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Development of an Inmoov-Based-3d Printed Prosthetic Hand Based On the Inmoov Model Using EMG Sensor-Based Motion Control

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ABSTRACT: Individuals with upper limb disabilities often face limited access to functional, affordable prosthetic devices, particularly in developing countries. This study developed a 3D-printed prosthetic hand based on the open-source InMoov design, controlled through an Electromyography (EMG) sensor-based system. The hand structure was fabricated using polylactic acid (PLA) filament, with fishing line as finger tendons and an ESP32 microcontroller serving as the main processing unit. EMG signals captured by a Muscle Sensor V3 were processed using Root Mean Square (RMS) feature extraction with an overlapping sliding window, then mapped to servo motor angles through a proportional linear mapping algorithm, following a 20-second adaptive calibration for each user. Testing involved 10 able-bodied subjects and 2 transhumeral amputee subjects. Results showed that the prototype successfully performed basic gripping and releasing movements with real-time response and minimal latency. The linear mapping approach proved more adaptive and computationally lighter than a Decision Tree-based classification originally planned, though calibration accuracy varied between individuals, indicating the need for personalized calibration. The design demonstrated a lightweight, sufficiently strong, and cost-effective alternative to commercial myoelectric prosthetics, although further refinement in tendon rigidity, shoulder ergonomics, and signal stability is still required for broader adoption.

Keywords - EMG sensor, InMoov design, motion control, prosthetic hand, 3D printing

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1. INTRODUCTION

Individuals with upper limb disabilities are those who experience the loss or limitation of hand function due to congenital abnormalities, accidents, or certain diseases. This condition directly affects the ability to perform daily activities, independence, and an individual's social and economic roles (Apriliyanto et al., 2025) [1]. Persons with disabilities in Indonesia also face significant challenges in engaging in sports and daily physical activities. Data from Statistics Indonesia (BPS) in 2020 indicates that approximately 0.3% of Indonesia's population experiences Type 3 impairment in finger and hand movement. When converted based on Indonesia's total population in 2020, this figure corresponds to approximately 810,000 individuals. Furthermore, approximately 66% of persons with disabilities face barriers in performing activities such as household chores, hobbies, and work, leading many to stop working altogether due to difficulties adapting to the demands of routine activities (Jameel et al., 2020) [2].

A prosthetic arm is an artificial device designed to replace part or all of the function of a lost hand, aiming to help users perform functional activities more independently. Ideally, a prosthetic arm enables users to perform various complex movements such as grasping, holding, and manipulating objects in their surroundings (Dunai & Novak, 2021) [3]. As an assistive device replacing a lost body organ, prosthetics play an important role in improving the independence and quality of life of persons with disabilities (Emzain et al., 2020) [4]. Broadly, upper limb prostheses can be classified into cosmetic (non-functional) prostheses, mechanical prostheses, and powered prostheses. However, despite significant advances in prosthetic technology, currently available prosthetics have not fully met users' functional needs, particularly in developing countries. These limitations include low movement flexibility, insufficient comfort, and relatively high costs stemming from system complexity and the specialized expertise required for fabrication. Consequently, the prosthetics in use tend to be simple and functionally suboptimal, contributing to low satisfaction and adoption rates among amputees, outcomes further influenced by factors such as age, gender, cause, and level of amputation (Hudaya et al., 2024) [5].

One solution to reduce production complexity and cost is to replace traditional actuation systems with a servo motor and tendon-based system. This mechanism mimics the working principle of muscles and tendons in the human arm, where finger movement is controlled by the pull of a string connected directly to the servo shaft (Raviprabhakaran, 2023) [6]. By using standard servos such as the MG995 or SG90 along with flexible strings, this system can achieve movement precise enough for daily activities such as grasping and holding lightweight objects (Shanofer et al., 2024; Tabassum, 2020) [7] [8].

On the other hand, the development of an intuitive control system is a crucial aspect in improving the acceptance and functionality of prosthetics. Sensor-based control such as Electromyography (EMG) allows users to operate the prosthetic directly through physiological signals generated by muscle contractions (Salazar & Rosero, 2024) [9]. This approach is more natural compared to traditional mechanical systems that require external input such as joysticks or buttons (Gazzela et al., 2021) [10]. The integration of EMG sensors with an Arduino microcontroller enables real-time signal processing and its conversion into servo motor movement commands, allowing the prosthetic to respond according to user intent with low cognitive load.

2. RESEARCH OBJECTIVES

2.1 To develop a prosthetic hand prototype for individuals with arm disabilities that is capable of supporting basic functional finger movements in daily activities.

2.2 To design a prosthetic hand based on 3D printing technology using the open-source InMoov design, in order to produce a prosthetic hand with a lightweight, sufficiently strong, and cost-effective structure, making it more accessible to users, particularly in low-budget settings.

2.3 To implement a sensor-based input system on the user's arm as a more intuitive control mechanism for determining the type and combination of prosthetic finger movements.

3. METHOD

3.1 Time and Place of Research

This prosthetic hand development activity was carried out over a period of 6 months, from January 2026 to June 2026. The activity included the design and electronic system planning stage, the component fabrication and testing stage, and the integration and dissemination stage in collaboration with partners. The design, programming, and assembly of electronic components were conducted at the Instrumentation and Electronics Laboratory of Universitas Sebelas Maret, while the mechanical structure fabrication process using 3D printing technology were conducted at the CV Enuma Technology.

3.2 Research Equipment and Materials

In the development of this prosthetic hand, an ESP32 microcontroller was used as the main processing unit for signal acquisition, Root Mean Square (RMS) computation, PWM signal control, and data communication via WiFi. It was connected to a Muscle Sensor V3 to capture EMG signals, along with four MG996R servo motors serving as actuators for finger and wrist movement. All electronic components were integrated on a manually assembled PCB circuit and powered by two separate power sources: a 4-cell LiPo battery with a 20A discharge rate, equipped with a 5V voltage regulator to stabilize the voltage for the servo motors and ESP32, and two 9V Alkaline batteries connected in series to meet the operating voltage requirements of the Muscle Sensor V3 (+9V, GND, −9V). In terms of structural design, the hand frame was 3D-printed using PLA material, with fishing line used as finger-pulling tendons and fabric material used as an arm holder (support).

In the design and programming stage, Autodesk Fusion software was used for 3D modeling, Creality Print was used as the slicer for configuring printing parameters (layer height, infill, support), Arduino IDE based on C++ was used for programming the ESP32, and Python was used for data logging, signal visualization (Matplotlib), and arm animation (Pygame). As research subjects in the testing and calibration stage, 10 able-bodied subjects and 2 transhumeral amputee subjects were involved.

3.3 Research Procedure

3.3.1 Design and Fabrication of the 3D-Printed Prosthetic Hand Structure

The structural design of the prosthetic hand was carried out by adapting the open-source InMoov design, which was subsequently modified using Autodesk Fusion 3D modeling software to meet the specific needs of the user partner. The adaptation process began with the most basic component, namely the finger phalanx structure along with the joint mechanism and tendon pathway, which was then developed modularly to form the palm structure, wrist hinge, and the forearm and upper arm shell casings.

The selection of the InMoov design as the development basis was based on its open-source nature, which allows free modification to adjust the size, proportions, and motion mechanisms without requiring design licensing costs. This approach aligns with the main objective of the development, namely to produce a cost-effective prosthetic hand that is easy to replicate in low-budget settings.

After the modeling process was completed, all design files were exported into a compatible format for further processing using the Creality Print slicer software. At this stage, printing parameters were configured, including layer height, infill, and support, to ensure precise print results while remaining efficient in terms of material usage and production time. The physical manufacturing process was carried out through three-dimensional (3D) printing technology, using polylactic acid (PLA) as the primary material. The selection of PLA was based on the optimal balance it provides between mechanical strength and device weight, resulting in a structure that remains lightweight yet strong enough to support the working load of the finger and arm mechanisms.

The initial printed results then underwent a post-processing stage before entering the assembly process. This stage included manual sanding of the joint areas to make finger movement more flexible. The final stage of the mechanical design was the assembly stage, which focused on combining the 3D-printed arm structure with the electrical actuation system. At this stage, the servo motors, electronic modules, and battery were mounted into the prosthetic casing, while the fishing line, serving as artificial tendons, was installed and tensioned to ensure that the pulling force could be transmitted optimally, allowing the gripping and finger-opening movements to be executed consistently. In addition to the finger motion transmission mechanism, the assembly also included the integration of the arm shell with the fabric-based connecting socket, which was designed according to the dimensions of the residual limb to ensure even weight distribution across the arm and prevent the device from shifting easily during use.

3.3.2 Design of the Signal Acquisition and Control System Based on EMG Sensors

The design approach used involves the acquisition of electromyographic (EMG) signals from the user's arm muscles, which are then processed into motion commands for the actuators. In terms of hardware, the data acquisition system was assembled on a PCB module. This circuit consists of a Muscle Sensor to capture muscle signals, an ESP32 microcontroller as the main processing unit, and MG996R servo motors as the mechanical actuators for finger movement. The analog signal captured by the sensor is transmitted to the ADC pin on the ESP32 for further digital processing. To optimize system stability at the prototype stage, motion identification was focused on two main conditions: full relaxation (rest) and full contraction (grip).

Digital signal processing was carried out through a feature extraction mechanism to obtain high-quality input data. The raw signal was extracted into several feature parameters, including Mean Absolute Value (MAV) to reduce noise, Root Mean Square (RMS) to analyze signal energy density, Waveform Length (WL) to identify waveform complexity, and Zero Crossing (ZC) to extract frequency-domain information. To avoid jitter in the servo motors caused by the unstable and random nature of EMG signal characteristics, the system applied an RMS feature extraction method using an overlapping sliding window approach, resulting in a smoother RMS value that more accurately represents continuous muscle activation levels.

The real-time RMS value was then mapped to the servo motor's rotation angle using a proportional control method based on linear mapping. Before use, the system underwent a 20-second adaptive calibration stage to record the user's specific EMG characteristics, in order to automatically obtain the lower threshold value (at rest) and the upper threshold value (at maximum contraction). This approach was chosen because it was proven to provide better accuracy compared to the Decision Tree-based classification approach initially planned in the early proposal stage, while also being computationally lighter for direct execution on the microcontroller (on-device/embedded processing) without requiring large memory capacity. To improve movement comfort, the system was also equipped with a dead-band parameter to reduce response to small signal fluctuations, as well as an asymptotic filter that gradually slows down the servo speed as it approaches the target angle, resulting in smoother finger opening and closing movements that resemble the natural motion characteristics of human muscles.

3.3.3 System Integration and Prototype Testing Procedure

The final stage of the research procedure was the integration of the 3D-printed mechanical structure with the electrical actuation system and control algorithm designed in the previous stages. At this stage, the system embedded in the ESP32 translated the user's muscle motion signals into Pulse Width Modulation (PWM) signals in real time, which were then transmitted to the servo motors to pull or release the finger strings in order to generate physical gripping force.

Functional testing was carried out through several stages. First, component-level testing was conducted to verify that the electronic circuit was able to execute motion instructions and produce a physical response to muscle contraction with minimal latency. Second, EMG signal calibration data were collected from several test subjects, including both able-bodied subjects and subjects with transhumeral conditions, to evaluate the system's consistency in distinguishing between relaxed and contracted states across different physiological characteristics. The data obtained included RMS values, finger angle mapping accuracy, and signal variation across subjects, which were used to assess the stability and responsiveness of the linear mapping algorithm.

Third, functional testing was carried out on the fully integrated prototype, including tests of the gripping and hand-opening movements, as well as mechanical durability testing of the string-pulling mechanism. The final stage was field testing conducted together with partners with disabilities, which included the process of fitting the device onto the partner's limb and direct evaluation of functional, ergonomic, and comfort aspects during use. The evaluation results from this stage served as the basis for the design adjustment and finalization process, as will be further discussed in the results and discussion chapter.

4. DISCUSSIONS

4.1 Evaluation of Prosthetic Hand Structure and Ergonomics

The test results showed that the prosthetic hand structure, developed based on a modification of the open-source InMoov design, was able to realize the basic functions of gripping and releasing objects reasonably well. However, it was found that the finger-actuating string was still too flexible, potentially reducing movement precision, and that the hand section required additional adhesive to improve stability during use. These findings indicate that although the InMoov design can be adapted at a low production cost, further adjustments to the details of the motion transmission mechanism are still needed for the grip performance to more precisely resemble the characteristics of a human hand grip.

Fig.1 3D-printed prosthetic hand results based on the InMoov design

In the shoulder section, the evaluation showed that the structure made entirely of 3D-printed material (full 3D printing) was still too rigid, causing discomfort to the user, particularly when the device was worn for extended periods. This condition indicates a trade-off between ease of fabrication using 3D printing and the level of ergonomic comfort, which leads to a recommendation for the use of combined materials. 3D-printed material for parts requiring structural rigidity, and flexible materials such as silicone rubber or medical foam for parts in direct contact with the user's body. However, further development is still needed for the connector between the prosthetic hand and the user's shoulder. Overall, these ergonomic evaluation results indicate that the open-source design adaptation approach is able to produce a functional structure at an affordable production cost, but long-term comfort aspects still require further design iteration, particularly at the contact points between the device and the user's body.

4.2 Performance Analysis of the EMG Signal Acquisition and Processing System

The EMG sensor-based control system developed aims to provide a more intuitive input method compared to a simple on/off control mechanism. The test results showed that this approach was successfully achieved through a combination of the Root Mean Square (RMS) feature extraction method using an overlapping sliding window approach and a proportional control algorithm based on linear mapping.

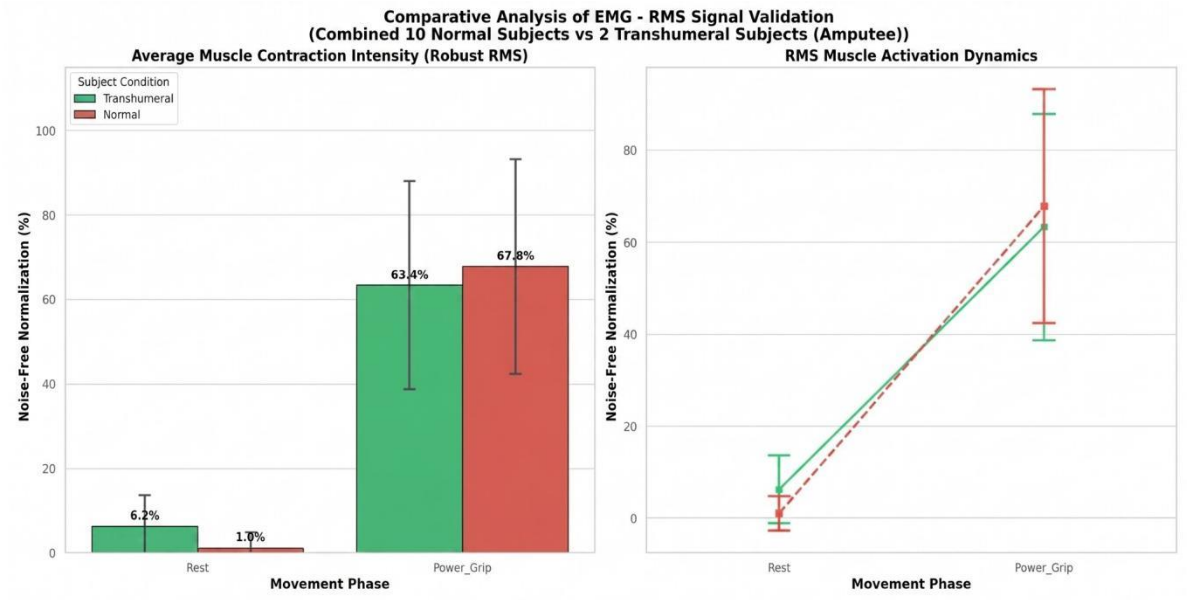
The use of RMS as the single parameter for signal power extraction proved effective in addressing the unstable and random nature of raw EMG signals. When the raw signal was used directly as the actuator input, the servo motor experienced jitter, resulting in less stable finger movement; the sliding window approach successfully smoothed the RMS value so that it was representative of continuous muscle activation levels and could be updated in real time. This represents one of the key achievements in fulfilling the objective of an intuitive control system, as the user does not need to perform excessive or repeated muscle movements to produce a stable motion response in the actuator.

The linear mapping algorithm applied also proved to be more adaptive compared to the initial proposal plan, which used a Decision Tree-based classification approach. Through a 20-second adaptive calibration stage for each user, the system automatically obtained the lower threshold value (at rest) and the upper threshold value (at maximum contraction), allowing the servo's range of motion to be adjusted according to each individual's specific EMG characteristics without requiring a complex model retraining process. This approach is also computationally lighter, as it can be executed directly on the microcontroller (on-device/embedded processing) without requiring large memory capacity, making it more consistent with the cost-efficiency principle that is one of the objectives of this development.

The addition of the dead-band parameter proved to play an important role in reducing excessive response to small signal fluctuations when the user maintained a gripping position, thereby preventing unwanted repeated movement in the actuator. Similarly, the asymptotic filter, which gradually slows down the servo speed as it approaches the target angle, successfully produced smoother finger opening and closing movements that resemble the natural motion characteristics of human muscles. The combination of these two mechanisms shows that the EMG sensor-based control system is not only capable of accurately detecting muscle activity but also of translating it into mechanical movements that are comfortable and intuitive for the user.

4.3 Comparison of EMG Signal Characteristics Between Able-Bodied and Transhumeral Subjects

Calibration data collection was carried out on 10 able-bodied subjects and 2 transhumeral amputee subjects to evaluate the system's consistency in distinguishing between relaxed and contracted conditions across different physiological characteristics.



Subject Group	Movement Phase	Number of Samples	Average (%)	Standard Deviation / SD (%)	Min (%)	Max (%)
Normal	Power_Grip	11485.0	67.84	25.43	0.0	100.0
Normal	Rest	21857.0	0.99	3.76	0.0	59.77
Transhumeral	Power_Grip	1444.0	63.35	24.61	23.55	100.0
Transhumeral	Rest	3255.0	6.22	7.39	0.0	34.81

Fig. 2 Comparison of Deltoid muscle EMG using RMS parameter signals between transhumeral and normal subjects

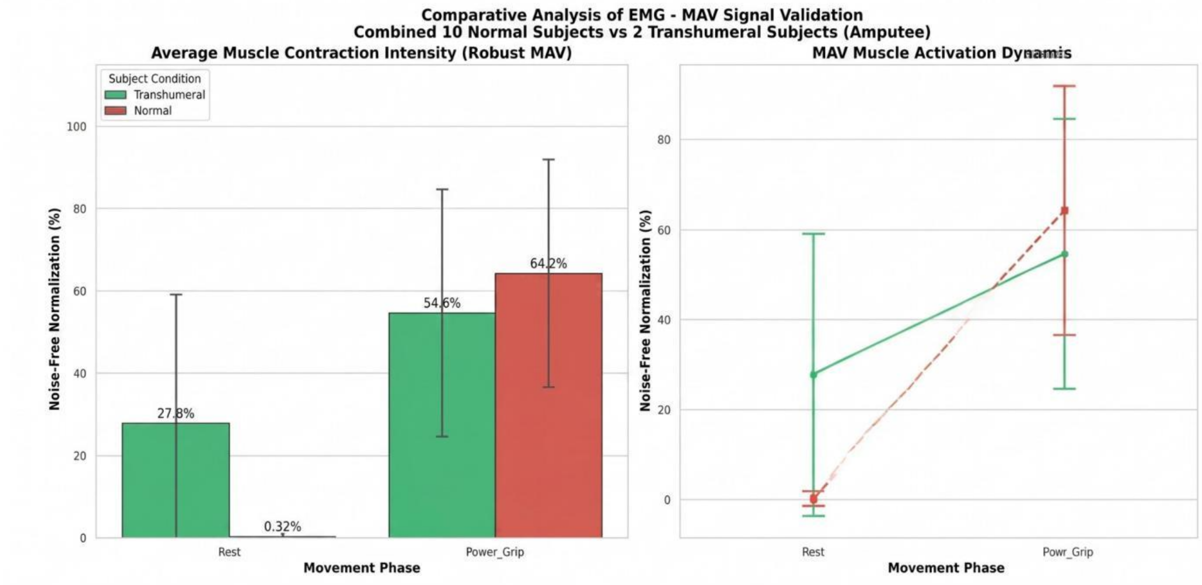
Table 1 Measurement results for transhumeral subject 1

Parameter	Rest Phase (Relaxed)	Power Grip Phase (Contraction)	Unit
RMS Average	12.45	685.32	ADC Unit (0-4095)
RMS Range	0 - 55	540-1045	ADC Unit (0-4095)
Average Finger Angle	148.2	124.5	Degrees (°)
Mapping Accuracy	96.20	82.80	Percentage (%)

Table 2 Measurement results for transhumeral subject 2

Parameter	Rest Phase (Relaxed)	Power Grip Phase (Contraction)	Unit
RMS Average	95.64	348.16	ADC Unit (0-4095)
RMS Range	0 - 164	228 - 984	ADC Unit (0-4095)
Average Finger Angle	169.57	70.73	Degrees (°)
Mapping Accuracy	94.21	60.71	Percentage (%)

The measurement results for transhumeral subject 1 showed an increase in the average RMS value from 12.45 ADC at rest to 685.32 ADC during contraction, with mapping accuracies of 96.20% and 92.80%, respectively. Meanwhile, transhumeral subject 2 showed an increase in RMS from 95.64 ADC to 348.16 ADC, with a mapping accuracy of 94.21% at rest, which decreased to 60.71% during contraction. The significant difference in mapping accuracy during the contraction phase between these two subjects indicates that the stability of EMG signals is strongly influenced by individual physiological conditions, meaning that the calibration process cannot be generalized and must be performed on a personal basis for each user.



Subject Group	Fase Gerakan	Number of Samples	Rata-rata (%)	Simpangan Baku / SD (%)	Min (%)	Max (%)
Normal	Power_Grip	11485.0	64.2	27.64	0.0	100.0
Normal	Rest	21857.0	0.32	1.66	0.0	38.2
Transhumeral	Power_Grip	1444.0	54.6	29.95	0.12	100.0
Transhumeral	Rest	3255.0	27.76	31.33	0.0	100.0

Fig. 3 Comparison of Deltoid muscle EMG using MAVparameter signals between transhumeral and normal subjects

Further analysis using the Mean Absolute Value (MAV) parameter for the combined group of 10 able-bodied subjects and 2 transhumeral subjects reinforced these findings. During the relaxed phase, the able-bodied group showed a very low average MAV of 0.32%, whereas the transhumeral group reached 27.76%. This difference indicates that the electrical activity of the deltoid muscle at rest is considerably higher in transhumeral subjects than in able-bodied subjects, meaning the baseline signal in the transhumeral group tends to be less stable and more prone to producing a high baseline signal even when the muscle is not actively contracting.

During the contraction phase (power grip), the able-bodied group recorded an average MAV of 64.2%, while the transhumeral group reached 54.6%. The relatively small difference between the two groups indicates that despite transhumeral amputation, the user's deltoid muscle is still able to produce an EMG signal strong enough to be utilized as a control source for the prosthetic system. In terms of data variability, the standard deviation in the transhumeral group was recorded to be higher than that in the able-bodied group, particularly during the relaxed phase (31.33% versus 1.66%), indicating that the baseline signal amplitude in transhumeral subjects varies considerably more, both between individuals and between measurement sessions.

4.4 Economic Feasibility and Design Accessibility Analysis

One of the main objectives of developing this prosthetic hand is to produce an assistive device that is economical and easily accessible, particularly in low-resource settings. The approach used to achieve this

objective is the utilization of the open-source InMoov design as the basis for the mechanical structure, combined with 3D printing technology and electronic components that are widely available on the market.
The use of the open-source InMoov design provides a significant advantage in terms of development cost, as the team did not need to allocate a budget for design licensing or for designing the structure from scratch. The modifications made were limited to adjustments in dimensions, joint mechanisms, and integration with the electronic system, so that most of the production costs were concentrated on the printing material and electronic components themselves. The selection of PLA as the primary printing material further supported cost efficiency, given that PLA is one of the most affordable and easily obtainable 3D printing materials compared to alternatives such as nylon or resin, without compromising the structural strength required to support the finger motion mechanism.

Fig. 4 3D-printed result using PLA filament based on InMoov design

In terms of the electronic system, the selection of components such as the ESP32 microcontroller, the Muscle Sensor, and the MG996R servo motor was also based on considerations of market availability and relatively affordable pricing compared to commercial EMG modules or specialized prosthetic actuators. The linear mapping-based control approach, executed directly on the microcontroller (embedded processing), also contributed to cost efficiency, as the system does not require additional computing units such as a mini PC or an external AI module to perform motion classification.
Compared to commercial myoelectric prosthetic hands, which generally have a high selling price due to the use of specialized materials and proprietary control systems, the prototype developed shows significant potential as a low-cost alternative. Nevertheless, several aspects still need to be considered before this device can be widely replicated, such as the cost of owning a 3D printer for parties wishing to produce it independently, the availability of electronic components in areas with limited market access, and the technical skills required for the assembly and calibration process. Therefore, the accessibility of this device does not depend solely on low material costs, but also on the ease of the replication process and the availability of technical support for parties intending to produce or use this prototype in resource-limited settings.

4.5 System Limitations

Although the prosthetic hand prototype has successfully demonstrated the basic functions of gripping and hand-opening movements based on EMG signals, several limitations were still identified during the development and testing process, both in terms of mechanical structure, electronic systems, and the control system.
In terms of mechanical structure, the finger-actuating string used was still too flexible, potentially reducing

movement precision, and the string-pulling mechanism experienced some slackening after repeated use. The shoulder structure, made entirely of 3D-printed material, was also still too rigid, causing discomfort during long-term use. In terms of signal acquisition, noise interference caused by electrode wire movement and variations in skin contact still affected the consistency of signal readings, while the limited number of test subjects among individuals with transradial disabilities meant that the calibration process could not yet be fully validated for a broader user population. In addition, the placement of electronic components on the arm structure still requires further adjustment to avoid compromising user comfort during use.

4.6 Development Recommendations

In terms of materials and structure, a hybrid material approach should be considered, combining 3D printing for parts requiring structural rigidity with flexible materials such as silicone rubber or medical foam for parts in direct contact with the user's body. In addition, the exploration of alternative materials that are lighter yet still affordable is also needed to maintain a balance between strength, weight, and production cost.

In terms of grip comfort, the addition of a protective layer or soft material on the surface of the prosthetic fingers is recommended to improve grip strength and reduce the risk of slipping when holding objects with slippery or finely textured surfaces.

In terms of signal acquisition, improvements to the placement and attachment of EMG electrodes are needed to minimize noise interference, for example through the development of a more stable electrode mount or the use of dry electrodes.

In terms of the control system, the function currently limited to two basic conditions (relaxed and gripping) needs to be further developed to enable the recognition of more complex finger movement variations, through the addition of movement classes to the classification model and the enrichment of a more diverse training dataset, including an expansion in the number and variety of test subjects among individuals with disabilities.

In terms of the socket and user interface, the development of an adjustable mechanism for the connecting socket is needed so that the device can be used by users with varying arm anatomical conditions, thereby increasing the flexibility and accessibility coverage of the device more broadly.

5. CONCLUSION

5.1 The developed prosthetic hand prototype has successfully supported basic functional finger movements, namely gripping and opening, which were validated through testing with disabled partners, demonstrating real-time response and minimal latency to the user's muscle contractions.

5.2 The design of the 3D-printed prosthetic hand using the open-source InMoov design and PLA material successfully produced a structure that is lightweight, sufficiently strong, and more economical compared to commercial prosthetics, thereby supporting the accessibility of the device in low-budget settings.

5.3 The implementation of the EMG sensor-based control system using the RMS feature extraction method and the linear mapping algorithm successfully provided a more intuitive input method for users in controlling the movement of the prosthetic fingers, although it is currently still limited to two basic movement conditions.

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