Design and Development of 3D-Printed Prosthetic Arm with Touch Sensing Technology for Improved User Control

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Abstract: ***The hand is a vital organ performing multiple tasks such as operations, inspections, adaptations, and explorations. The loss of a hand significantly impacts functionality and imposes a psychological burden on amputees. Despite numerous developments, only 30 to 50 of upper extremity amputees use their prostheses. To increase acceptance and overcome the limitations of current prostheses, this research proposes a biomechatronic-based prosthetic hand design that closely mimics the human hand in terms of cosmetics, grasping ability, and controllability. The design anatomically reproduces the bone connection structure and ligaments in the human hand, resulting in a lightweight and user-friendly prosthetic hand.***

Keywords: Prosthetic hand, Touch-Sensing Technology, 3D Printing, Biomechatronic

1. Introduction

The hand is one of the most important organs of the human body, enabling a variety of tasks such as examination, adaptation, and exploration.[1] The loss of a hand imposes two significant burdens on the amputee: a severe reduction in functionality, as the individual is unable to perform most grasping and manipulation tasks, and the onset of psychological challenges. Over the past 30 years, numerous prosthetic hands have been developed, with ongoing research striving to improve these devices. To overcome the limitations of current prostheses and enhance their acceptability, prosthetic hand designs must closely mimic the human hand in terms of cosmetics, grasping ability, and controllability. Ideally, prosthetic hands should provide users with functions like those of natural hands, including tactile exploration, grasping a range of objects from small to heavy, and manipulation in daily activities.[2]

Before developing this prosthetic hand, an extensive analysis and review of previous designs and literature on dexterous robotic hands were conducted. Existing dexterous artificial hands primarily use conventional means of actuation and fabrication, resulting in high system complexity, significant weight, volume, and lengthy fabrication times. In many cases studied, the actuators used lack biomimetic behavior, creating human interface control problems. Additionally, the actuators and transmission elements in existing artificial hands are often noisy, complicating use for the human operator.

To address these issues, a prosthetic hand was developed using a biomechatronic approach and mechatronics principles, aiming to closely replicate the natural hand while ensuring the device is lightweight, user-friendly, and efficient for the human operator. The design of this artificial hand is based on anatomically reproducing the bone connection structure and ligaments found in the human hand.

2. Anatomy of Hands

To define clear parameters for the operation of the bionic hand, it is necessary to examine the anatomy behind a functional hand which allows it to move in the way that it does. The project aims to produce a bionic hand capable of replicating the movement of the hand as closely as possible, so the actual structures of the hand are a very important consideration. The motion of the hand should be biomimetic, meaning that any motion it makes should visually appear human and realistic. The human hand has 27 Degrees of Freedom (DOF): 4 in each finger, 3 for extension, and flexion, and 1 for abduction and adduction; the thumb is more complicated and has 5 DOF, leaving 6 DOF for rotation and translation of the wrist.[3] There are a total of 27 bones with 36 articulations and 39 active muscles. Most manufacturers of prosthetic hands limit their designs to have a much lower number of degrees of freedom because of considerations about power, space, weight, and control, but as a biomimetic mechatronic hand, this project should aim to imitate the hand as closely as possible. Each finger (not including the thumb) consists of four bones. The visible finger segments which protrude from the palm are called phalanges. proximal from tip to base respectively. In the palm, metacarpals attach each phalange group to a group of bones called the carpals at the base of the palm and these bones allow the wrist to rotate and translate on the radius and ulnar bones of the forearm. Much of the hand’s actuation originates from muscles in the forearm, which move the hand using tendons attaching to the various bones of the hand, these are referred to as extrinsic muscles. Some motion comes directly from muscles inside the hand called intrinsic muscles.

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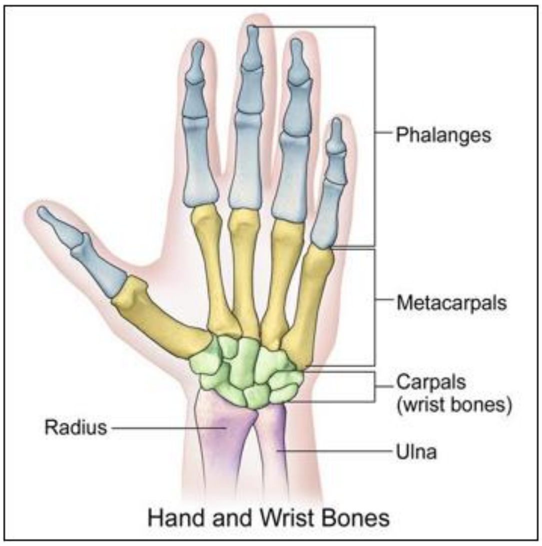


Figure 1: Hand Anatomy and Function | Bone and Spine

3. Mechanical Design

3.1 Finger Linkage Design

The human hand was studied visually and anatomically while grasping and handling different objects. One single finger was the starting point for the entire design process. The adjustment and positioning of each finger are functionally significant to get more physiological prehension without any interference. The finger design process began with determining what was required for each finger. The finger consists of three individual pivot joints which can almost be individually actuated through muscular tendons.[4].

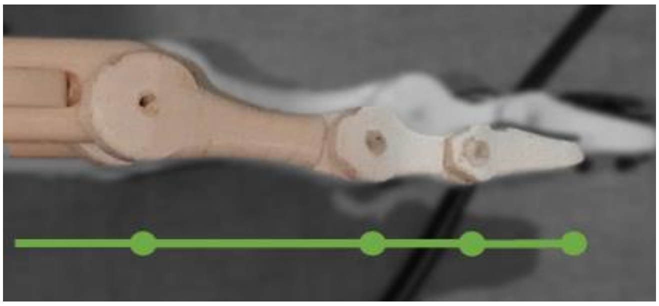


Figure 2: Illustration of link and node of a single finger

The finger design presented could be used with two degrees of freedom, one to control flexion and extension, and the other to control the radius of the finger curl. Actuation of the cables used for flexion of fingers is done using the servo motors. One small servo motor is dedicated to each finger and a pulley is attached to the shaft of the motor. As the motor rotates in the direction of wrapping the actuation or flexion cable, the phalanges of the finger close and rotate towards the palm to compensate for the pull.


(a) (b)

Figure 3: Black string indicates forward bending and red indicates reverse straight (a) Finger straight position (b) Finger during bending

3.2 Finger Joint

The mechanism's design closely resembles that of a bar system, wherein a single action, such as rotating a pulley with a motor, initiates movement. The arrangement of the pulleys ensures that this initial action results in the desired motion of other components. This system effectively reduces the weight of the hand, making it easy to implement.

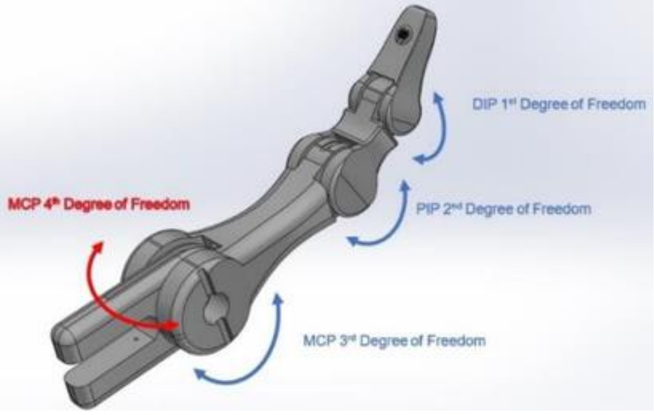


Figure 4: Finger with four Degrees of Freedom (DOF)

3.3 Thumb and Palm Design

The thumb of a prosthetic hand plays a crucial role in enabling different grasp types, akin to the importance of the opposable thumb in the biological human hand. The shape of the thumb allows prosthetic hand users to perform various grasps, such as pinch, handle, and power. To achieve these three grasp types, at least two degrees of freedom (DOF) are required for the thumb: one for adduction/abduction and one for flexion/extension. Actuators are employed to facilitate the individual movement of the thumb.

The design features the thumb mounted on the palm at an angle of 30 degrees towards the fingers. The thumb is actuated by dual MG90S micro servo motors, ensuring precise movement. [5]

Figure 5: The black box illustrates the MG90S position to rotate thumb inward and outward. The yellow box shows all the string transferring from fingers to palm and then forearm with the servo wire and front facing linear actuator for wrist motion

3.4 Wrist and Forearm

For wrist rotation, a triple linear actuator is utilized, providing an additional degree of freedom of movement. The forearm houses both the linear actuator body and the piston rod, which extends or retracts as needed. This setup offers three degrees of freedom: pitch, roll, and heave, which are commonly used in amusement park rides and simulators. Following the wrist actuators, the electronics and battery are strategically placed to fill the space and help distribute the weight of the major components.

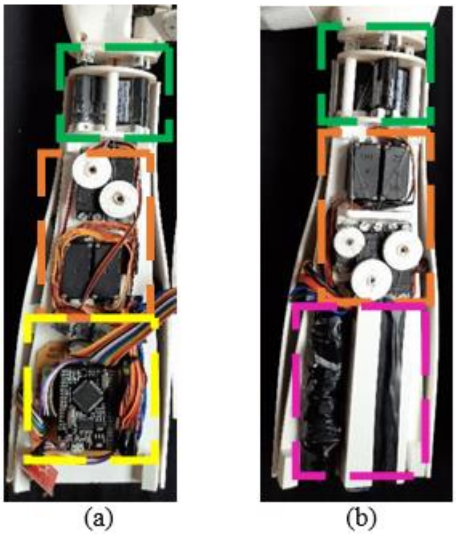


Figure 6: Internal of the forearm. The green box shows the linear actuators (a), followed by an orange box for servos (a) followed by a yellow box on the front side showing controller and electronics (a), and a pink box showing the battery compartment and power management unit (b).

3.5 Control Consideration

An Arduino microcontroller is used as the main control board due to its ease of use and flexibility, accommodating both beginners and advanced users. The prosthetic arm requires multiple inputs and outputs for sensors and actuators, making the Arduino Mega Pro an ideal choice. This compact version of the Arduino Mega offers a higher clock speed while operating at lower voltages and is more robust compared to the traditional Mega.

3.6 Sensors, Actuators, body and Grip

Sensors are strategically located on the tips of each finger and thumb of the prosthetic hand. These sensors enable users to gauge the force applied while holding objects, ensuring delicate items are handled gently and heavier objects are grasped securely. The sensors are Force Sensing Resistors (FSRs) that alter their resistance when force is applied. Specifically, Force Sensor Resistor 0.2” (5.08 mm) is used, with a resistance range from 100 ohms to 1000 ohms, accommodating forces from 0.1N to 100N with 98% efficiency.

The sensors operate within a temperature range of -30°C to +70°C, which surpasses the average human hand’s temperature sensitivity (15°C to 48°C). For instance, while a human hand can only tolerate water at 60°C for a few seconds, this prosthetic arm can endure 70°C for up to 10 minutes before the sensor’s touch sensitivity degrades due to permanent deformation.

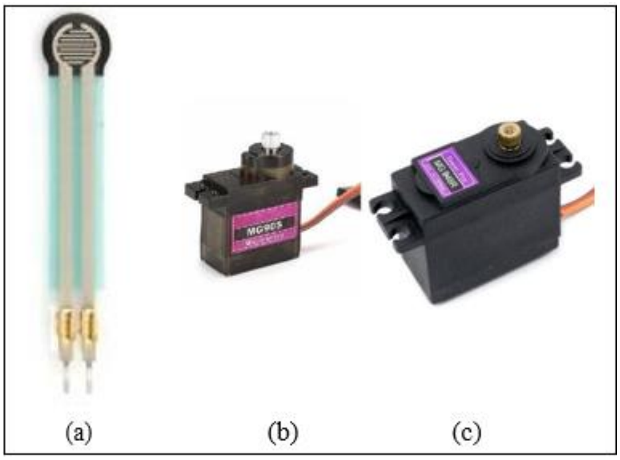


Figure 7: Pressure sensor and servo motors. Force sensor 0.2” (5.08mm dia) (a), MG90S Servo Motor (b), MG996R Servo Motor (c)

Choosing the appropriate servo motor for finger movement and weight lifting was critical. The MG996R-Metal Gear servo motor was selected for the fingers due to its 11kg/cm torque at 6.8V, lightweight (55g), and cost-effectiveness compared to alternatives like the DS3218 Digital RC High Torque servo motor. For thumb rotation, the MG90S-Metal Geared servo motor, providing 2.2kg/cm torque at 6.6V, is more than sufficient. The linear actuator used has a torque of 25N at 12V and a constant speed of 15mm/s.

The custom body and finger designs are 3D printed using PLA (Polylactic Acid), a biodegradable, user-friendly, strong, versatile, and non-toxic material. To enhance grip, rubber pads are applied to each fingertip, with pressure sensors embedded within the pads to detect forces without compromising the grip.

Table 1: Specifications of all the actuators that are used

Specification	Linear Actuator PQ12	MG996R Servo	MG90R Servo
Supply voltage(V)	12	6	6
No-load speed	8 mm/s	180 deg/s	180 deg/s
Stall torque (N)	45	1.078	0.215
Stall current (A)	0.5	2.5	0.7
Diameter (mm)	15	20	12
Height (mm)	37	50	26
Mass (g)	15	55	36

For actuation, an EMG Mayo Sensor (sEMG) is employed. This non-invasive sensor is placed on the skin's surface over the monitored muscles, detecting electrical activity from muscle fibers using small electrodes. These signals are then amplified and analyzed by the Arduino Mega in the forearm.

4. Electronic Design

The design incorporates a custom handmade PCB that houses the Arduino Mega Pro at its center. On the right side of the PCB, indicated in the red box in the figure below, are the servo connectors. The left side hosts the main power supply for all actuators and the Arduino Mega Pro, sourced from a 12V 2S lithium-polymer battery, as well as the display port for a 2.4” TFT Display, indicated in the blue box. At the top of the PCB, five connectors with internally pulldown resistors for the force sensors are located, indicated in the yellow box. The schematic diagram below illustrates the electrical connections for the servos, linear actuators, force sensors, and battery connectors.

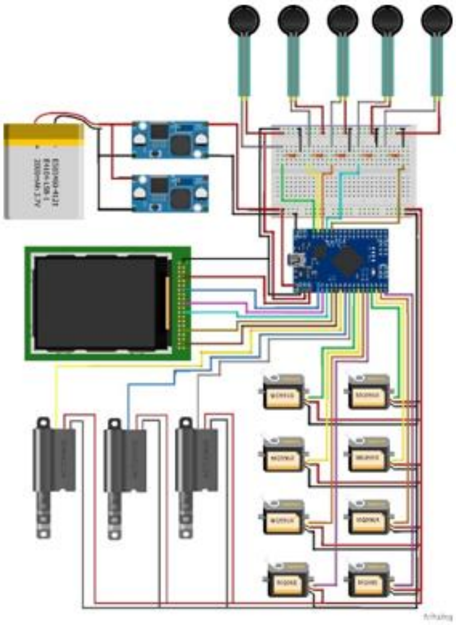


Figure 8: Diagram of electrical connection

Additionally, the 2.4-inch TFT display is used to show pressure sensor readings and battery voltage. The design allows for the addition of extra sensors, such as temperature and humidity sensors. These can be inserted into the fingers to provide readings of pressure, temperature, and humidity.

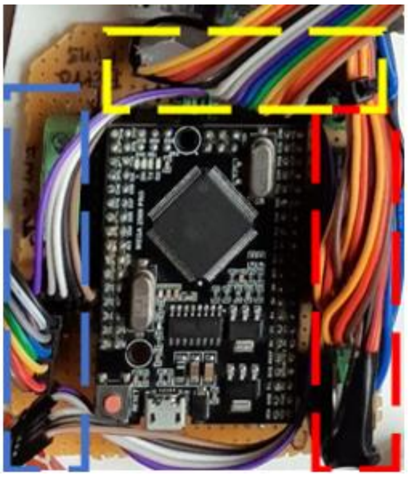


Figure 9: The yellow box shows force sensors connection, the blue box shows power input and display connection, and the red box shows actuators connection

5. Performance of the Prosthetic Arm

The prosthetic hand was tested by grasping various everyday objects. The grasping force was measured using a load cell, typically recorded in kilograms, and converted to Newtons (N).[6] The average force required to grasp an object was 20.00 ± 0.81 Newtons. During the assessment, the prosthetic arm was controlled using five potentiometers through the Arduino microcontroller and a single-channel EMG signal. The graph below shows the input signal of the EMG sensor, with a normal reading of around 330mv and a maximum reading of up to 570mv. A threshold of 400mv was set to achieve the most accurate results while grasping objects.

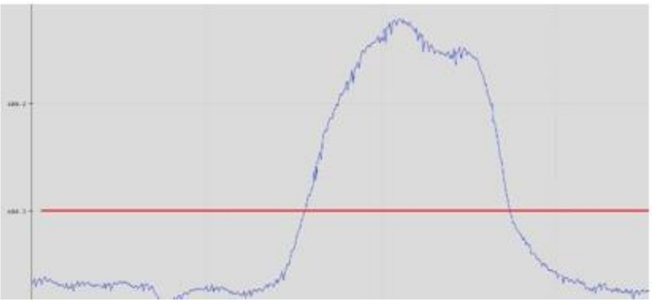
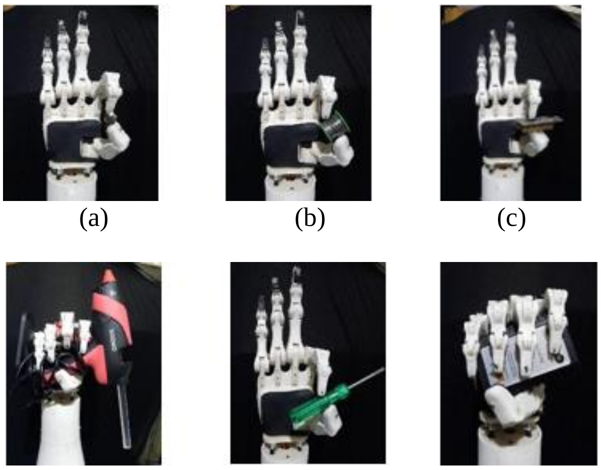


Figure 10: The graph of EMG sensor detection of muscle movement and red line shows the threshold value to change position of the finger using actuators.

6. Results

The purpose of this study was to compare the functionality and performance of a 3D-printed prosthetic arm equipped with touch-sensing technology to that of an actual human hand. To effectively demonstrate the distinctions and similarities between the two, a comprehensive collection of images displaying the prosthetic arm and the human hand in parallel was included in the research.

The 3D-printed prosthetic arm with touch-sensing technology was compared to the natural functionality of an actual human hand to provide an unbiased evaluation of both systems. The inclusion of these comparative images served multiple purposes. Firstly, it allowed for a direct visual representation of the prosthetic arm alongside the human hand, highlighting any discrepancies or resemblances. This visual contrast aided in conveying the findings and observations made during the study.



(a) (b) (c)

(d) (e) (f)

Figure 11: The number of objects that can be held by the prosthetics hand (a) Push Button (b) Soldering iron wire reel (c) Arduino mega pro (d) Glue Gun (e) Screwdriver (f) Battery Charger

Additionally, this comparison sheds light on the potential enhancements that touch-sensing technology offers in terms of user control and satisfaction with prosthetic devices. By showcasing the prosthetic arm's capabilities and benefits compared to a natural hand, the significance of the research outcomes was better emphasized. The strategic incorporation of these images enhanced the comprehensibility and impact of the research. Visual aids can capture attention, evoke emotions, and facilitate a deeper understanding of complex concepts. In this case, the images provided researchers, medical professionals, and the public with a tangible and relatable representation of the advancements made in the field of prosthetics.

In the development of the prosthetic arm, finger movement was facilitated by connecting servos to each finger, allowing for 10 stages of movement ranging from 0 to 180 degrees. The data for finger positions was artificially generated and arranged in ascending order. The natural movement of human fingers was replicated by ensuring precise control over the servos. Furthermore, pressure sensors were integrated into the fingertips, enabling the detection of pressure ranging from approximately 100 to 2000 units. The readings provided by these sensors facilitated intuitive interactions between the prosthetic arm and objects or surfaces.

Table 2: 10-stage servo data

Finger 1	**Finger 2**	**Finger 3**	**Finger 4**	**Finger 5**
0	0	0	0	0
18	18	18	18	18
36	36	36	36	36
54	54	54	54	54
72	72	72	72	72
90	90	90	90	90
108	108	108	108	108
126	126	126	126	126
144	144	144	144	144
162	162	162	162	162
180	180	180	180	180

Table 3: Touch sensor data

	1	**2**	**3**	**4**	**5**
Before Touch	250	350	400	480	600
Threshold	400	550	700	900	1000
After Touch	800	1000	1100	1150	1200

Linear actuators played a crucial role in the movement and positioning of the prosthetic arm. The positions of the actuators at the "Retracted Position," "Middle Position," and "Extended Position" were determined by referring to the artificially generated data. These positions were set at 1000, 1500, and 2000 units, respectively, to achieve controlled and precise arm movements. The integration of the data into the design and control mechanisms of the prosthetic arm allowed for the replication of intended functionalities.

Table 4: Linear actuator data for wrist movement

	Actuator 1	Actuator 2	Actuator 3
Retracted Position	1000	1000	1000
Middle Position	1500	1500	1500
Extended Position	2000	2000	2000

By incorporating sample data and utilizing technologies such as servos, pressure sensors, and linear actuators, the prosthetic arm was able to closely mimic the movements and functionalities of a natural limb. A more natural and functional user experience was achieved, enhancing the individual's ability to perform daily tasks. Additionally, a greater sense of autonomy and confidence was instilled, as the prosthetic arm enabled individuals with limb differences to regain a higher level of dexterity and control.

Overall, the integration of artificially generated data into the development of the prosthetic arm facilitated the creation of a sophisticated and functional device. By leveraging technologies such as servos, pressure sensors, and linear actuators, individuals with limb differences were able to experience an improved quality of life and reintegrate into daily activities with enhanced ease and confidence.

7. Discussion

The findings of this research demonstrate the potential of touch-sensing technology to significantly improve user control and satisfaction with prosthetic devices. By integrating touch sensors into a 3D-printed prosthetic arm, users were able to interpret touch sensations and translate them into intuitive and natural movements. The prosthetic arm was lightweight, customizable, and cost-effective, making it accessible to a larger population of users.

The significance of this research lies in its potential to contribute to the advancement of prosthetic technology. The use of 3D-printing technology and touch-sensing technology opens new possibilities for the development of customized and adaptive prosthetic devices. The findings of this research can inform the design of future prosthetic devices, which can help to improve the quality of life for people with limb loss.

The potential implications of this research for future studies include exploring the use of touch-sensing technology in other areas of prosthetic devices, such as improving grip strength or providing feedback on temperature or pressure. Further research is also needed to investigate the generalizability of the findings to other populations and settings.

One of the limitations of this study is that it involved a small sample size and was conducted in a laboratory setting. Future studies could involve larger sample sizes and investigate the use of the prosthetic arm in real-world settings.

8. Conclusion

The integration of touch-sensing technology into a 3D-printed prosthetic arm has the potential to significantly improve user control and satisfaction with prosthetic devices. This research highlights the potential of touch-sensing technology to enhance the quality of life for individuals with limb loss and offers important implications for the future development of prosthetic devices. This paper presented the design and development of a 3D-printed prosthetic arm equipped with touch-sensing technology to enhance user control. The incorporation of touch sensors allows the prosthetic arm to interpret touch sensations and translate them into intuitive and natural movements, thereby improving user control and satisfaction. The prosthetic arm, weighing 1.93 kg, is lightweight, customizable, and cost-effective at $290 or ₹24,300 INR, making it accessible to a larger population of users. This research demonstrates a promising approach toward the development of advanced prosthetic devices that can offer improved functionality and user experience. The use of 3D printing and touch-sensing technology opens new possibilities for the creation of customized and adaptive prosthetic devices. Further research is needed to explore the full potential of this technology in enhancing the quality of life for individuals with limb loss. In conclusion, the integration of touch-sensing technology into prosthetic devices represents a significant advancement in the field. The findings of this study provide a foundation for future research and development, aimed at creating more effective and user-friendly prosthetic solutions.

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Author Profile

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