

Design and Fabrication of a Client-Driven Electromechanical Prosthetic Arm Restoring Elbow Mobility and Grasp Function

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Abstract— This paper presents the design and fabrication of a client-centered and low-cost myoelectric prosthetic arm for a below-elbow congenital amputee with the aim to restore elbow mobility and grasp function for daily activities. The proposed system uses non-invasive surface electromyography by acquiring biceps and triceps muscle signals using MyoWare 2.0 Muscle Sensor and disposable snap electrodes placed on skin surface without any surgical implantation. Arduino Mega 2560 microcontroller was used to generate the actuation commands through threshold-based control logic. The mechanical system consists of a strap system for body-arm interface, a client-specific elbow socket fabricated using anatomical molding, 3D-printed PLA forearm structure and a parallel jaw gripper with symmetric four-bar linkage mechanism. Two linear actuators were selected based on engineering analysis for gripper force requirement of 9.81 N and elbow torque requirement of 1.87 N·m with SF of 2.0 so the client's functional requirement of strength training and weight constraint of 10 lbs could be addressed. Personalized threshold calibration was performed using client's muscle signals recorded during the enactment of tasks like mug-gripping, putting on socks or lifting a dumbbell to ensure intuitive control. Client's occupation as a radiologist was taken into consideration by maintaining electromagnetic compatibility as a primary constraint throughout the prosthetic arm development. By combining accessible and affordable materials with thoughtful control strategies and client-centered design approach, this project aims to deliver a practical and scalable approach to modern prosthetic engineering.

Keywords—below-elbow amputation, client-driven design, myoelectric prosthetics, surface electromyography (sEMG)

I. PROBLEM STATEMENT

The absence of a limb hinders one's ability to perform routine activities of daily living. While advanced prosthetics exist, their high cost makes them inaccessible to a large portion of the global population. Affordable alternatives often compromise on comfort and functionality, making them impractical for daily use.

These limitations and experiences were also expressed by the client. The client's body powered harness prosthesis was

reported to be uncomfortable and heavy during extended wear causing stiff shoulder and mechanically incapable of elbow flexion. Based on interviews and need assessment conducted with the client some functional requirements were established for the prosthetic system. The requirements of the clients were an arm that allowed elbow bending, extension and flexion with natural range of motion, must weigh no more than 10 lbs, must cost no more than \$2000, must grasp a tube bar and a coffee mug, and should be comfortable for extended daily use. These requirements informed the design constraints guiding the mechanical and electrical design decisions. create these components, incorporating the applicable criteria that follow.

II. RELATED WORK

Various types of prosthetic arms were explored before making a mechanism and design decision for the client. The different prosthetics explored are:

A. Passive Prosthetics

A passive prosthesis is an artificial limb that does not move on its own. They have no motors or electronics, but they get the job done. Whether it is a cosmetic hand that helps someone feel more confident in public, or a simple tool attachment that lets a person ride a bike again, passive prosthetics prove that good design does not have to be complicated [1]. The examples are shown in figure 1.

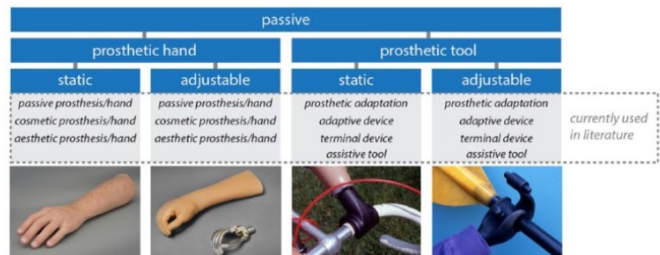


Fig. 1. Types of passive prosthetic hand and prosthetic tool from [1].

B. Electromagnetic Prosthetic System

Electromagnetic prosthetic systems use magnetic fields created by electric currents to move joints and gripping

mechanisms. Designing upper-limb prosthetics involves achieving a good trade-off among grip forces, position accuracy, weight, control ease, and energetic efficiency. Electromagnetic actuation has received considerable attention as it is quiet, mechanically simple, and compatible with myoelectric controllers [1]. By using electrical current to produce a magnetic field that generates motion, electromagnetic actuation can be used to provide either attractive-, repellent- or torqued-based motion [1],[2].

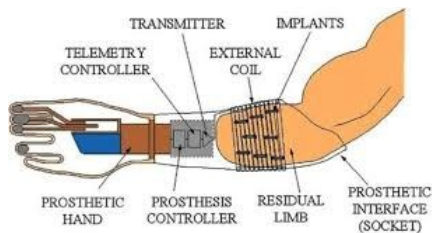


Fig. 2. Electromagnetic Prosthetic System from [2].

C. Pneumatic and Hydraulic Systems

Pneumatic system uses compressed air and hydraulic system use pressurized fluids like medical grade silicon oil to actuate motion in prosthetic limbs joints and fingers. Both function like muscles which can expand, contract or bend. The absence of magnets and ability to provide smooth, quiet motion make them suitable for medical environments. They can also be used to make low-cost functional prototypes, so they have high scope in prosthetic design [4].

D. Shape Memory Alloy (SMA) Systems

Shape Memory Alloys (SMAs) are special metals that can “remember” their shape after being heated or cooled. The contraction when heating and relaxation upon cooling acts like artificial muscles making them effective actuator alternatives in prosthetic systems. Research has shown that SMA actuated prosthetic limbs can produce grip forces of approximately 1.6 N to 40N depending upon the number of fingers, wire diameter and actuator configuration. These systems are compact, silent and lightweight with no magnets and minimal moving parts. [5].

E. Myoelectric System

Myoelectric prosthetic systems are bionic systems that use muscle signals from the residual limb of the user. The muscle signals are then sent to the microcontroller. Logic is written to actuate the desired actuators based on the muscle threshold [6].

III. INTRODUCTION

Following a systematic evaluation of the current prosthetic technologies against the client’s functional requirements, the myoelectric design was selected for further development. The myoelectric system was selected because it utilizes electromyography signals generated by the client’s residual limb muscles enabling natural and intuitive voluntary control of the prosthetic hand [6][7]. This signal-driven control strategy mirrors the natural neuromuscular intent of the user making it a more functional and biomechanically intuitive experience. Furthermore, the incorporation of an electromechanical

actuation system reduces physical effort required to operate the device addressing one of the key limitations reported by the client. The design also aligns with the project’s affordability constraints as the system can be assembled using accessible low-cost components without compromising core functionality.

The client’s occupation as a radiologist who works with CT scans and X-rays also put a constraint on the final system. Fully electromagnetic systems which rely on external magnetic coils for actuation present a higher risk of interference in such radiological environments whereas the electromechanical components employed in present design generate localized electromagnetic fields during operation limited in range and magnitude and present no significant compatibility concerns in CT and X-ray environments [8][9][12]. However, it is acknowledged that operation in close proximity to MRI systems would require additional electromagnetic shielding assessment as MRI environments impose strict restrictions on all current-carrying and ferromagnetic devices [11].

IV. DESIGN APPROACH

This study focuses on the design and development of a personalized, low-cost, and functional myoelectric prosthetic arm for a client with a forearm amputation. The goal is to create a system that balances functionality, affordability, and ease of use while meeting the specific needs of the user. The prosthetic system utilizes upper limb bicep motion to control elbow movement, while myoelectric signals are used to operate the hand, enabling a reliable grip system and flexible elbow movement. The system design can be explained in two main divisions: Mechanical Design and Electrical System.

A. Mechanical Design

The mechanical system was further divided into strap system, elbow system, forearm and gripper.

1. Strap System

The strap system is designed as a preliminary prototype intended to attach to the user’s upper arm and the 3D-printed forearm. The structural components consist of steel bars selected for their high strength and ability to maintain rigidity under load. These bars are connected using steel bolts and screws, allowing for straightforward assembly and adjustable configurations. A custom strap bracket was modeled in Autodesk Inventor [13] and 3D printed using Bambu Studio, utilizing PLA (Polylactic Acid) as the fabrication material [14]. PLA was chosen for its lightweight properties, ease of manufacturing, and suitability for rapid prototyping, enabling efficient design iterations during development. The system incorporates an adjustable nylon or polyester fabric strap, providing a secure and comfortable fit while allowing flexible adjustment.

The strap system position and structural support to stabilize the device, enable controlled upward movement and return to its original position, and prevent unwanted downward or backward motion of the forearm. This prototype allows for the evaluation of functionality, adjustability, and overall user comfort. The prototype system is shown in figure 3.

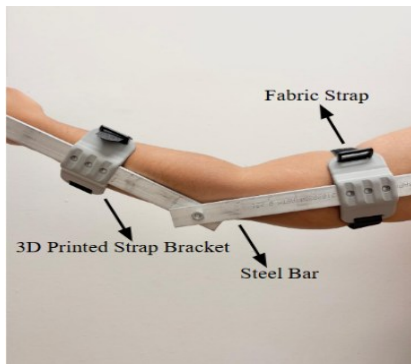


Fig. 3. Strap system prototype with 3D-printed strap bracket and adjustable fabric strap (which will connect the residual limb to 3-D printed forearm)

2. Elbow Mold Fabrication

The materials used in this procedure were a mold tube sheet, cardboard for base support, Genesis V alginate impression material from Lifecast Body Simulation Ltd., and TC-5130F fast-curing silicone. A stable casting setup was prepared using a mold tube sheet supported by a cardboard base. Genesis V alginate was mixed with water to form a liquid impression material and poured into the mold container [15]. The client then inserted the residual limb into the alginate and maintained a fixed position until the material fully set, capturing the exact anatomical geometry.

After curing, the limb was carefully removed to obtain a negative mold. TC-5130F fast-curing silicone, combined with silicone pigments, was then poured into the alginate mold to produce a positive replica of the residual limb. The silicone was allowed to fully cure before demolding. The same procedure was repeated for the upper arm to forearm region to capture the full limb geometry.

These replicas will be used for physical fitting, alignment, and iterative design of the prosthetic forearm.

3. Gripper



Fig. 4. CAD rendering of an open source two-finger servo motor gripper [16]. This shows the bilateral pivoted mounted PLA finger arms with triangular lightening cut-outs; the symmetric four bar linkage that connects the servo horn to each finger; and the cylindrical servo motor mounting position located at the back of the assembly.

The gripper used in this study is a modification of the open-source A-11 Design servo-motor gripper [16], consisting of two identical finger arms connected to central pivot axes and driven by a symmetric four-bar linkage mechanism as seen in figure 4. The actuator will produce equal and opposite displacement of both rocker-type finger arms simultaneously, characteristic of a parallel jaw gripper [17]. This configuration ensures synchronized motion while the lever action of the rocker arms

provides a mechanical advantage well suited to prosthetic applications [17][18][19]. Polylactic acid (PLA) has been selected as the primary structural material due to its easy availability and established use in prosthetic prototyping, supporting a lightweight yet structurally adequate construction of rapid design iteration. All joints will be secured with fasteners and pivot pins, and silicone pads will be applied to each fingertip to enhance frictional contact and distribute contact pressure across smooth surfaces [20]. The gripper design is currently in progress, with components to be fabricated using Fused Deposition Modeling (FDM) in accordance with established open-source prosthetic fabrication protocols [21][22], followed by full assembly, range-of-motion verification and functional evaluation within the broader prosthetic system.

B. Electrical System

The electrical system is the brain and muscle of the prosthetic arm. It reads the user's muscle signals, processes the captured signal and converts it into intended physical movement. The electrical system is divided into three main subsystems: surface EMG signal acquisition circuit, the signal processing and control unit and the actuation system.

1. Surface EMG Signal Acquisition

When the muscles in the residual arm above the elbow were flexed, electric signals were collected from the bicep and tricep muscles. These are called surface electromyography signals (sEMG). Surface EMG electrodes were directly placed on the skin over the belly of bicep and tricep muscles after cleaning the area with alcohol wipes for clear signal acquisition. Two active electrodes were placed a few centimeters away from each other along the muscle fiber direction from where the electrodes picked up local voltages. One reference electrode was placed on an electrically neutral site such as the collar bone.

Spark Fun's MyoWare 2.0 Muscle Sensor was used for signal acquisition which has built in signal filtering and gain function. The MyoWare analyzes electrical activity and outputs an analog signal that represents how hard the muscle is being flexed [23]. The harder the flex, the higher the MyoWare output voltage was observed. During the signal acquisition and data collection, the client was asked to contract the muscle as if they were doing daily activities like holding a mug, lifting a dumbbell, pushing a shopping cart, wearing socks, etc. This allowed the design to be personalized to the client's residual limb muscle signals. The testing setup for collecting this data is shown in figure 5. Figures 6 and 7 show the serial plotter graph when the client was asked to enact mug-gripping and dumbbell lifting task respectively by contracting his muscles in order to study his muscle signal thresholds for activities ranging from low strength to high strength.

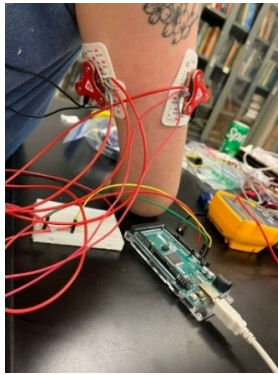


Fig 5. sEMG signal acquisition and data collection

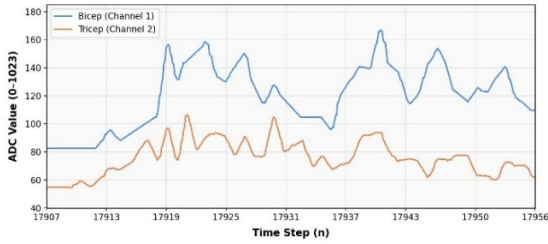


Fig. 6. Analog sEMG output of the biceps (blue) and triceps (red) muscles in the serial plotter for a mug-gripping task muscle flexion [25].

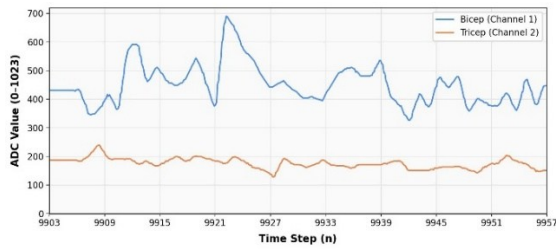


Fig. 7. Analog sEMG output of the biceps (blue) and triceps (red) muscles observed in the serial plotter for a dumbbell lifting task muscle flexion (x-axis: time step; y-axis: ADC value) [25].

2. Signal Processing and Control

The filtered sEMG signals were sent to the microcontroller for signal processing and control stage. The microcontroller reads the user's muscle activity through the incoming analog values and converts it into specific motor commands for the prosthetic arm. For prototyping purposes, an Arduino Mega was used to process these signals [24]. Logic was written according to the client's muscle thresholds as per data collected shown in the graphs above while enacting different activities. Figure 8 illustrates the logic control flow chart that was used to program the movement of actuators according to the clients' muscle signal thresholds. Channel 1 processes muscle signals to classify grip open, hold or close commands whereas channel 2 processes muscle signals to classify elbow extension, flex or hold at a certain angle command. Debounce timer is implemented in each channel to avoid unnecessary triggers or unintentional prosthetic arm movement.

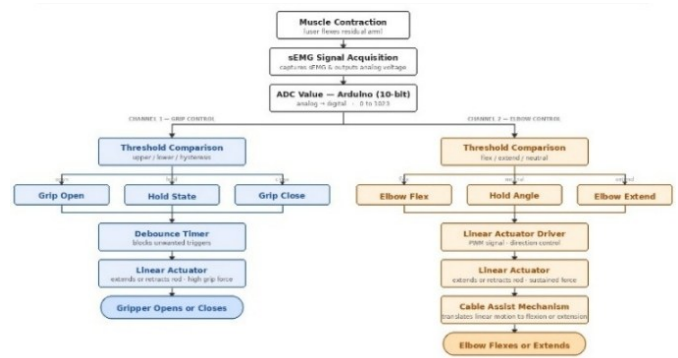


Fig. 8. Logic Control Flow Chart [25].

3. Actuation and Movement

The processed commands from the microcontroller were sent to a linear actuator and stepper motor for various movements as shown in early-stage prototype of electrical system in figure 9. Integration of final circuit with revised decision of using two linear actuators and the complete actuation system with mechanical assembly is currently in progress.

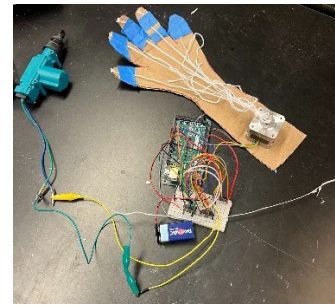


Fig. 9. Early-stage prototype of the electrical system

V. INTRODUCTION

A. Forearm Design

A 3D-printed forearm will be designed based on the measurements taken from the client's upper arm and elbow to ensure proper fit and secure attachment to the elbow joint similar to the one shown in figure 10. The design will also consider effective weight distribution to enhance comfort and usability. Additionally, the forearm will be developed to accommodate and support the necessary electronic components required for enabling elbow and hand movements.



Fig.10. Prefabricated commercially available forearm [16]

B. Elbow Design

The next phase for the elbow part focuses on transitioning from the physical mold to a functional digital and structural prosthetic component. The silicone replica of the residual limb will be digitized using 3D scanning to generate an accurate STL file representing the client's anatomical geometry. This model will serve as the basis for prosthetic socket design, where accurate shape capture is essential for proper fit and load distribution.

The STL file will then be imported into CAD software for refinement, including smoothing surface irregularities and correcting molding artifacts. The geometry will be modified to design a supportive elbow interface that ensures comfort and stability for the residual limb.

A custom structural component will be developed to extend from the elbow mold and integrate with the prosthetic forearm. This component will act as the primary load-bearing interface, with attention given to pressure distribution for improved wearability. Figure 11 shows the molded elbow geometry alongside a reference CAD model, providing context for the transition from physical casting to the proposed structural design and integration.

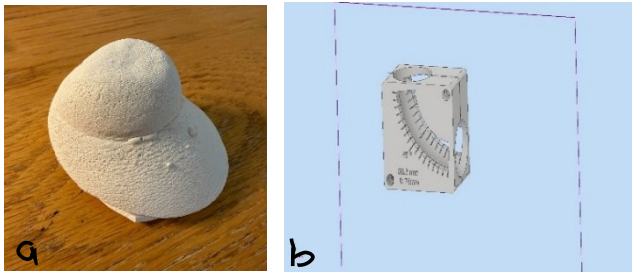


Fig. 11. (a) Silicone replica of the client's residual elbow obtained from the molding process; (b) reference CAD model illustrating a representative elbow support geometry and its potential integration with a prosthetic forearm system.[10],[15].

The design will also be adapted to integrate with the upper arm strap suspension system. Attachment points will be incorporated to provide stability and distribute load across the upper arm and shoulder. Finally, the model will be fabricated using 3D printing for rapid prototyping. The prototype will be evaluated for fit, comfort, and performance, followed by iterative modifications to achieve a functional and user-specific prosthetic system.

C. Signal Filtering

The input sEMG signals remain somewhat noisy, despite built-in filtering. Further signal processing, such as Kalman filtering, will likely need to be employed to translate the input signal to a usable actuation signal.

D. Actuation and Movement

The selection of most compatible actuators for the client's need was revised in favor of two linear actuators because of the mechanical advantage and force output provided by the

actuator. This decision was made considering client's weight requirement (10 lbs.) for the arm as stepper motors tend to be heavier and functional requirement of strength training which requires sustained high force gripping. Both actuators will be powered by rechargeable lithium battery integrated inside the forearm shell because of its stable discharge under sustained load, high energy density and compatibility with voltage requirement of linear actuator and Arduino Mega 2560 control system [24][26][27].

Modelling the forearm as a uniform beam rotating about the elbow, the minimum elbow torque requirement was calculated as (where m = total mass of forearm, g = acceleration due to gravity and L = distance between elbow pivot and center of mass of forearm).

$$T = m \times g \times L = 1.27 \times 9.81 \times 0.15 = 1.869 \text{ N} \cdot \text{m}$$

Considering the safety factor of 2.0 under dynamic loadings, the torque still falls within the rated output of compact linear actuators like Actuonix L12 series [26]. For gripping, the estimated required actuation force to grasp a mug or a tube bar was (where m = mass of mug or tube)

$$F = m \times g = 1 \times 9.81 = 9.81 \text{ N}$$

which also falls within the force range of the same linear actuator [26]. After successful integration of the mechanical and electrical system, the functionality of the whole system will be tested. The actuator is expected to provide smooth movement of the prosthetic arm for the client's functional requirements.

VI. INTRODUCTION

A. Strap System

Future improvements to the strap system may focus on enhancing comfort, durability, and adjustability. The current design can be upgraded by incorporating padding or soft-liner materials to reduce pressure points and improve long-term wearability. More advanced fastening mechanisms, such as quick-release buckles or Velcro-based systems, could improve ease of use. Additionally, the existing steel bars can be replaced with lighter and higher-strength materials, such as aluminum or composite materials, to reduce overall weight while maintaining structural integrity and improving user comfort.

B. Forearm Design

For the forearm design, the 3D-printed forearm could be fabricated from more durable materials than PLA, such as ABS, PETG, nylon, or reinforced composite filaments, to enhance structural integrity, impact resistance, and long-term reliability.

C. Elbow Design

Future work could focus on improving geometric accuracy and functional performance of the elbow interface. Direct 3D scanning of the residual limb could be explored to reduce errors from molding. The design could also be refined to accommodate functional elbow motion, targeting a flexion range of approximately 0° to $90\text{--}120^\circ$ for daily activities. Material enhancements, such as flexible or multi-material

printing, could be considered to better replicate soft tissue compliance and improve comfort.

D. Electrical System

Future enhancement could focus on use of dry electrodes, wireless communication for sEMG data logging and close loop feedback control for force control.

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