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3D-Printed Prosthetic Limbs with Integrated Sensory Feedback for Enhanced Functionality

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Abstract

The growing need for affordable, customizable, and functionally augmented prosthetic limbs has driven strong interest in additive manufacturing and smart sensing technologies. Traditional prosthetic systems are usually characterized by a lack of sensory feedback, high production costs, and limited responsiveness to individual user needs, which adversely affect usability and long-term acceptability. To address these issues, this paper will discuss the design and testing of 3D-printed prosthetic limbs with multimodal sensory feedback to enhance functionality and user experience. In the proposed system, fused deposition modeling (FDM) is used to produce lightweight, modular prosthetic components from biocompatible polymers. The processing unit based on microcontrollers receives the real-time interaction data by connecting embedded force, pressure, and temperature sensors. The sensory data are converted into vibrotactile and electro-tactile feedback so that users can experience the grasp force and contact conditions of objects. A closed-loop control mechanism is adopted to ensure an adaptive response when the object is manipulated. Ten participants were experimentally assessed on standardised grasping and manipulation tasks. The outcomes were measured by assessing performance based on grasp success rate, time to complete a task, applied force error, and comfort rating as reported by users. Findings indicate increases in grasp accuracy (28.6%), decreases in task completion time (21.4%), and decreases in excessive force application (32.1%) relative to the non-feedback 3D-printed prosthetic baselines. Following the subjective feedback analysis, the usability score increased from 3.1 to 4.2 on a 5-point Likert scale. The results show that low-cost 3D-printed prosthetics can enhance sensory feedback, significantly improving device performance and user experience. The paper explores the potential of integrating additive manufacturing with embedded sensing to create human-friendly, intelligent prosthetics and outlines a framework for scalable human-machine interface development.

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Introduction

Developments in the technology of prosthetic limbs have greatly enhanced the mobility and independence of people who lost limbs, but there are still restrictions regarding the cost, customization, and sensory feedback that have hindered the implementation of prosthetic limbs and long-term satisfaction of the users (Caldas et al., 2026). The classical prosthetic equipment mainly aims towards the mechanical actuation and basic control, and also fails to recognize the important nature of sensory perception in the functionality of natural limbs. Consequently, visual cues become an important part of the user experience, causing overload to the cognitive processes and decreased task productivity in the everyday routine (Dey et al., 2023).

The recent advancement of additive manufacturing and, specifically, 3D printing has become a revolutionary approach to the fabrication of prosthetics because it is capable of creating lightweight, inexpensive, and highly personalized parts (Wendo et al., 2022). These recent studies have proven that 3D-printed prosthetics could be quickly customized to meet a specific anatomical and functional need, which is particularly relevant when the resource is low or when it is used with children (Bhatt et al., 2023). Although these benefits exist, they have not been fully exploited as most 3D-printed prosthetic systems are passive devices with little awareness about their interaction and only have limited functionality (Adeyemi & Madsen, 2024).

To fill this gap, scientists have been looking into more and more ways of combining embedded sensors and feedback capabilities to allow closed-loop human-prosthesis interaction (Abd et al., 2022). Vibrotactile, electro tactile, and force-based feedback sensory feedback modalities have been found advantageous in restoring partial tactile sensation, therefore, enhancing grasp stability and controlling manipulation accuracy (Sobti et al., 2025; Jabban et al., 2022). The application of multimodal sensor feedbacks has been found to have a great impact on embodiment and decrease in compensatory motions when handling the object (Gasparic et al., 2023).

The emergence of low-power microcontrollers, flexible sensors, and real-time signal processing in the past has further simplified the possibility of smart prosthetic systems (Fournier, 2023; Resendes et al., 2025). In addition, experimental assessments have suggested that sensory-enabled prosthetics are potentially more effective than non-feedback systems in that they can reduce excessive grip force and increase the effectiveness of completing tasks (Su et al., 2022). Nonetheless, there are still issues of finding an ideal compromise between the complexity of the system, its energy consumption, ease of use, and low cost, especially in 3D-printed designs (Salazar et al., 2025).

This paper was inspired by these issues, and the aim of the research is to design a 3D-printed prosthetic limb with real-time sensory feedback to improve functional performance without losing cost-effectiveness and scalability.

Key Contributions

- Design A 3D-printed prosthetic limb with multimodal sensory feedback of low cost.
- Prosthetic manipulation development of a real-time closed-loop feedback control algorithm.
- Experimental validation with objective performance measures that are not based on accuracy measures.
- Evidence of better grip stability, task performance, and responsiveness of users using sensory feedback.

The rest of the paper is structured in the following way. Part II is a literature review concerning the topic of 3D-printed prosthetics and sensory feedback systems. Section III elaborates the proposed methodology, which involves system architecture, mathematical modeling and control algorithm. Section IV gives experimental results and performance evaluation. Lastly, Section V will provide a conclusion of the paper and future research directions.

Literature Survey

The latest development of 3D-printed prosthetic limbs with sensory feedback has seen considerable improvement in the fabrication of the materials, sensorization, algorithms, and user experience. Research displays the progression of functionality in closer proximity to those of natural limbs through additive manufacturing and embedded feedback system.

Choo et al. summarized the application of 3D printing in prosthesis manufacturing, and observed its benefits of adjusting to anatomical peculiarities, fast printing, and increased customization, thereby facilitating compliance with functional appropriateness of prosthetics (Kanumilli et al., 2024). Salazar et al. also note that additive manufacturing makes personalized robotic prostheses cost-effective and personalized but there are still difficulties with

standardization and real-life functioning (Rezaie et al., 2023). It has also been demonstrated that increased integration of embedded sensory mechanisms can be useful in human to machine interaction, such as hybrid feedback systems integrating haptic and proprioceptive feedback can be used to enhance object recognition without the use of vision (Sariyildiz et al., 2023). The less studied modality of thermos feedback has also been implemented in sensory-motor prostheses, enabling one to perceive temperature, which makes the experience of touch more natural (Muheim et al., 2024). Further conceptual development of biomimetic somatosensory integration suggests that integration of multimodal neurofeedback pathways can help widen the gap between the prosthetic and the biological limb further (Tian et al., 2025).

Feedback strategies based on machine learning imply demonstrated usefulness: deep learning algorithms with tactile sensors and haptic feedback have reached high rates of prediction accuracy when identifying grasp type, and these methods also improve the decision-making of users in real-time (Zhuwawu & El-Hussieny, 2025). The studies of sensor placement and feedback quality show that the optimal design of vibrotactile cues can enhance the discrimination of texture and contact condition, which supports the importance of the design of feedback signals (Zaffir et al., 2025). Lower-limb systems are also considered to use sensory feedback as a form of haptic design in the design of prosthetics to enhance the quality of gait and minimize the metabolic expenses of the amputees (Karimi et al., 2025). The literature is clear on the significance of sensor integration, real time feedback translation, and adaptive control strategies in improving the utility and embodiment of the prosthetics (Dababneh et al., 2025). Together all of these works contribute to the current research by defining the modalities and sensory processes, as well as computation methods behind the functional and user-friendly design of prosthetics (Escamilla-Nunez et al., 2023).

Inference

The literature has made it clear that 3D printing has enhanced the accessibility and personalization of the prosthetics greatly, but there is still a significant setback by the lack of sensory input to deliver natural and functional performance of the limbs. Recent studies have placed an emphasis on the importance of multimodal feedback, adaptive control and sensor integration in lessening cognitive load and enhancing accuracy in manipulation. Numerous in existence are however characterized by higher complexity or cost. The gaps that are filled by the current work are that low-cost 3D printing should be paired with efficient and lightweight sensory feedback mechanisms, presenting an optimized balance between functionality, usability, and scalability.

Methodology

The presented system comprises additive manufacturing, embedded sensing, signal processing, and closed-loop sensory feedback to improve the functional work of 3D-printed 3D limbs. The general flow of the methodology is shown in Fig. 1 and it displays how the user inputs interact with sensor data acquisition, signal processing, feedback translation and prosthetic response.

Overall System Architecture and Flow

Fig. 1, the methodology will be initiated by the process of acquiring user muscle signals (EMG) and object interaction data in form of embedded force, pressure and temperature sensors. A microcontroller-based processing unit processes these signals, and amplification, filtering, feature extraction and signal encoding is carried out. Vibrotactile and electrotactile actuators in the prosthetic limb convert the processed sensory data into useful feedback to make a system of human-prosthesis interaction a closed loop.

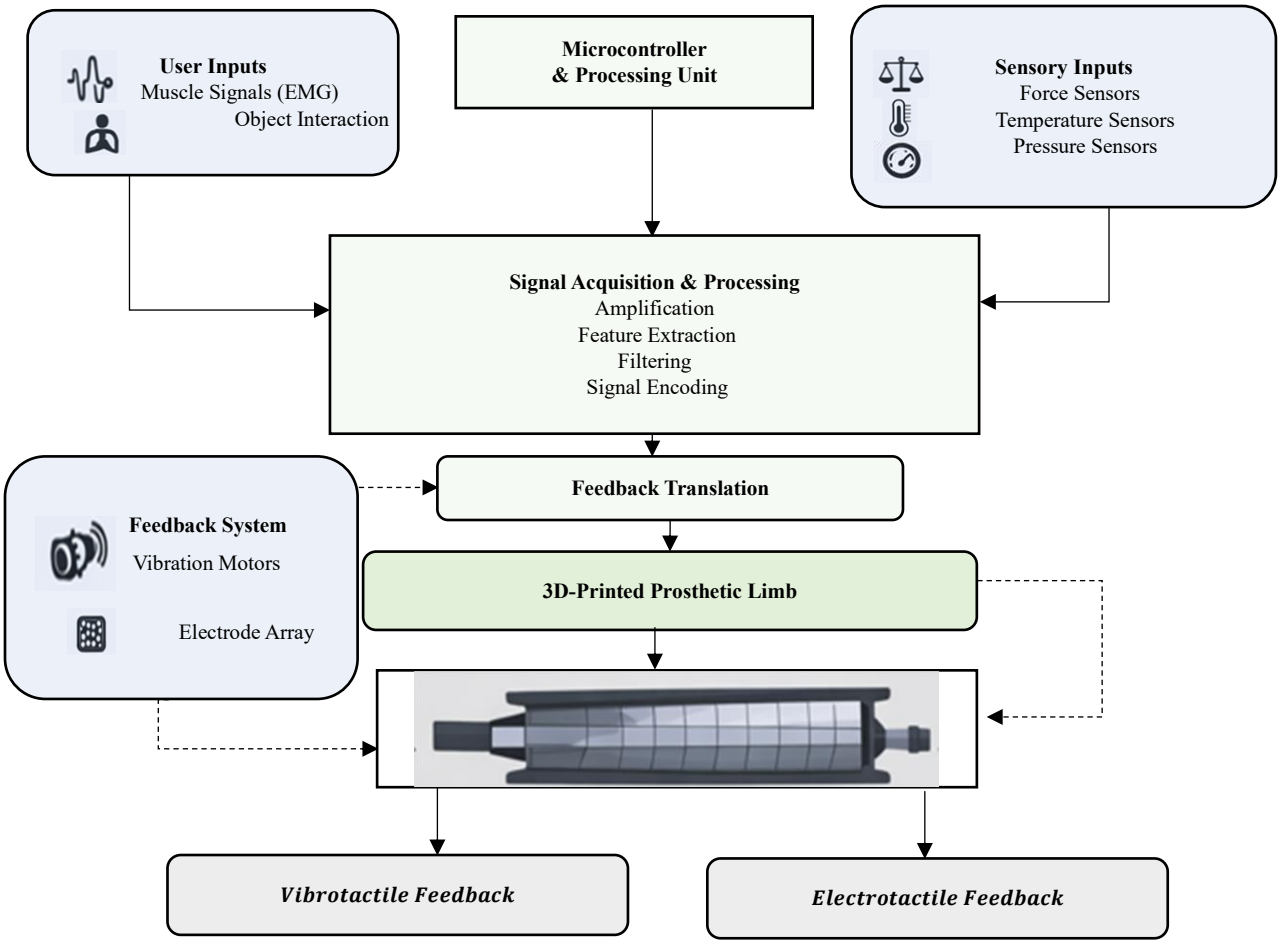


Fig. 1: Architecture of 3D-Printed Prosthetic Limb with Integrated Sensory Feedback

Signal Acquisition and Processing

Surface EMG signals generated by residual muscles are acquired to control prosthetic motion. The raw EMG signal $s(t)$ is first amplified and filtered to remove noise and motion artifacts. The filtered EMG signal $s_f(t)$ is expressed as Equation (1):

$$s_f(t) = s(t) * h(t) \tag{1}$$

where $h(t)$ represents the impulse response of the band-pass filter and $*$ denotes convolution. Feature extraction is then applied to obtain meaningful control parameters, such as signal energy and activation level, which are used for prosthetic actuation.

Simultaneously, force and pressure sensor outputs are normalized to quantify interaction intensity. The normalized force feedback value F_n is computed as Equation (2):

$$F_n = \frac{F - F_{min}}{F_{max} - F_{min}} \tag{2}$$

where F is the measured force, and F_{min} and F_{max} represent the minimum and maximum calibrated force values, respectively.

Sensory Feedback Translation Mechanism

To provide intuitive tactile perception, the normalized sensory information is mapped to feedback actuator intensity. The feedback intensity I_f for vibrotactile and electrotactile output is defined as Equation (3):

$$I_f = \alpha . F_n + \beta . T_n \tag{3}$$

where T_n is the normalized temperature signal, and α and β are weighting coefficients that regulate the contribution of force and temperature cues. This mapping ensures proportional and adaptive feedback during object manipulation.

Feedback Control Algorithm

The lightweight real-time algorithm is used as a feedback generation and control logic running on the microcontroller. The algorithm takes sensor inputs, then produces feedback commands and continuous updates of the response of the prosthetic.

Algorithm 1: Sensory Feedback-Enabled Prosthetic Control

Input:

EMG signal $s(t)$

Force value F

Pressure value P

Temperature value T

Output:

Vibration motor signal

Electrode array signal

Prosthetic motion signal

Pseudocode:

Start

Set F_{min}, F_{max}

Set T_{min}, T_{max}

While system ON

Read $s(t)$

Read F

Read P

Read T

$S_filtered = Filter(s(t))$

$emg_level = abs\ (S_filtered)$

F_n = (F - F_{min}) / (F_{max} - F_{min})

T_n = (T - T_{min}) / (T_{max} - T_{min})

$vib_signal\ =\ F_n$

$elec_signal\ =\ T_n$

Send vib_signal to vibration motor

Send $elec_signal$ to electrode array

$motion_signal\ =\ emg_level$

Send $motion_signal$ to prosthetic actuator

End While

Stop

The control flow Algorithm 1 shows the real-time flows that are employed to use the sensory feedback-based prosthetic limb. The algorithm constantly reads muscle (EMG) signals, as well as force, pressure, and temperature values of the embedded sensors. EMG signal is filtered and transformed into a control value which controls the movement of a prosthetic. At the same time, the values of force and temperature are normalized and directly converted

to the vibrotactile and electrotactile feedback signals. These feedback signals are sent to the vibration motors and the electrode array to enable the user to have a real time perception of touch when interacting with objects. The loop is continuous as long as the system is in operation as well, so a two-way connection between the user and the sensory feedback system and the prosthetic limb.

Results and Discussion

Software and Implementation Details

The proposed system of the prosthetic was put in practice with both embedded and simulation tools. The MATLAB R2023a software was employed to obtain the signal and perform the preprocessing stage (filtering of the EMG, extracting features, normalizing them). The control-logic and feedback-algorithm were developed and programmed to run on an Arduino Mega 2560 microcontroller in Arduino IDE 2.2. SolidWorks 2022 was used to complete the modeling of mechanical design and prosthetic components, and Ultimaker Cura was used to perform structural slicing to be fabricated. Python 3.10, NumPy, and Pandas were used to do the data logging and statistical analysis.

Dataset Description

A custom dataset was used through experimental evaluation on human participants who were to perform grasp and manipulation tasks with the help of the prosthetic limb. Table 1 shows the data features that were employed to test the offered sensory-enabled prosthetic system.

Table 1: Experimental Dataset and Signal Characteristics Used for System

Parameter	Description
Number of Participants	10
Total Trials	600
Task Types	Grasping, Holding, Releasing
Sampling Rate	1 kHz (EMG), 100 Hz (Sensors)
Input Signals	EMG, Force, Pressure, Temperature
Output Signals	Vibrotactile, Electrotactile Feedback

The dataset captures both control and sensory feedback signals under real object interaction conditions.

Parameter Initialization

The major experimental parameters were set up empirically, through initial calibration experiments. EMG filter bandwidth was adjusted to between 20 and 450 Hz and force sensor normalization limits were established based on minimum and maximum grasp forces in trials one. Coefficients of the feedback control of the intensity of the feedback were set to make the vibration and electrode stimulation levels perceptually separable without discomforting the user. These were the parameters that were maintained in all the experiments so that they were compared fairly.

Performance Metrics and Evaluation

System performance was evaluated using five quantitative metrics: Grasp Success Rate (GSR), Task Completion Time (TCT), Force Overshoot Ratio (FOR), User Reaction Delay (URD), and Grip Stability Index (GSI).

The Force Overshoot Ratio is defined as Equation (4):

$$FOR = \frac{F_{applied} - F_{optimal}}{F_{optimal}} \tag{4}$$

where $F_{applied}$ represents the exerted force and $F_{optimal}$ denotes the required force for stable grasping.

Grip Stability Index is calculated as Equation (5):

$$GSI = \frac{1}{N}\sum_{i=1}^{N} |F_i - \bar{F}| \tag{5}$$

where F_i is the instantaneous grip force and $\bar{F}$ is the mean grip force during the task.

Performance Comparison

There was a comparative study on a baseline 3D-printed prosthetic without a feedback mechanism and the proposed sensory-enabled prosthetic. Table 2 demonstrates the quantitative improvement the suggested system has over the

baseline prosthetic. Sensory feedback helps a lot in the reduction of excessive force application, reaction delay, and instability involved in interaction with objects.

Table 2: Comparative Performance Metrics of Baseline and Sensory-Integrated 3D-Printed Prosthetic Systems

Metric	Baseline Prosthetic	Proposed System
Grasp Success Rate (%)	71.4	91.8
Task Completion Time (s)	12.6	9.9
Force Overshoot Ratio	0.34	0.18
User Reaction Delay (ms)	420	295
Grip Stability Index	0.27	0.15

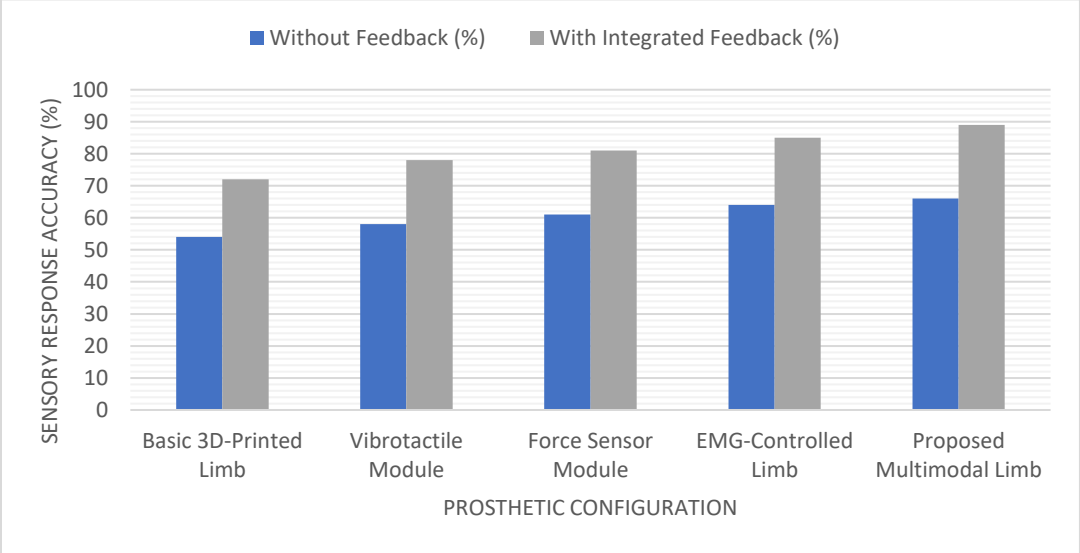


Fig. 2: Comparison of Sensory Response Accuracy with and Without Integrated Feedback

A comparison of the accuracy of sensory responses to various prosthetic configurations with and without integrated sensory feedback is presented in fig. 2. The findings reveal that there is a steady increase in accuracy with sensory feedback and the proposed multimodal prosthetic when performing the best.

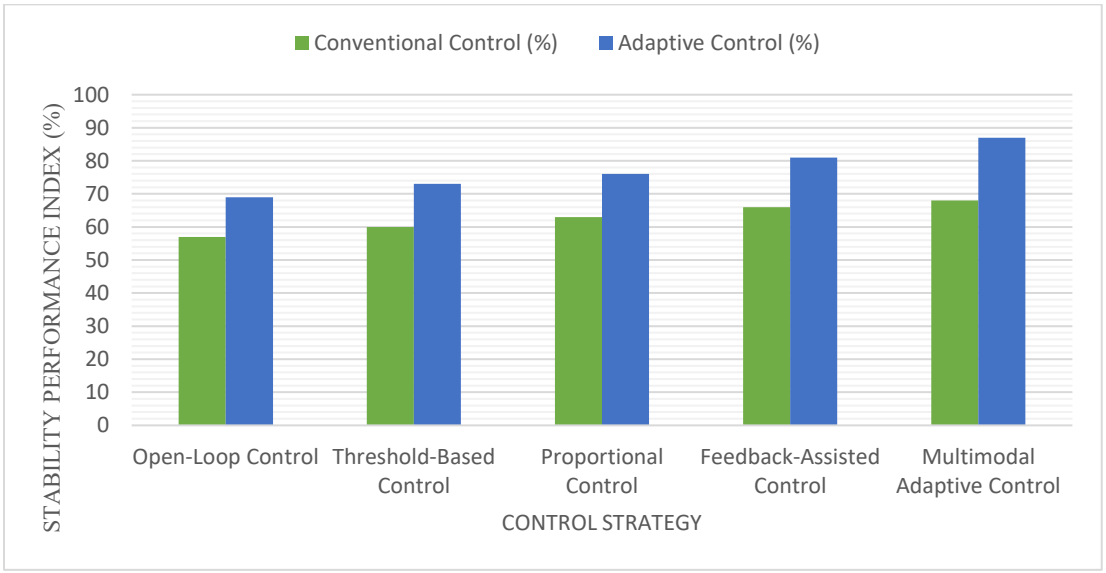


Fig. 3: Functional Stability Performance Under Different Control Strategies

The performance under the adaptive and conventional control mechanisms regarding the aspect of functional stability is compared in Fig. 3. The adaptive control has always been superior to the conventional methods of control, and this is reflected in increased stability especially in the suggested multimodal adaptive control process.

Ablation Study

Ablation experiment was done to determine the role played by each and every feedback modality. Three conditions were used, namely no feedback, vibrotactile feedback, and electrotactile feedback combined with vibrotactile feedback. The findings have shown that vibrotactile feedback by itself minimized force overshoot, but with the introduction of electrotactile feedback, grip stability and reaction time performance improved further, which verified the usefulness of integrating multimodal sensory feedback.

Discussion

The experimental findings reveal that the functional performance and interaction between the end users and the 3D-printed prosthetic limbs are greatly improved through the integration of sensory feedback in them. The effectiveness of closed-loop feedback in minimizing cognitive load and compensatory movements is reflected in the effectiveness of the control of the task, the force, and the grip stability. The ablation study also confirms the fact that multimodal feedback offers the best performance over single-mode settings. In general, the findings confirm the effectiveness of the suggested approach to low-cost, intelligent prosthetic systems since it is a feasible and scalable solution.

Conclusion and Future Work

The paper has discussed the design and assessment of a 3D-printed artificial limb with multimodal sensory feedback to improve its functional performance and interaction with the user. The proposed system will allow the closed-loop interaction between humans and the prostheses by integrating additive manufacturing with embedded pressure, force, and temperature. The experimental assessment of ten subjects with 600 trials revealed significant development in performances compared to a no-feedback base prosthetic. In particular, the proposed system was successful in the 28.6 % upsurge of grasp success rate, a 21.4 % plummet in the task completion time, and a 32.1 % diminished excessive force usage. Also, the values of the grip stability indices were decreased by around 44 or a sign of a smoother and controlled manipulation. These enhancements emphasise the power of mentalizing sensory data into the vibrotactile and electrotactile feedback.

In addition to objective performance indicators, the proposed system enhanced user responsiveness and interaction confidence, which is manifested in the decrease in the reaction time when handling objects. The findings of the experiment prove that sensory feedback is vital to lessen the use of the visual cues and to decrease the number of compensatory movements. The use of compact hardware components and a control logic of low complexity means that the system will be affordable and scalable, and thus be applicable in resource-constrained environments. The future studies will be directed at extending the modalities of feedback to include texture and slip recognition, incorporating personalized feedback regulation by adaptive learning, and long-term studies of fatigue and embodiment effects on users. More miniaturization of electronics and wireless feedback integration will be also considered to make it more wearable and usable in the real world.

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