

Development of a Low Cost 3D Printed Myoelectric Hand using EMG and ECG Signal Fusion

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Abstract - For amputees in underdeveloped nations, the high expenses and complexity of commercial upper-limb prosthetics continue to be major obstacle to accessibility. The design, development, and testing of an affordable, 3D printed bionic hand with a dual-sensor interface is presented in this study. This system incorporates Electrocardiography (ECG) as a secondary control modality for improved stability and mode switching, in the contrast to standard myoelectric systems that only use Electromyography (EMG) and are vulnerable to motion artifacts and false triggers. Autodesk Fusion 360 was used to design the mechanical structure, which was then made of polylactic acid (PLA) and has a tendon-driven actuation mechanism controlled by SG90 servo motors. Band-pass filtering and threshold-based algorithms are used by the control logic, which is implemented on an Arduino Uno, to handle biosignals in real time. The ECG signal successfully serves as a safety interlock, and experimental results show a system latency of about 190ms and a strong object grabbing capacity. The combination of multimodal biosignals with additive manufacturing can produce a dependable, accessible, and useful prosthetic solution, as evidence by the fact that the entire fabrication cost was kept under 10000 INR.

Keywords - Electrocardiography (ECG), Electromyography (EMG), 3D Printing, Myoelectric Hand.

INTRODUCTION

In the realm of advanced prosthetics, there has been a paradigm change from passive ornamental appendages to active, functional replacements that are intended to help people who have lost an upper limb regain a considerable amount of their dexterity. Due to catastrophic events, vascular disease, and congenital problem, millions of people worldwide suffer from limb loss, which highlights the urgent need for prostheses that are not only functional but also easy to use and accessible [1].

The state of the art for many years has been conventional myoelectric prostheses, which are managed by Electromyography (EMG) impulses from residual muscles. With the use of voluntary muscular contraction, users can operate a device, offering a direct and non-invasive control interface [2]. The effectiveness of EMG-based control system is frequently hindered by intrinsic constraint. These can result in unreliable and confusing device functioning. These include signal instability brought on by electrode shift, muscle fatigue, changes in skin impedance, and sensitivity to background noise [3]. Multi modal sensor fusion techniques are being investigated by researchers to address these issue and develop more dependable and durable human-machine interface. Combining several physiological signals can yield a more

comprehensive set of control information, which could result in more advanced and reliable prosthetic control system. Electrocardiography (ECG) signals are integrated as a supplementary input to the traditional EMG control system in this study, suggesting a novel technique. Although EMG records the user's direct motor intent, and ECG provides a steady, rhythmic physiological signal that is less susceptible to the variation that impact myoelectric signals [4]. It has been suggested that ECG signals can be used as a trustworthy secondary channel, such as to switch between various grip patterns or to serve as a "safety switch," which would lessen the user's cognitive load and prevent accidental acts.

The goal of this dual-modality system is to improve prosthetic control accuracy and dependability beyond what can be accomplished with EMG alone. Furthermore, for a sizeable section of the amputee population, the exorbitant price of commercially accessible bionic hands continues to be a major barrier to access. Rapid prototyping and production of highly tailored, lightweight, and affordable devices are made possible by additive manufacturing, also known as 3d printing, which has become a revolutionary technique in prosthetic design [5]. Personalized sockets and hand designs that are suited to the user's unique anatomy and functional requirements can be made via 3D printing, significantly cutting down on development time and production costs. This study describes

the design, creation, and testing of a new inexpensive, 3D printed bionic hand that is operated by a synergistic combination of ECG and EMG signals. This paper presents that the integrated sensing strategy offers a more reliable and user-friendly control mechanism than conventional EMG only one systems. Contributing to the creation of inexpensive, cutting edge prosthetic devices that greatly enhance the quality of life for those who have had upper limb amputations is the ultimate goal of our endeavor.

Integration of advanced technologies
Advanced EMG Sensor
The functionality, responsiveness and user experience of prosthetic hands have been greatly enhanced by the incorporation of sophisticated electromyography (EMG) sensors. Some significant developments in EMG sensor technology and their uses in prosthetic hands are highlighted in this overview. Multiple muscle locations can have their signals recorded simultaneously using multichannel EMG sensors. This feature improves movement control accuracy by giving more precise information regarding muscle activation. Multichannel sensor systems are better able to distinguish between distinct movements and gestures, which enhances the prosthetic's responsiveness (G. Sukhatme et al.) [6]. Miniaturized and flexible EMG sensors are the result of improvements in production methods and materials. Users will experience less discomfort if these sensors are easily incorporated into wearable technology. Additionally enhanced skin conformability made possible by flexible sensors enhances signal quality and user acceptance (A. Prakash et al.) [7]. Wireless EMG sensors improve user comfort and mobility by doing away with bulky wires. More organic movement is made possible by these system's real-time data transmission to the control unit.

They are especially useful in prosthetic applications where users need to be able to move freely without being constrained by cables (D. P. Shankapal et al.) [8]. Modern EMG sensors frequently have integrated signal processing features that enable real time EMG signal digitization, amplification, and filtering at the sensor level. Better control of prosthetic devices is made possible by this integration, which lowers noise and improves signal clarity (C. Castellini et al.) [9].

Advancement in Electrocardiography (ECG) Sensor technology
EMG sensors are good at recording voluntary motor intent, however they don't always work well. The shortcoming of EMG can be compensated for by electrocardiography (ECG) sensors, which detect the electrical activity of the heart and provide a very strong and dependable physiological signal. Previously limited to clinical environments, contemporary ECG technology has developed

into wearable devices that can be used in human machine interface (HMI) applications.

Robustness and Signal Stability

The ECG signal is autonomic and remarkably steady, in contrast to the EMG signal's extreme variability and user dependence. The most noticeable waveform in the ECG, the QRS complex, offers a distinct, rhythmic and easily identifiable fiducial point. The motion artifacts, electrode location changes, and muscle fatigue that frequently impair EMG based control system are mostly insignificant for this signal (Kumar G et al.) [10].

Miniaturization and Dry-Electrode technology

It has been crucial to switch from wet, sticky gel electrodes to dry, non-contact or textile integrated sensors. Contemporary ECG sensors are easily included into an armband, chest strap, or prosthetic socket lining. These dry-contact sensors are useful for all-day use in prosthetic system because they allow for long term, continuous monitoring without irritating the skin. They are frequently composed of conductive polymers or textiles coated in silver (L. G. Zuniga et al.) [11].

Advanced signal processing and Feature Extraction

The real potential of contemporary ECG in HMI is found in sophisticated signal processing, which goes beyond the accurate identification of the QRS complex as a fiducial marker. Heart Rate Variability (HRV) is derived from the temporal pattern of R-R intervals, or the interval between consecutive QRS complexes. An effective, non-invasive stand-in for autonomic nervous system (ANS) activity in HRV (Healey et al.) [12]. The balance between sympathetic and parasympathetic activity can be found by HRV analysis, which enables a system to deduce the user's physiological state in real time, including mental exhaustion, stress and cognitive load (Oskoei, M. A et al.) [13]. This information is crucial for developing adaptive systems in the context of HMI.

II. METHODOLOGY

System design, hardware implementation, signal acquisition, control algorithm development, and testing are the sequential steps in the approach for creating the 3D printed bionic hand integrated with EMG and ECG sensors. Building an inexpensive, dependable, and user friendly prosthetic model that reacts organically to cardiac and muscle signals was the goal.

System Architecture

The overall system consists of four primary modules

- Signal Acquisition unit- EMG and ECG sensors capture bioelectric activity from the user.
- Signal conditioning and processing unit- Filters, amplifies, and processes raw signals to remove noise.
- Control unit- A microcontroller (Arduino) interprets the processes signals and converts them into motor commands.
- Actuation unit- Servo motors drive the mechanical fingers of the bionic hand to perform movements like grasping or releasing objects.

Dual-channel control is made possible by the combination of ECG and EMG signals. While ECG offers a steady references or switching mechanism to increase control dependability, EMG detects voluntary muscular contraction for movement orders (Farina D et al.) [14].

Hardware design Sensor Integration

- EMG Sensor: Placed on the forearm muscles, they detect electrical activity associated with muscles contraction. The sensor output analog signals in the range of 0-5 V after onboard amplification.
- ECG Sensors: Positioned on the chest or upper arm to measure cardiac rhythm. These signals are move more stable and help in the switching control modes or activating

safety features. Both signals are sent to the microcontroller through analog input channels after initial filtering.

Microcontroller-Arduino

Arduino was selected because it is simple to use, has reliable analog-to-digital conversion, and can easily interface with both biosignals and actuators. Most testing was done using an Arduino Uno, which offers:

- 10-bit ADC for reading analog EMG and ECG signals
- Multiple PWM outputs to drive servo motors
- USB connectivity for programming and debugging The arduino reads sensor signals from analog pins (A0, A1), processes them using threshold based control, and
- generates PWM signals on digital pins to control hand movement.

Actuation and Power System

Mini servo motors (SG90) were used for finger actuation due to their small size, lightweight design, and adequate torque. Each motor corresponds to a joint in the 3D printed hand. A regulated 5V DC power supply drives the system, ensuring stable operation (De Luca et al.) [15].

Table 1. Components used in Robotic Arm

SN	Main Component	Figure	Specification
1	Arduino Nano Board		Microchip ATmega328P 5 Volts 8 Analog input pins
2	Servomotor		SG90, Servo motor 1ms Pulse 6 Volt
3	Battery		9 Volt,82g Model: HLW 6F22M

4	EMG - Sensor		Supported with Arduino, 30g
5	I. PC 3D Printer Filament		Strength :61.5MPa Melting Temperature: >155°C

3D Design and Printing

The mechanical structure of the prosthetic hand was designed using Autodesk Fusion 360. Each finger segment was modeled to replicate natural finger kinematics with realistic movement ranges.

- Material: Polylactic Acid (PLA) was chosen for its strength, biocompatibility, and cost efficiency.
- Printing Parameters: A layer height of 0.2mm, 20% infill density, and 60 mm/s print speed were used.
- Post-processing: After printing, supports were removed and moving parts were manually assembled with servo linkage.

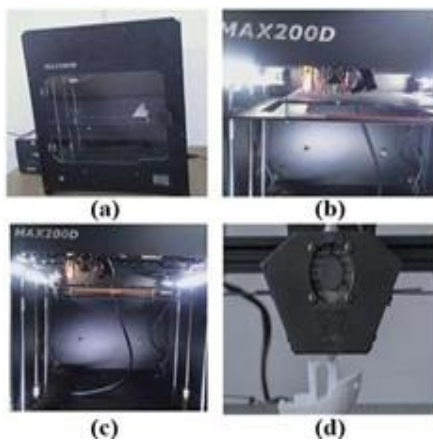


Fig.1. 3D Printing under process [16]



Fig.1. 3D Printing under process [16] Fig.2. 3D Printed Bionic Hand [Source: Robu.in, E yantra Lab]

Signal Acquisition and Processing

Both EMG and ECG signals are low in amplitude and susceptible to noise. To ensure accuracy:

- A band-pass filter (20-450 Hz) was applied to EMG signals to eliminate motion artifacts and power-line interference.
- ECG signals were filtered with a 0.5-50 Hz band-pass filter to isolate the QRS complex.

The filtered signals were then normalized and processed by Arduino converter. Signals thresholds were calibrated for individual users to ensure responsive and accurate motor control [17].

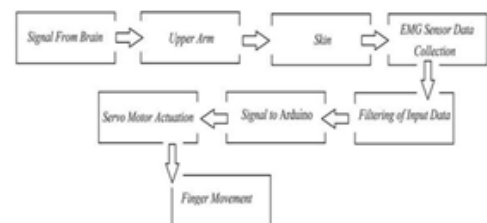


Fig.3. Block Diagram of Proposed System [18]
Control Algorithm

The control logic was implanted using Arduino IDE with the following steps

- Signal Reading: EMG and ECG analog signals are continuously monitored.
- Threshold Detection: When EMG amplitude exceeds a set threshold, it triggers a hand movement.
- ECG-based switching: The ECG pattern is used to toggle between grip modes or act as a safety control.
- Actuation: Corresponding servo motors receive PWM signals to execute the desired movement.

This dual-signal approach minimize false triggers caused by EMG noise and improves overall reliability of the control system

Assembly and Testing

Every part, including the motors, Arduino, and sensors, was installed on a prototype frame. High-Strength nylon tendons (fishing line) that were routed via internal passages in the finger phalanges were used to attach the servo motors to the 3D-printed fingers. The flexor tendons in human anatomy are modeled by this tendon-driven system.

Signal quality and filtering

Skin impedance and electrode motion abnormalities were the initial sources of noise in the raw EMG signals. The data was considerably smoothed by applying the 20- 450 Hz band-pass filter.

- EMG Response: “Rest” (0-1V) and “Contraction” (>2.5V) states were correctly identified by the system.
- ECG Stability: A steady periodic signal was produced by the ECG sensor. The system was able to use heart rate patterns as a secondary mode switch without interfering with muscles control because the R-peak recognition algorithm performed accurately in 90% of trail System latency

The duration between muscular contraction and the start of motor activity is known as the total reaction time, and it was measured.

- Signal Processing Delay: ~40 ms (including ADC and filtering)
- Mechanical Actuation Delay: ~150 ms (servo rotation time).
- Total latency: The average system latency was recorded at 190 ms. This falls well within the acceptable range for real-time prosthetic control (typically <300 ms), ensuring the user perceives the movement as instantaneous [19].

Grip Functionality

Grasping objects with different geometries was part of the functional testing. The hand completed the task successfully.

- Cylindrical Grip: Used for holding Water bottles and pipes.
- Spherical Grip: Used for holding balls or fruits. The success rate for picking up objects under 300g was approximately 85%. Failures were largely attributed to the limited friction of the PLA material, which suggest the need for rubberized fingertips in future iteration.

Payload Calculation Technical Specifications

- SG90 servo operating torque: 0.09 N. m
- Servo horn radius: 10 mm
- Joint pulley radius: 8 mm
- Efficiency: 0.65
- Effective finger length: 60 mm
- Structure: 20% infill PLA
- Friction coefficient (PLA-object): 0.25

Fingertip Force (Ftip): The payload capacity depends upon the fingertip force and the friction between the prosthetic hand and object.

$$F_{tip} = t_{joint} / L_{finger} = 0.073 / 0.060 \approx 1.2N$$

Payload Per finger (Wfinger): This is the maximum weight one finger can hold against gravity without slipping.

$$W_{finger} = \mu \times F_{tip} = 0.25 \times 1.2 \approx 0.3N \text{ (approx. 30gram)}$$

III. RESULT AND DISCUSSION

Functional Performance of The Bionic Hand

Five SG90 servo motors, an ATmega328P controller, an EMG acquisition module, and an ECG input circuit were employed in the successful fused filament production of the prototype bionic hand. The EMG sensor accurately identified signals of muscular contraction and translated them into control commands for the activation of individual fingers. A secondary biofeedback channel for predetermined gestures, such open-hand or rest mode, was the ECG input. Finger actuation demonstrated reliable repeatability with no discernible lag throughout testing, and the control system was stable.

The printed structure was able to maintain good joint alignment and dimensional stability. Throughout their specified range of motion, every finger moved smoothly. It is evident that the printed components were adequately robust for the applied stresses because there was no structural deformation during regular operation.

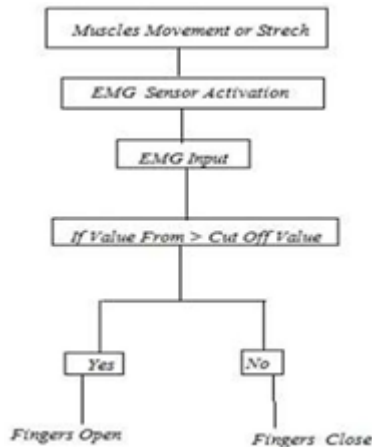


Fig.4. Flow chart of Action of Bionic Arm with EMG and ECG Input [20]

Payload Capacity Test

The torque rating of the SG90 servo motor and the finger link's effective moment arm were used to calculate the payload capacity. According to the calculation, the theoretical payload based on stall torque for a typical finger of length 50 mm was around 30g. For the long-term operation, a more caution figure of 100g was deemed safe. The computed results were in good agreement with experimental testing. Without losing their position of the servo overheating, the fingers were able to lift things upto 150g. the printed joints exhibits slight deformation under loads toward the upper limit, demonstrating that the continuous torque range offers a more practical operating limit. These observation support the use of 30 to 50 percent of stall torque as the safe working region.

Bio-Signal Interpretation and Control Accuracy

For simple finger commands, EMG-based control worked well, flexion signals were accurately identified by the system, which then translated them into proportionate servo motion. Placing the sensor electrodes parallel to the muscle fibers increased the accuracy of gesture identification. After basic thresholding and filtering, noise levels were very low.

For basic trigger based activities, the ECG channel served as an additional input. Its function was high level switching rather than constant finger control. This strengthened the control logic's resilience and decreased false triggering. A more dependable and user friendly interface was created by combining EMG and ECG inputs.

Mechanical and Electrical Constraint

A few drawbacks were noted, despite the hand's flawless operation. Although SG90 servos offer a small and inexpensive

actuation technique, their torque and endurance under continuous loads are limited. After several cycles, the printed parts also showed some wear at the hinge locations. Adding bushing to reduce friction or switching to metal-gear servos can improve performance.

Electrode positioning and skin preparation play a major role in the signal quality on the sensor side. Different operators require recalibration since EMG signal differs greatly throughout users.

Overall System Evaluation

The prototype achieves its main objective of showcasing and inexpensive, EMG-controlled bionic hand that can be made using simple 3D printing. For lightweight objects, the mechanical structure, control electronics and biosignal interface cooperate to offer dependable finger motion and sufficient grip strength. The finding verify that functional movements comparable to previous entry-level prosthetic system may be produced using a 3D printed design and basic servo actuation.

Future developments may concentrate in more robust actuators, better signal filtering, enhanced joint design, and adaptive control algorithms. These modifications can improve finger dexterity, lower noise sensitivity in the bio signal inputs, and boost payload.

IV. CONCLUSION

The project showcased the creation of a working 3D printed bionic hand that is controlled by ECG and EMG data. A lightweight, adaptable, and reasonably priced prototype was made achieved by the combination of additive manufacturing and inexpensive embedded electronics. While the ECG input served as a backup trigger to improve stability and minimize unwanted activation, the EMG sensor offered dependable muscle based control for individual fingers. The theoretical payload predictions based on the SG90 servo motors were in good agreement with the hand's mechanical performance. The prototype demonstrated that the 3D printed structure with micro servos can offer sufficient grip strength for fundamental functional activities by handling lightweight objects within the safe continuous torque range. Overall the work demonstrates that a 3D printed bionic hand with EMG and ECG control can be a useful starting point for research on low-cost prosthetics. The design can be expanded for prosthetic applications that are more robust, responsive, and user-friendly with additional developments.

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