Design of an Auxiliary 3D Printed Soft Prosthetic Thumb

Akash Jain, Deepanshika Gaur, Chinmay Bindal, Ranganath M. Singari, and Mohd. Tayyab

Abstract Advancement in intelligent prosthetics and increased popularity for wearable technology has paved the way for the evolution of robotic appendages. The paper presents the design of an additional prosthetic thumb which seeks to extend human capabilities by improving hand manipulation and grasping ability. The device is engineered to be lightweight so that it is completely portable and comfortable to wear throughout the day. Thermoplastic polyurethane (TPU) is selected as the material for fabrication due to its high abrasion and chemical resistance, thus ensuring excellent durability. 3D printing is chosen as the manufacturing process as it is cheap, quick, and easily accessible. Moreover, it allows easy customization, thus allowing the user to modify the prosthetic thumb according to their preference. The device presents a wide range of applications from playing an extra note on the piano to improving grip on large objects. It aims to revolutionize the use of wearable robotics to upgrade human capabilities and open new avenues for enhanced human–robot integration.

Keywords Additional prosthetic thumb · Sixth finger · Soft wearable robot · 3D printed prosthetic · Human enhancement

1 Introduction

Prosthetics are often associated with artificial limbs or organs used to replace damaged parts of the body. However, its application is not limited to conventional meaning and can be used to extend or supplement human capabilities. The word *prosthesis* originates in Greek from prostithenai, meaning 'to add in place' [1]. This essence of addition is explored in our work through an extra thumb seeking to enhance gripping and manipulation ability of the hand.

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Humans have evolved to have five digits on both hands along with intricate wrist mechanism to carry out various complex tasks. An additional thumb will change the way we perceive and interact with our environment. It will open new avenues for enhanced human integration with robots and promote the use of prosthetics to advance human capabilities. From playing an extra note on the guitar to picking up large objects with ease, the possibilities are endless.

Several robotic appendages have been developed as human enhancements [2–4]; however, they suffer from lack of accessibility, due to their complex nature. The prosthetic thumb is designed to be simple and easily manufacturable. With the rise in popularity for additive manufacturing and an increase in the number of people with desktop 3D printers, the prosthetic thumb would be easily accessible. It will allow personalized customization and facilitate effortless integration in people's lives.

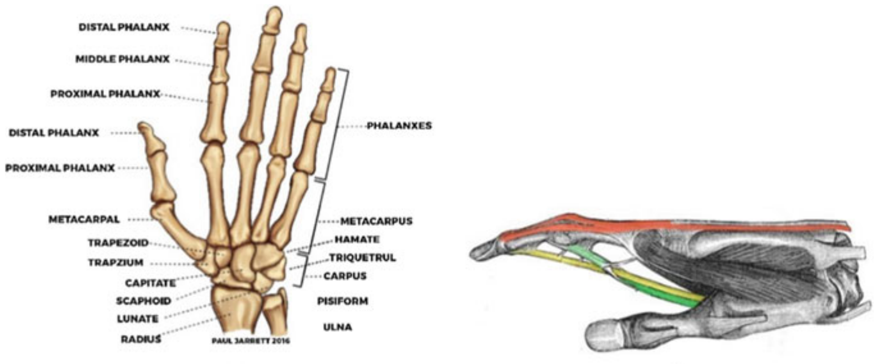
2 Requirements and Challenges

The prosthetic thumb should feel natural and comfortable when worn. There are numerous factors which dictate a successful design. The following requirements are summarized as a result of consultation with doctors and literature review of prosthetics.

1. *Portability*: The device should be lightweight and completely portable, thus allowing the user to freely move around while wearing the prosthetic thumb.
2. *Wearability*: The system developed must be comfortable to wear and the user should be able to easily put-on and take-off the device when required.
3. *Non-restrictiveness*: There must not be any constraints on the mobility of joints, hence allowing the user to freely use their hand.
4. *Durability*: The prosthetic thumb must be resistant to the environment so that it can be used easily in day-to-day activities.
5. *Safety*: The device must be completely safe to wear and must not pose any risk to human health.

3 Design Conceptualization

A basic outline of the prosthetic thumb is first formulated which is then further refined to produce a more elaborate system. This section presents the whole conceptualization process including the general structure of the device and the actuation mechanism employed.



(a) (b)

Fig. 1 Hand and wrist anatomy, **a** skeletal structure, **b** flexor and extensor tendons

3.1 Structure

To simulate natural movement, the structure of the prosthetic thumb is based on the anatomy of the human hand. The thumb comprises two narrow bones called phalanges which precede a metacarpal bone leading to the carpal bones in the wrist (see Fig. 1a). Ligaments form connective tissue between the bones and tendons serve the purpose of connecting muscles with the bones for movement [5]. Accordingly, the prosthetic thumb is designed to have three short segments corresponding to the metacarpal and the phalanges. Flexible filament serves the purpose of the ligament at the joints, while the tendon wires connecting to servomotors correspond to muscle operation. Angles provided at the joint facilitate the motion of the thumb.

3.2 Movement

Fingers comprise flexor and extensor tendons to carry out bending and stretching motion, respectively (see Fig. 1b) [6]. However, flexion and extension require two sets of tendons, thus increasing complexity along with the number of motors required. The problem is solved through the use of elastic material at the joints such that extension is the natural state of the thumb. Flexion is carried out through tension in the string, and its magnitude dictates the position of the thumb along with gripping strength. Release of tension causes the thumb to return to its original position, thus allowing a wide range of motion through the use of a single motor.

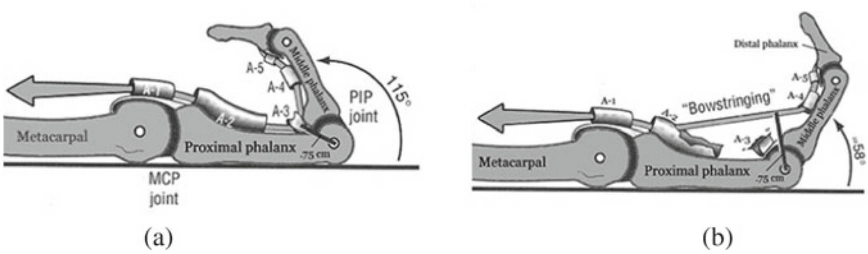


Fig. 2 Importance of the flexor pulley system. **a** The function of annular ligaments as pulleys. **b** Bowstringing effect leading to the reduction of power and loss of movement

3.3 Flexor Pulley System

Flexor tendons are tethered to the bones through annular ligaments acting as pulleys, thus providing efficient pulling force (see Fig. 2a). Damage to annular pulley leads to a bowstringing effect (see Fig. 2b), therefore causing a reduction of power along with the restriction of normal hand movement [7]. Tubular holes are cut passing through each segment of the prosthetic thumb to provide passage for the flexor tendon. This ensures that the tendon runs along with the thumb and efficient transmission of power takes place. Each of the segments thus acts as an annular pulley while simultaneously serving the purpose of providing structure to the whole thumb.

3.4 Mounting

The prosthetic thumb must be interfaced with the hand in a non-restrictive manner. To warrant this, the thumb is provided with a base that snugly fits into the side of the palm. A piece of soft fabric with elastic properties is used to secure the device. This ensures proper blood circulation and minimal restriction in normal hand movement. Servomotor along with electronics and battery is mounted on the wrist in the form of a watch. A Bowden cable running from the tip of the thumb connects to the servomotor at the wrist. The outer sheath of the cable prevents damage to the user during thumb operation. The whole setup is designed to be lightweight and portable so that it can be comfortably worn in daily life.

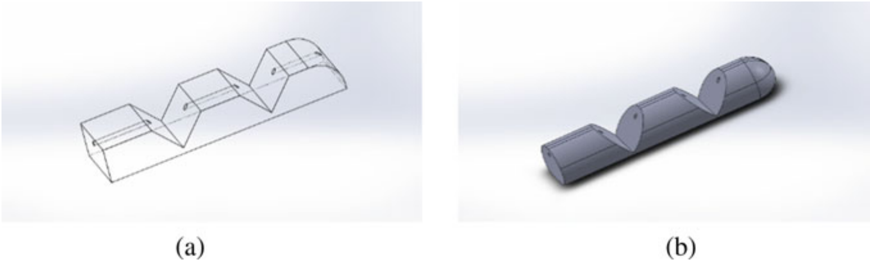


Fig. 3 Development of CAD model, **a** basic model, **b** final design

4 Design Conceptualization

4.1 CAD Model

Figure 3 illustrates the conceptualized design of the prosthetic thumb. It consists of three short segments with angles provided at the joint to facilitate the movement of the thumb. Tubular holes are cut through the device which acts as a flexor pulley system, thus ensuring the efficient transmission of tension. They also provide a path for the tendon and facilitate flexion of the prosthetic thumb. The device is provided with a flat base and a structured design to ensure quick printing and easy customization. The edges are smoothened out with a fillet to provide a more natural feel. The mounting base is not included in the diagram as it can be separately designed uniquely to each individual.

4.2 Material and Manufacturing

Each customer has a specific demand, and catering to the needs of every individual has given rise to customized solutions. 3D printing is one of the most powerful tools for providing personalized products as it allows easy modification to meet customer demands. Moreover, the process is quick, cheap and highly accessible. It is used in medical applications for custom implants and prosthetics due to its high adaptability. 3D printing is chosen as the process for the manufacturing of the prosthetic thumb as it allows the device to be tailored according to the specific needs of the user.

The material for the prosthetic thumb is required to have high elasticity in order to facilitate movement and excellent durability to allow usage in daily life. Rubber is the ideal choice for application; however, it cannot be 3D printed. Referring to the chart in Fig. 4, it can be observed that elastomers and polymers fall under the category of flexible materials. A combination of thermoplastics and elastomers produce a new 3D printable class of materials called thermoplastic elastomers (TPE) [8]. They have several variations with elasticity depending on the type of TPE and chemical

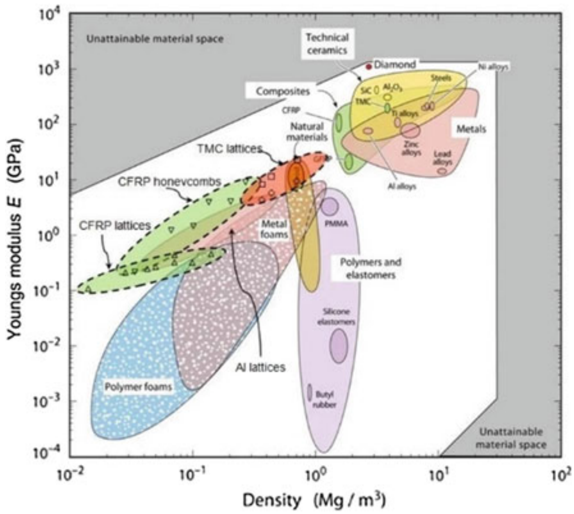


Fig. 4 Young's modulus indicates a material's elasticity

formulation used. Thermoplastic polyurethane (TPU) is a commonly used printable grade of TPE and is selected for prosthetic thumb due to its high elastic range and excellent printability [8]. Properties such as fatigue, abrasion, and chemical resistance ensure long operational life, whereas its soft and flexible nature guarantees comfort while preventing accidental harm to the user.

4.3 Actuator

The position of the prosthetic thumb along with gripping strength depends on the magnitude of the tension in the string. The actuator employed must, therefore, provide positional control to facilitate the movement of the thumb. Apart from this, the actuator must be small enough to fit comfortably in the wrist of the user and shall provide sufficient torque for the general gripping application. Both the servo and the stepper motors meet the requirements and are ideal for use as an actuator for the prosthetic thumb. 28BYJ-48 is a commonly available 5 V stepper motor that fits the required dimensions [9]. MG90S is a metal-geared 5 V servomotor of similar dimensions [10]. Comparing the datasheets of both the motors, it can be noticed that MG90S servomotor provides greater operating torque and hence is chosen as the actuator for the prosthetic thumb.

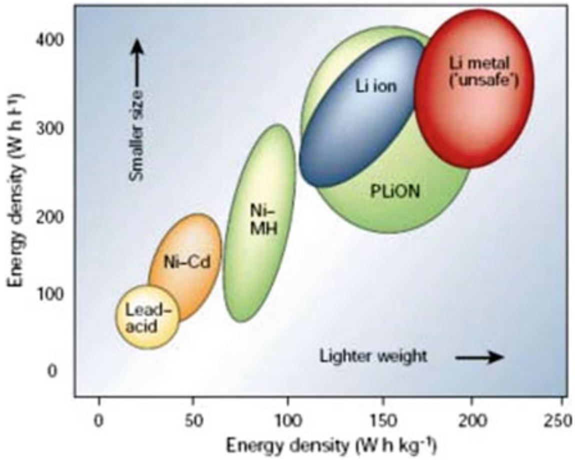


Fig. 5 Graphical representation of various types of batteries

4.4 Battery

The power system for the prosthetic thumb must be lightweight, rechargeable, durable, and medically safe for use in prosthetic devices. Figure 5 presents a visual representation of different characteristics of various batteries. As we move higher up on the graph, energy density increases along with lighter weight and smaller size. All these desirable characteristics make Li-ion an attractive choice for use in the prosthetic thumb.

They possess excellent charge density and do not display memory effort over multiple charge cycles. Moreover, they have a low self-discharge rate, require little maintenance, and are suitable for use in proximity to the human body [11]. With advancements in technology, features such as fast charging make this an excellent choice. Their small size and low weight make them suitable for mounting on the wrist with little discomfort. Considering all these factors, the Li-ion battery is chosen for use with the prosthetic thumb.

5 Control System

Buttons and switches are the most commonly employed methods for the control of prosthetic devices. However, they require to be physically operated and take away a certain degree of freedom. Flex sensors rely upon the movement of the wrist or fingers and hence do not provide independent control. The mechanism used to operate the prosthetic thumb must allow effortless control without affecting the natural movement of the user. Electro-biological signals prove to be a great solution as they can be easily detected and interfaced with the prosthetic thumb. Their low cost of implementation and relatively simple processing system make them an ideal candidate.

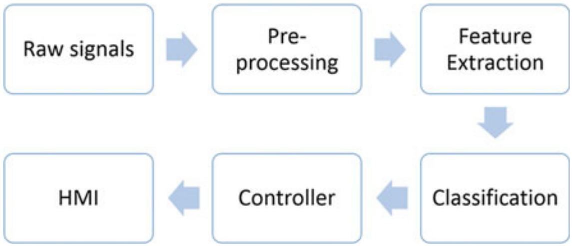


Fig. 6 Stages of an EMG control system

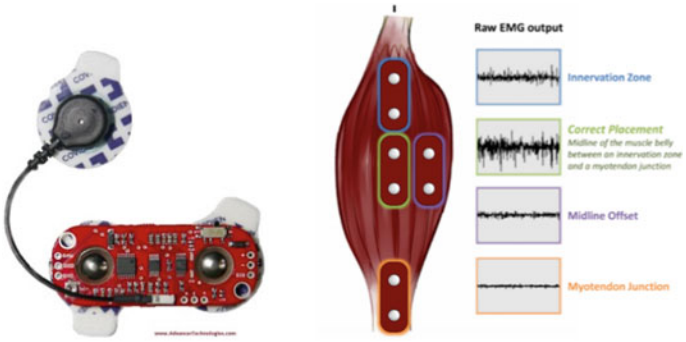
Intentionally generated electrical signals from various parts of the body are used as the control mechanism. EEG and EMG are two types of signals which can be used for the control of the prosthetic thumb.

Electromyographic (EMG) signals are produced due to neuromuscular activity and typically lie in the range of 100 μV to 90 mV. They display a standard behavior which makes them an ideal candidate for control systems. Moreover, their signal level can be easily distinguished due to high electric potential. Electro-encephalographic (EEG) signals, on the other hand, correspond to the brain (neural) activity and generate amplitudes below 100 μV [12]. These signals are harder to condition compared to EMG signals and are ideal for use in patients with neuromotor disabilities. Since the prosthetic thumb is intended for healthy individuals, EMG signals are selected as the control mechanism for the device.

The control system using electromyographic signals involves detection via electrodes placed on the user. The raw data is then filtered and processed before being communicated to the controller. Command signals are then sent to the motors which actuate the prosthetic thumb. The whole process is illustrated in Fig. 6. Surface EMG is used to detect the electrical signals using conductive gel electrodes which measures the complete electrical activity of a large region of muscle fibers. These electrical signals correspond to the force exerted by a muscle (or group of muscles) in real time. The common application of surface EMG includes myoelectric prosthesis, control of a limb in virtual reality and generation of biofeedback for muscular pain (Fig. 7).

Myoware muscle sensor by Advancer technologies [13] is used to detect muscle activation signals. It is appropriate for generating raw EMG signal and analog output signal for Arduino. The sensor is designed for a reliable output with low power consumption. It operates on a single power supply (+2.9 to +5.7 V) with polarity reversal protection and allows adjustments in sensitivity gain. The sensor is placed along the length of the muscle, with the electrode closest to the wire connections placed at the middle of the muscle and the second electrode on the circuit board toward to end of the muscle. The third electrode attached to the black wire is placed away from the muscle which needs to be sensed.

Our muscles generate a wide range of voltage for a simple motion of the thumb. Sample data is collected corresponding to different movements, and an appropriate signal is determined for flexion and extension of the thumb. The collected data is then processed to associate electrical signals with muscle movements. This is achieved



(a) (b)

Fig. 7 **a** Myoware EMG muscle sensor, **b** correct electrode placement

using a classification technique: probabilistic neural network (PNN). The classifier gives a high level of performance accuracy for complex biological signals. Using PNN, the dataset is trained to classify the voltage range to specific thumb movements. Once training and testing are completed, a model is developed which is capable of providing the prosthetic thumb the desired movement.

6 Prototype Development

A sample prototype of the prosthetic thumb was developed by 3D printing it on a Creality CR10 3D printer with TPU as the filament material. The layer height and the wall thickness were kept at 1.2 mm and an infill of 25% was provided with cubic pattern. No supports or build plate adhesion were employed.

The printed thumb is illustrated in Fig. 8. The model is tough and durable while possessing elastic properties to facilitate the motion of the thumb. The dimensions of the prosthetic matches with other digits on the hand and hence can be comfortably integrated without any discomfort. The model is interfaced with Arduino to develop a working prototype. MG90S metal-geared servomotor is used as the actuator for controlling the tendon movement and hence the motion of the thumb. Li-ion battery is used to power the device, and Myoware muscle sensor is used to pick up signals from the forearm.

7 Conclusion

An additional prosthetic thumb for extension of human abilities was proposed, and the detailed design of the device was presented. The thumb was designed for use

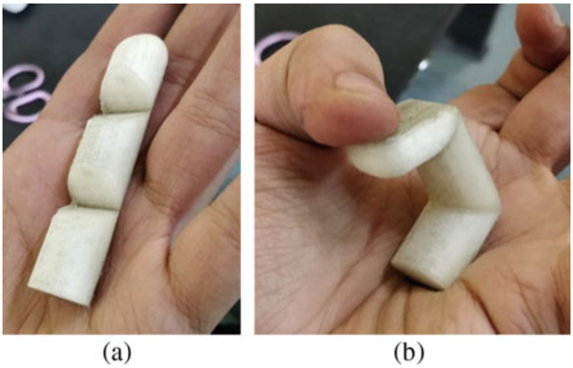


Fig. 8 Developed prototype of the prosthetic thumb. **a** Initial extension position, **b** flexion of the thumb

with healthy individuals to enhance gripping and manipulation ability. Utilizing 3D printing, the prosthetic thumb can be easily customized and manufactured in a small amount of time with little cost. TPU as the material of the thumb makes it durable and fit for use in daily life while providing elasticity in the joints to facilitate motion of the thumb. The control system utilizing EMG signals provides autonomy to the device and promotes advanced user control. The prosthetic thumb aims to promote the development of robotic devices to enhance human capabilities. It possesses vast potential in medical, military, and space applications. There is a huge scope for further research including implementation of haptics, changes in the brain due to extra digit, fatigue, and life cycle of the thumb and several others.

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