switch between these control modes using the selection button. Once sEMG calibration of each participant was completed, the stimulation array was affixed to the upper arm, and each channel of every participant was sequentially tested and calibrated to ensure distinct, comfortable perception of the tactile feedback. All experiment instructions were provided through the PC interface.

2) Target Position Matching Experiment: *Target positions matching tasks:* Participants were required to complete 16 distinct target position matching tasks (Fig. 1(A)), which involved muscle contraction to control the prosthetic hand. Each task combined one of four hand apertures control actions (2cm, 4cm, 6cm, and 8cm) with one of four wrist FE angles: 15° extension(E15), 30° extension(E30), 15° flexion(F15), and 30° flexion(F30). These combinations resulted in 16 unique motion pairs. Participants switched between hand aperture and wrist angle control using a button located on the table.

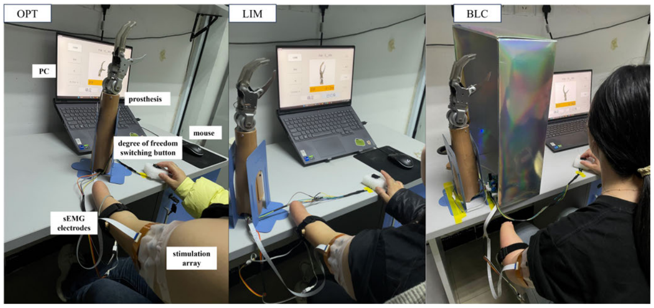
Tactile encoding: as shown in Fig. 1(A), a spatial tactile encoding strategy was adopted. Four stimulation channels were assigned to correspond with the target positions. For wrist control: CH1-E30, CH2-E15, CH3-F15, CH4-F30; and for hand aperture: CH1-2cm, CH2-4cm, CH3-6cm, CH4-8cm. Each stimulation channel was activated only when the prosthetic hand's position was within ±2° (for wrist angle) or ±0.25cm (for hand aperture) of the target. For instance, when the wrist reached within ±2° of a target angle, the corresponding tactile stimulus was triggered. The maximum stimulus duration per channel was limited to 2 s to avoid adaptation.

Tactile feedback modality: Three tactile feedback modes were employed to study their impact on substituted sensation: VIB: vibration eccentric mass motor actuators were activated; ELE: electrical currents were delivered to the skin; HyVE: both VIB and ELE feedback were simultaneously provided. As shown in Fig. 2(B), ELE stimulation was delivered for a maximum of 0.5 s, while VIB stimulation could last up to 2 s. The HyVE mode aimed to combine the immediacy of ELE with the comfort of VIB, potentially improving users' control over the prosthetic movements.

Vision condition: To systematically investigate the role of vision, three conditions were tested (Fig, 3): optimal vision (OPT), limited vision (LIM) and blocked vision (BLC). Under the OPT condition, the prosthesis was positioned directly in front of the participant, enabling fovea visual input. In contrast, under the LIM condition, the prosthesis was placed on the left front of the participant, allowing only peripheral vision. Participants were encouraged to rely more on tactile feedback. In BLC condition, the prosthesis was fully occluded by a box, forcing participants to depend solely on tactile feedback.

The experimental paradigm consisted of three sessions: a learning session, a pre-test session, and a formal testing session. The learning session aimed at making participants to grasp motion-sensation mapping scheme through a standardized training protocol with passive control mode. The purpose of the pre-test is to test whether the participants can distinguish the tactile stimulation, and then adjust their muscular strength in time in compliance with the feedback to complete the prosthesis task.

Learning session: In this session, participants were familiarized with the motion-sensation mapping using a passive control mode. The prosthesis was automatically driven through



(A) (B) (C)

Fig. 3. Experimental scenarios under three kinds of visual conditions. (A) optimal vision (OPT), (B) limited vision (LIM), (C) blocked vision (BLC).

eight target positions: four hand apertures (2cm, 4cm, 6cm, 8cm) and four wrist angles (F15, F30, E15, E30). Each target was held for 9s, during which sequential tactile feedback was provided: VIB from 0-3s, ELE from 3-6s, and HyVE from 6-9s. This cycle was repeated twice. Through this repetitive multimodal stimulation, participants were able to internalize the tactile encoding scheme.

Pre-test session: The pre-test session consisted of three blocks, corresponding to the three tactile modes (VIB, ELE, HyVE). Each block comprised five randomly selected tasks from the 16 possible combinations. A 50s countdown was initiated upon task display. Two time points were recorded, T1 and T2. T1 reflected the reaction time of participants (from task onset to prosthesis movement initiation), indicating attentiveness. T2 reflected total task time consumed by the target task, calculated as (CT+T1). Participants switched degrees of freedom using the button and confirmed successful task completion by clicking a mouse. At that moment, the system recorded the prosthesis's actual position, reset it, and initiated a 5 s rest period before the next trial. Trials were considered successful if: 1) T1 $<$ 5 s and T2 $<$ 50 s; 2) Wrist error $\leq \pm 4.5°$ and hand aperture error $\leq \pm 0.6$ cm.

Anomalous trials included: 1) T1 $>$ 5 s or T2 $>$ 50 s; 2) Prosthesis position not within any valid target range; 3) Task completion outside defined error margins. These data were excluded from data analysis. Confused trials referred to instances where the final position was incorrect but fell within another target's error range. Only participants achieving $>$80% success rate (SR) in all three pre-test blocks advanced to the formal testing session. Otherwise, they repeated the learning phase until proficiency was demonstrated.

Formal testing session: The main experiment employed a 3 (vision) $\times$ 3 (tactile mode) mixed-design (Fig. 1(B)), conducted across 9 blocks (3 OPT groups, 3 LIM groups, and 3 BLC groups). The order of OPT and LIM blocks followed an ABBA counterbalancing design to minimize learning effects [36], where the A represents OPT condition and B represents LIM condition. Each block included 16 trials with random tactile feedback assignment. The specific experimental process is consistent with the pre-test session. Additionally, at the end of each block, participants completed a Visual Analog Scale (VAS) to assess their fatigue level, which served as a confounding control factor to ensure the reliability of the results.

Finally, participants evaluated tactile feedback preferences and experimental comfort, addressing aspects, such as comfort of wearing the array, stimulation sensation, skin contact stability, any signs of skin irritation or redness, and impact on arm movement. The entire experiment lasted approximately 1 to 1.5 h. Notably, amputee A1 participated across five consecutive days to preliminarily assess how familiarity with the prosthetic system influenced task performance.

D. Statistical Analysis

The key metrics used to evaluate experimental outcomes include Categorical Analysis of Task Completion Outcomes, Control Precision Error (CPE), Completion Time (CT), and Participant Feedback Preference. The experiment consisted of a total of 9 blocks (3 visual conditions $\times$ 3 repetitions), each consisting of 16 trials. With 10 non-disabled participants, the total number of trials reached 1440. Of these, 38 trials were excluded due to uncontrollable prosthetic reactions caused by electrical interference during the ELE feedback mode. This results in a valid dataset of 1402 trials. Categorical Analysis of Task Outcomes quantifies the distribution of successful, erroneous, and confused trials under different combinations of visual and tactile feedback conditions.

Control Precision Error (CPE) was calculated as the absolute deviation between the prosthetic hand's final position and the intended target. Since wrist FE angles and hand aperture positions are measured in different units (degrees and centimeters, respectively), CPE values were normalized as a percentage to ensure comparability across task types:

$$CPE = \frac{|Arrival\ position\ angle - Target\ \ position\ angle|}{angle\ between\ \ adjacent\ target\ positions} \tag{1}$$

Completion Time (CT) refers to the effective task duration, defined as CT = T2−T1. CT = T2−T1, where T1 is the participant's reaction time and T2 is the total time recorded upon task confirmation.

Feedback Preference: Participants' subjective preferences regarding the three tactile feedback modes (VIB, ELE, HyVE) were collected post-experiment through a preference ranking questionnaire.

Data from non-disabled participants and amputees were analyzed separately. Due to the limited number of amputated participants, results for each were reported individually without inferential statistics. For the non-disabled group, normality tests indicated that the data did not conform to a normal distribution. Consequently, non-parametric statistical methods were employed to analyze the impact of experimental variables on prosthetic control. The Friedman test was employed to determine the main effects of visual condition and tactile feedback mode on both CPE and CT. Where significant differences were observed, post-hoc comparisons were conducted using the Wilcoxon signed-rank test. The statistical significance level was set at $p<0.05$, with Bonferroni correction applied to control for multiple comparisons. Due to the small amputee sample size, no statistical tests were applied to their data; instead, their performance was reported descriptively to provide preliminary insights.

III. Results

A. Categorical Analysis of Task Completion Outcomes

Figure 4 shows the distribution of successful, erroneous, and confused trials across all experimental sessions for 10 non-disabled participants, stratified by tactile feedback mode and visual conditions. Among the feedback modalities, HyVE consistently yielded the highest task SR and the lowest rates of both erroneous and confused trials under both optimal (OPT) and limited (LIM) vision conditions. Particularly, under the OPT conditions, the HyVE modality achieved an SR of 96.98%, representing the best performance across all conditions. In contrast, although ELE feedback showed relatively balanced performance, it was associated with a higher proportion of erroneous trials under all visual conditions, suggesting a potential source of system instability. Furthermore, under the blocked (BLC) vision condition, the VIB modality showed the highest rate of confusion trials (20.73%), indicating a reduction in control accuracy when visual information was restricted.

To further investigate position-specific errors, confusion matrices were generated for both wrist and hand target positions under three visual conditions (Figure 5). For wrist FE control, participants achieved 100% accuracy in distinguishing between flexion and extension from the neutral position under the OPT and LIM conditions, with most confusion arising in discriminating between degrees of movement rather than direction. However, under the BLC condition, confusion increased, with some participants completely losing track of the prosthesis position and confusing flexion with extension. For hand aperture control, the BLC condition resulted in the lowest SR for the 8 cm target, with an SR of only 75.7%. These findings suggest that the absence of visual input (BLC condition) substantially increased target position confusion during prosthetic control, particularly for finer or extreme motor commands.

B. Control Precision Error (CPE)

Figure 6 presents the CPE across all non-disabled participants under different tactile feedback modes and visual conditions. Under OPT visual condition, the CPEs for VIB, ELE, and HyVE feedback modes were 5.71(5.71) %, 8.57(3.33) %, and 5.71(7.14) %, respectively. Under LIM visual condition, the CPEs were 5.71(5.71) %, 8.57(5.00) %, and 5.71(7.14) %, respectively. Under BLC visual condition, the CPEs were 5.71(5.71) %, 6.67(10.47) %, and 6.67(8.57) %, respectively. Statistical analysis using the Friedman test followed by Wilcoxon signed-rank post hoc comparisons revealed that CPE under the ELE feedback mode was significantly higher ($p<0.001$) than that of VIB and HyVE under the OPT and LIM conditions. Data from amputee participants showed a similar trend. Among them, participants A2 exhibited the highest CPE across all conditions, reaching16.90(12.14) % under the LIM condition with ELE stimulation.

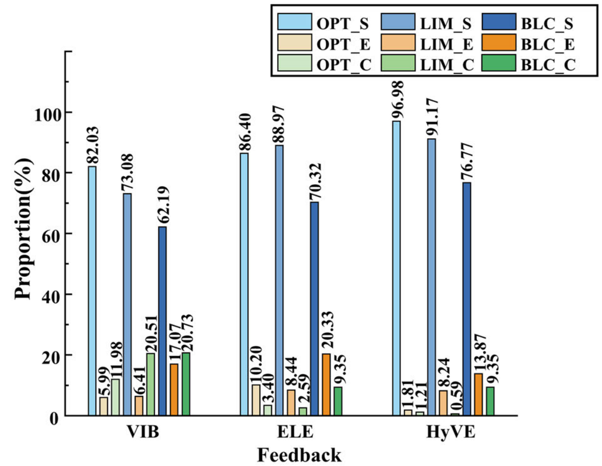


Fig. 4. Proportions of successful, erroneous, and confused trials across all experimental trials. Erroneous trials occur when the prosthetic hand's final position falls outside the target error range (±4.5° for wrist FE/±0.6cm for hand opening-closing) or when the task CT exceeds the threshold. Confused trials refer to instances where the final position lies within the error range of an incorrect target position. S: Successful trials; E: Erroneous trials; C: Confused trials.

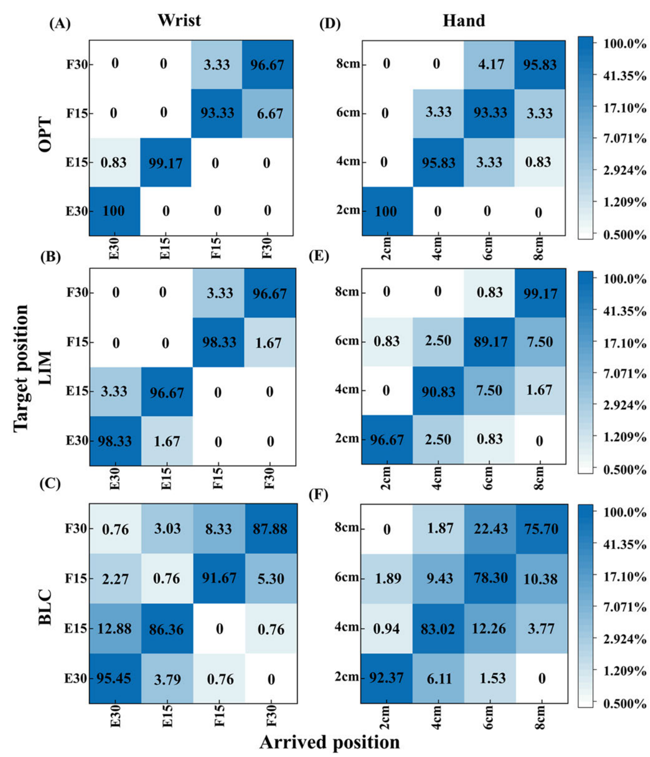


Fig. 5. Confusion matrices for wrist FE and hand aperture: target positions vs. actual prosthetic positions under six conditions: (a) wrist under OPT, (b) wrist under LIM, (c) wrist under BLC, (d) hand under OPT, (e) hand under LIM and (f) hand under BLC. Confusion predominantly occurs at wrist FE angles. For the hand, the 4cm and 6cm aperture positions are more prone to confusion.

C. Completion Time (CT)

Figure 7 shows the task completion time (CT) results for all non-disabled participants across the three feedback modes under each visual condition. Under OPT condition, the CTs for VIB, ELE, and HyVE were 16.72(10.11) s, 13.61(6.21)

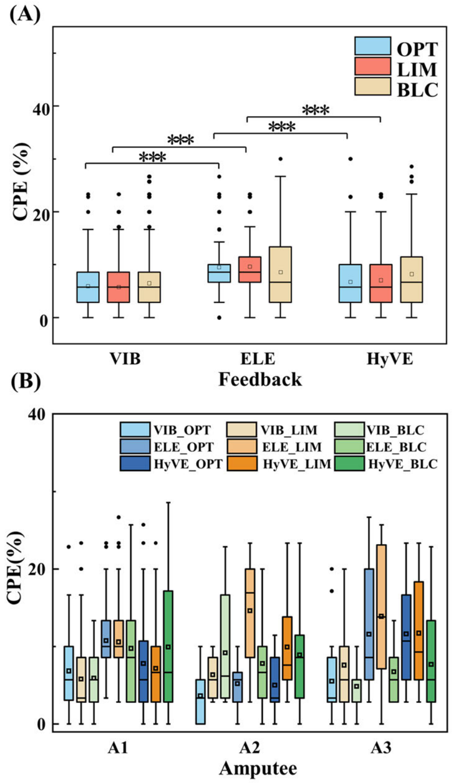


Fig. 6. Overall CPE results under three tactile feedback modes and three visual conditions: (A) For non-disabled participants, the ELE feedback mode resulted in significantly higher CPE than the VIB and HyVE modes under both OPT and LIM visual conditions (p<0.001). (B) For amputee participants, the results were comparable to those of the non-disabled participants, with the ELE mode showing higher CPE than VIB and HyVE.

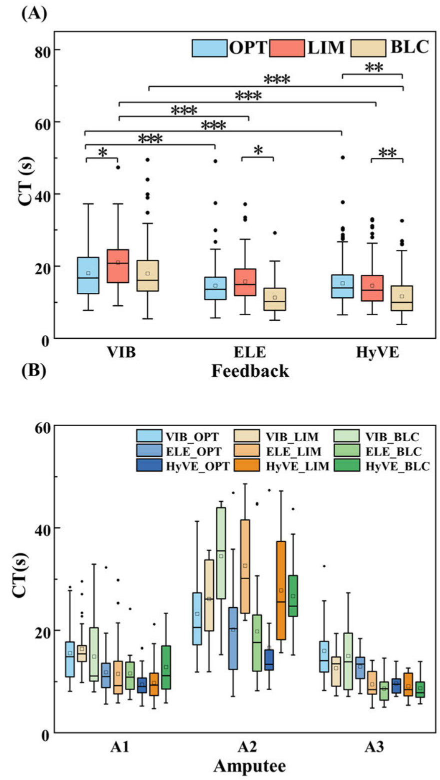


Fig. 7. Completion time (CT) results under three tactile feedback modes and three visual conditions: (a) For non-disabled participants, CT with VIB feedback was significantly longer than with ELE and HyVE feedback under both OPT and LIM visual conditions (p<0.001). Additionally, VIB feedback under LIM vision resulted in a significantly longer CT compared to OPT vision (p<0.05). (b) For amputee participants, overall CT was also longer for VIB compared to ELE and HyVE.

s, and 14.00(6.53) s, respectively. Under LIM condition, the CTs were 20.82(9.12) s, 14.92(7.40) s, and 13.39(7.15) s, respectively. Under BLC condition, the CTs were 16.09(8.47) s, 10.25(6.25) s, and 9.98(6.87) s, respectively. Statistical analysis revealed that VIB feedback resulted in significantly longer CTs compared to both ELE and HyVE under the OPT and LIM conditions ($p<0.001$). Additionally, the CT for VIB under the LIM condition was significantly longer than under the OPT condition ($p<0.05$). Under the BLC condition, the HyVE feedback modality achieved a significantly shorter CT than VIB ($p<0.001$). Furthermore, for the HyVE modality, the CT under BLC conditions was significantly shorter than under both OPT and LIM conditions ($p<0.01$). For the amputee participants, a similar pattern emerged: VIB generally resulted in longer CTs compared to ELE and HyVE. Specifically, participant A2 exhibited the longest CTs across all conditions, a result likely influenced by age-related factors such as reduced cognitive processing speed and less consistent task performance.

D. Feedback Preference

As shown in Figure 8, a majority of participants($n = 7$), including two amputees (A1 and A2), expressed a preference for the HyVE modality. Interestingly, amputee participant A1 initially favored the VIB mode during the first day of testing but shifted preference to HyVE after completing five consecutive days of experimentation. Four participants preferred the ELE mode, while only two chose VIB as their preferred feedback method. Regarding the least preferred modes, eight participants identified VIB as their least favored, whereas only one participant chose HyVE as least preferred.

IV. Discussion

This study explored the application of three tactile feedback modalities – ELE, VIB, and HyVE – in fine motor control tasks for prosthetic systems, utilizing spatial encoding strategies to convey position information. The results demonstrate that HyVE feedback mode effectively combines the advantages of electrotactile stimuli and vibrotactile stimuli while mitigating their respective limitations. Among the three modalities, HyVE exhibited superior performance in task completion rate, accuracy, and stability, especially under visual constraints, suggesting its strong potential for closed-loop prosthetic control. The findings also highlight how tactile feedback can effectively compensate for limited visual input, reducing reliance on constant visual monitoring and reinforcing its practicality in daily prosthetic use.

In real-world prosthetic multisensory feedback—particularly visual and auditory—is typically available. While some studies have eliminated visual and auditory cues

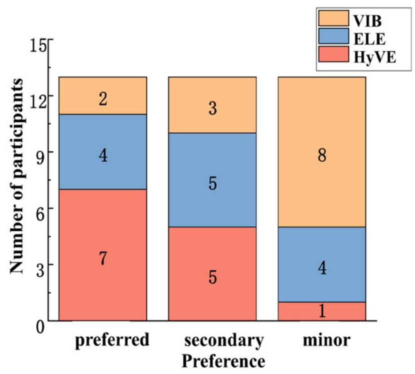


Fig. 8. Participants' preferences for the three tactile feedback modes: HyVE was preferred by 7 participants (including amputees A1 and A2), ELE by 4, and VIB by 2. VIB was the least preferred by 8 participants, while only 1 participant selected HyVE as the least preferred.

to isolate the effects of tactile feedback [7], [24], [37], [38], [39], others emphasize the crucial role of vision and sound in transmitting prosthetic state information [40]. Therefore, completely removing these cues may not accurately reflect how tactile feedback functions in naturalistic settings [30]. To simulate real-world use more accurately, this study maintained visual input in all conditions, including a limited (LIM) and optimal (OPT) condition, as individuals often rely on peripheral vision during hand movements. Auditory feedback was also preserved, as it is insufficient on its own for proprioceptive information [29], but can improve user comfort—especially for amputee participants.

Interestingly, the task SR under the LIM condition was statistically comparable to that under the OPT, whereas the SR under the BLC visual condition was lower, with increased instances of positional confusion. This is likely due to the requirements of fine motor control tasks, where participants must finely adjust muscle force to guide the prosthesis to target positions. In OPT conditions, participants could utilize visual input for coarse positioning and rely on tactile feedback for precise adjustments, ensuring efficient and accurate control. In LIM conditions, visual input was reduced but still sufficient for rough positioning, while tactile feedback refined the control. However, in BLC conditions—where visual information was entirely absent–tactile feedback became the sole source of positional information. Because tactile input is less intuitive than visual cues, participants experienced greater cognitive load, resulting in more errors and confusion, particularly in wrist FE control.

Although VIB feedback is generally rated as more comfortable and user-friendly compared to ELE feedback [41], its poor real-time performance in setup by using eccentric mass motor actuators (with response times reaching up to 350∼450 ms [13]) makes it less suitable for fast-paced adjustments [42]. This was also reflected in significantly longer CTs under both OPT and LIM visual conditions compared to ELE and HyVE ($p<0.001$) in our setup by using eccentric mass motor actuators. This aligns with existing literature on the limitations of the same kind of vibrotactile feedback. Additionally, vibrotactile feedback also exhibited the highest confusion rates, likely due to its lower spatial resolution [43], [44]. Given the same electrode spacing, vibrotactile stimuli are more prone to causing confusion between adjacent positions, thereby reducing task accuracy. When visual feedback was absent, participants received less multisensory information, limiting their ability to verify and adjust feedback. Consequently, VIB performance under BLC did not significantly differ from OPT and LIM in CT, indicating that vibrotactile stimuli alone cannot provide the precise and timely feedback necessary for effective prosthetic control.

In contrast, ELE feedback delivers clear and localized sensations through low-current electrical stimulation [18], [45], which facilitated spatial perception. Despite its higher accuracy, only a minority of participants preferred ELE due to its discomfort and need for precise calibration [43]. Prior to experimentation, individual current thresholds were determined for each participant to avoid overstimulation, as users generally exhibit higher sensitivity to electrical stimuli.

Additionally, a significant drawback of ELE feedback is its tendency to interfere with surface electromyography(sEMG) signals [6], [41]. Although several artifact removal algorithms exist [46], [47], [48], they proved insufficient in this study, where the prosthesis-provided sEMG system could only access envelope signals. The resulting signal interference likely contributed to the increased rate of erroneous trials and significantly larger constant position errors (CPEs). Furthermore, 38 trials were excluded due to strong interference artifacts, further highlighting this limitation.

HyVE feedback emerged as a balanced and effective modality, delivering stable performance across visual conditions. Statistically, HyVE achieved SRs exceeding 90% and maintained error and confusion rates as low as 1.81% and 1.21%, respectively, under OPT conditions. HyVE's CTs were similar to those of ELE, while its CPEs were comparable to VIB, suggesting an effective trade-off between precision and comfort. Unlike electrotactile mode or vibrotactile mode alone, HyVE avoided extreme weaknesses across all indicators. Notably, over half of the participants preferred HyVE, including amputee participant A1, who initially preferred VIB but shifted to HyVE after five consecutive days of repeated exposure. This change highlights the role of system familiarity in improving multimodal information integration for prosthetic control [49].

In BLC conditions, HyVE achieved a task SR of 76.77%, the highest among the three feedback types. This result demonstrates that high-quality tactile feedback can effectively compensate for visual information loss [50], aligning with multisensory integration theory [51]. According to this theory, the nervous system continuously reassesses the reliability of sensory modalities [28], [51], [52], enabling optimal perceptual inference via internal models and Bayesian integration [32]. By simultaneously activating distinct sensory pathways(vibrotactile pathway and electrotactile pathway), HyVE enables users to derive more robust sensory estimates, facilitating improved motor planning and execution [29].

The promoted performance of HyVE feedback likely stems from its ability to alternate and combine sensory modalities, promoting clearer perception and mitigating sensory adaptation [53]. This supports prior research emphasizing the importance of multimodal sensory integration in motor learning and internal model formation [27]. By drawing from multiple sources, the central nervous system can adjust control strategies more dynamically, facilitating accuracy, efficiency, and learning capacity [54], [55].

While previous studies have explored hybrid tactile feedback systems most work has centered on simple discrimination tasks and has not examined their advantages in complex motor tasks or user experience [19], [22]. Other studies using separate tactile interfaces (e.g., electrotactile /vibrotactile /mechanical actuators) lacked integrated designs, resulting in bulky systems with limited practicality [20]. Although informative, these studies have limited real-world relevance.

This study introduces a novel HyVE tactile feedback system that integrates vibrotactile stimuli and electrotactile stimuli with visual feedback to support enhanced prosthetic control and user satisfaction. It contributes to the field in three main ways. First, by integrating vibrotactile signal, electrotactile signal, as well as visual feedback, the system enhances proprioceptive feedback through enriched sensory transmission and integration. Second, the effects of feedback modes on CT, CPE, and SR were quantitatively assessed, deepening our understanding of how different sensory cues influence closed-loop control. Finally, findings demonstrate how tactile feedback can effectively supplement or even compensate for visual deficits, offering insights for designing and optimizing prosthetic systems suited to real-world challenges.

Despite these promising results, several limitations warrant future exploration. First, the study utilized preprocessed envelope sEMG signals, restricting the ability to accurately remove artifacts induced by electrotactile stimuli. Future research should incorporate raw signal acquisition for more effective artifact suppression. Second, the prosthesis was mounted on a table rather than worn by participants, due to its weight. While this approach minimized muscle fatigue [56], [57], it also reduced ecological validity. Lighter prosthesis or fatigue mitigation strategies should be developed for more realistic testing. Third, the tasks centered on position-matching and did not involve daily functional tasks like object manipulation. Broader task paradigms are needed to comprehensively evaluate real-world applicability. The eccentric mass motor actuators resulted in long delay in feedback stimulation, Piezoelectric-based motor actuators should be employed to explore the efficiency of VIB feedback in future. Finally, the small sample of amputee participants limits generalizability. Future studies should involve a larger cohort to validate the findings and further refine the HyVE system.

V. Conclusion

This study investigated the use of a hybrid vibro-electrotactile (HyVE) tactile feedback mode to enhance proprioceptive information transmission and improve control performance in prosthetic applications. Through the design and comparison of different feedback modalities and visual conditions, the effectiveness of HyVE tactile feedback in closed-loop prosthetic control was comprehensively evaluated.

The findings demonstrate that the HyVE feedback mode—by integrating the strengths of electrotactile (ELE) and vibrotactile (VIB) stimulation—successfully overcomes many of the individual limitations associated with each modality. Among the 10 non-disabled participants and 3 transradial amputees, over 50% identified HyVE as their preferred feedback mode, underscoring its superior usability and greater potential for practical application compared to single-modality feedback.

Additionally, the results reveal that tactile feedback can effectively compensate for limited visual input, enabling users to perform fine motor control tasks without continuous visual monitoring. This highlights the promising role of high-quality tactile feedback systems in enhancing the functionality, autonomy, and daily usability of prosthetic devices.

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