

Study on bio-inspired multi-phalangeal prosthetic hand as a terminal device

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Abstract— Upper limb amputation may be a result of surgery, trauma, disease, or due to a congenital manifestation. Regardless of its cause, losing hands is the most devastating situation because we use them everyday. Experiencing such long-term disability can affect mental, emotional and social well being of an individual. Upon addressing this issue, millions of money have been poured in developing artificial substitution devices, from simple traditional cosmetic prostheses that are body-powered and cable-driven systems to highly complex electromechanical devices in research laboratories known as bionic arms. The realisation for prosthetic devices was after World War II due to large number of imputed soldiers returning home. The US Navy Bureau of Medicine and Surgery and the US Army Surgeon General initialised a national treatment program of artificial limbs prostheses replacement. In a research article by *Clement, 2011* men are 67% highly probable of losing their hands. It further states that, this commonly happens during the productive working years at 60% chance between ages of sixteen to fifty-four. Botswana Demographic Survey Report for 2017 illustrates that there are 9, 520 persons with arm impairment. The majority of these impairments mostly occur at industrial workplaces, recreational activities like sports, and day to day automobile accidents. In this study, the clinical importance of existing prosthetic devices is investigated. The prosthetic devices are reviewed in contrast with the unique problems faced by users on the service or product delivery, maintenance and practical implications of the devices are assessed. We found out that users have reported social issues, dissatisfaction, and discomfort more especially in old traditional devices. They find them unsuitable for showing affection because of their unusual shape and feel. And they go well with certain clothing styles.

Keywords—Amputation; Upper limb; Prosthesis

I. INTRODUCTION

A. Background

The human arm is a complex system capable of performing sophisticated movements and gestures that enable us to interact with the environment. Losing hands is the most devastating situation, considering that we use them to manipulate things daily. Before and after surgery patients go through counselling. Henceforth, it is not wrong to say amputation does not only

affect persons physically but both physically, emotionally, socially and psychologically [1].

From Botswana Demographic Survey Report for the year 2017, there are 9 520 persons with arm impairment. In a research paper by *Clement, Bugler and Oliver*, they present that man are the most highly probable group with 67% chance of losing their hands [2]. It further states that, this commonly happens during the productive working years at 60% chance between ages of sixteen to fifty-four. In most cases, the majority of this impairments mostly occur at industrial workplaces if safety is not highly exercised, recreational activities like sports, and day to day automobile accidents.

Age Group	Blind/Vision Impairment				Hearing Impairment				Speech Impairment				Disability				Impairment of Leg(s)				Impairment of Arm(s)				Remoteness		Self-Care				Total		
	Number		Percentage		Number		Percentage		Number		Percentage		Number		Percentage		Number		Percentage		Number		Percentage		Number		Percentage						
0-4	94		126		136		383		720		383		720		383		720		383		720		383		720		383		720		383		720
5-9	1,226	2.7	710	4.2	1,226	13.6	392	1.9	277	0.5	395	3.9	240	3.9	3,024	3.3																	
10-14	2,256	4.9	439	4.0	851	10.7	440	1.7	417	0.8	118	4.0	118	4.0	4,248	4.6																	
15-19	1,748	3.9	1,020	6.1	807	10.7	353	3.1	307	0.6	118	4.0	118	4.0	4,248	4.6																	
20-24	2,045	4.4	876	5.2	675	8.7	799	3.8	401	0.8	118	4.0	118	4.0	4,248	4.6																	
25-29	1,990	4.4	681	4.0	651	8.4	514	2.0	343	0.7	118	4.0	118	4.0	4,248	4.6																	
30-34	2,749	6.2	1,132	6.8	887	11.4	1,056	3.8	354	0.7	118	4.0	118	4.0	4,248	4.6																	
35-39	2,137	5.2	696	3.0	479	6.2	1,220	4.7	979	2.0	118	4.0	118	4.0	4,248	4.6																	
40-44	2,601	5.8	1,031	6.1	312	4.0	1,317	5.0	757	1.6	118	4.0	118	4.0	4,248	4.6																	
45-49	3,330	7.4	846	5.0	443	5.7	824	3.2	437	0.9	118	4.0	118	4.0	4,248	4.6																	
50-54	3,494	7.8	811	4.8	187	2.4	2,050	7.9	600	1.3	118	4.0	118	4.0	4,248	4.6																	
55-59	2,000	4.5	1,042	6.3	130	1.7	1,948	7.5	572	1.2	118	4.0	118	4.0	4,248	4.6																	
60-64	2,721	6.1	552	3.3	234	3.0	1,930	7.3	404	0.8	118	4.0	118	4.0	4,248	4.6																	
65-69	2,720	6.1	1,139	7.1	78	1.0	1,880	7.2	824	1.8	118	4.0	118	4.0	4,248	4.6																	
70-74	2,777	6.2	824	4.9	-	-	2,540	9.7	328	0.7	118	4.0	118	4.0	4,248	4.6																	
75+	10,888	24.2	4,770	28.3	221	2.8	8,146	30.8	1,628	3.4	118	4.0	118	4.0	4,248	4.6																	
Total	46,339	100.0	14,844	100.0	7,744	100.0	26,118	100.0	9,520	100.0	9,520	100.0	9,520	100.0	4,248	4.6																	

Figure 1: Distribution of population with disabilities by age, source - <http://www.statsbots.org.bw/sites/default/files/Botswana%20Demographic%20Survey%20Report%202017.pdf>.

Tons of money have been invested in rehabilitation engineering to assist individuals with disabilities and aid physical and psychological recovery of lost limbs and/or have defects in their bodies [3]. The realisation of the need for these artificial limb systems was after World War II. The US Navy Bureau of Medicine and Surgery and the US Army Surgeon General initialised a national treatment program of artificial limbs prostheses replacement [4].

Although many prosthetic hands have been proposed and developed, similar research papers have highlighted that most patients prefer traditional hook devices or other simple mechanism as terminal devices - see [5, 6, 7, 8]. Size, weight, appearance and power requirements and other not stated limitations are still imposing a challenge in methods of actuation and degrees of motion in both Externally powered and Body powered prosthesis [9].

B. Purpose of Study

In this paper, we describe the design of a bio-inspired Body power mechanical hand that requires a single actuator and successfully grasp and pick object. Favourable properties of the device include

- Is 3D printed, which offers opportunity for scalability, simple and quick edits, rapid manufacturing processes and more
- The hand resembles the human arm when under-actuated. its is not stiff nor loose.
- needs a single actuator
- works with no need for sensory feedback

The design of the arm start with research work from literature on understating the arm as a biological system, amputation and the clinical significance of artificial limbs. Their follows the designs of our fingered hand.

II. METHODS

In this chapter we study the biomechanics of the hand from both visual aspect and anatomical viewpoint when grasping. We also look into amputation and the use of prosthesis as a method of replacing the impaired hand.

A. The Human Hand

In this section the authors analyse the hand from an anatomical and functional viewpoint, and graphical simulations of the hand, it is essential to understand the biological system of the hand to coordinate the hand gestures. The hand is a prehensile, multi-fingered appendage extending the forearm [10]. It combines mobility, muscle strength, dexterity, and sensitivity. Capable of being expressed into several grips when grasping an object. These grasping mechanism is made all possible by coordination of several pairs of antagonistic muscles to control the fingers' gestures. To fully appreciate the interplay of this muscles, it is important to appreciate and understand the movements at each joint and, the anatomical relationships, actions of the tendons and muscles acting on those joints.

Each finger has three joints:

- Metacarpophalangeal (MP or knuckle) joint between the metacarpal and proximal interphalanges,

- Proximal interphalangeal (PIP) joint between the proximal and middle phalanges, and
- Distal interphalangeal (DIP) joint between the middle and distal phalanges.

This joints allow the fingers to flex to different gestures when picking and/or grasping an object. The most common are

- **Power grasp** – mainly used for holding objects by wrapping the fingers around the object and pushing it against the inner part of the palm, with counter-pressure from the thumb and the hand position is static. Such grips includes cylindrical grip, spherical grip and lateral prehension (thumb is adducted).
- **Precision grasp** – the object is held between the tip of the index finger and thumb, and usually supported by the first digit of the middle finger. The hand's position is dynamic. Such grips include palmar prehension (pulp to pulp), tip-to-tip, and lateral prehension (pad-to-side; key grip).
- **Hook grasp** – used to suspend or pull objects.



(a) cylindrical grip

(b) spherical grip

Figure 2: Power grips [11]



(a) tripod grip



(b) tip-to-tip grip



(c) palmar grip

Figure 3: Precision grips [11, 12]

Although the terms grasp and grip can be used interchangeably, it is important to differentiate the two (2) words. The first difference is that, grip is to hold or seize an object in the hand while grasp is the action to grip. As of other

sources of information, there are mainly two (2) types of grasps. The power grasp and precision grasp. In this paper we recognise the hook grasp as the other type as it can have many gripping positions as well as the involvement of other fingers while holding objects.

In the precision grip the thumb is abducted in both the metacarpophalangeal and the carpo-metacarpal joints, whereas in the power grip both joints are adducted [13]. The power grip is the strongest when the hand is held dorsiflexed, the combined fingers form one jaw of the clamp with the palm as the other jaw. The thumb in the adducted position is pressed with the pulp surface against the object to be grasped, and this, according to Napier, introduces an element of precision into the power-grip complex, Landsmeer continues. The thenar muscles are used in all forms of power grip except hook grip [14].

The human hand consists of two types of muscle groups which are, extrinsic muscles and intrinsic muscles. The former extends to the forearm while the latter are within the palm. Extrinsic muscles are made up of the long flexors and extensors that coordinate the index, middle and finger they are the thenar (thumb) and hypothenar (little finger). The movements of the fingers except the thumb are based on interplay of several muscles. Although, the thumb and the thenar and hypothenar have intrinsic muscles they also have extra extrinsic muscles to serve other purposes that add more favourable capabilities.

B. Amputation

Amputation is the accidental or surgical removal of a body part. Upper limb amputation as an example, commonly are the result of a traumatic injury but may also be a result of a planned operation to prevent the spread of disease in an infected finger or hand. In the least cases, amputated limbs can be replanted (reattached). However, in most cases, surgical replanting may be impossible and advisable that the patient is denied replanting due to medical reasons and complications such as rejection or a spread of disease. Other reasons include, amputated part could be chronically painful, stiff, and/or the patient having an abnormal or absent feeling.



Figure 4: Upper limb extremity amputation levels, source-
<https://www.prostheticsindia.org/wp-content/uploads/2018/10/amputation-types-upper-limbs.jpg>

There are different kinds of arm amputation and people can be amputated due to a number of reasons. The most common include:

- Cancer
- Birth defects
- Cardiovascular diseases, particularly from diabetes or peripheral arterial disease
- Injury (for example, from a motor vehicle crash, work-related accident, or military combat)

Before surgery, the surgeon examines the hand. Often they do imaging like X-rays or others to assess the part. The type of amputation will depend on the part and the amount of tissue being removed based on the extent of the injury and health of the remaining part.

During surgery, the surgeon closes the wound of the amputated area by shortening the bone or tendon so that there's enough soft tissue to cover the bone and rearranging the skin to cover the wound. Recently, in more complicated and sophisticated surgeries, the surgeon may shape the stump to fit a prosthesis later.

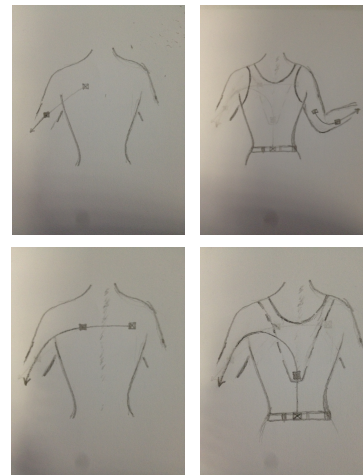


Figure 5. Human force harnessing points and architectures

C. Prosthesis

The evolution of robotic systems has formed highly specialised artificial limb devices to address amputation and save humanity. These bio-inspired technologies are applied in the neuroscience field to design prosthetic implantable limbs that resemble real limbs as in touch, control, and appearance [10]. This device is called a prosthesis. The prosthesis type will depend on the location and length of the stump, functionality, lifestyle needs, and the most notifiable, appearance. They

should enable a person to perform daily activities independently and comfortably. Quite a number of reasons could be drawn from the use of the devices by patients. They restore the length of the partially amputated area, allow the hand amputee to stabilise and hold objects.

At best, a prosthesis may enable the patient to function as well or nearly as well as before the amputation. Successful use of prosthesis depends on a patient's medical conditions, physical & cognitive capabilities, characteristics of the amputation stump, and how well the prosthesis socket fits and connects to the body.

There are two types of modes of controls so far; body-powered (cable transmission) and externally-powered (mainly electric motor driven). These devices are mostly manufactured and used in the western countries and the cost of an externally-powered prosthetic hand ranges from \$4,000 to \$20,000; depending on the mode of control. [4, 15, and 16] states that 90% of upper limb impairment is currently using body-powered prostheses due to their simplicity, inexpensiveness, functionality, reliability, and sensory proprioceptive feedback of shoulder motion harnessing and the tension cable transmission. However, chunks of money are invested in externally-powered devices. Thus, this leaves an enormous gap between the two devices.

Quite a number of control mechanisms can be formulated from body motions. As illustrated in Figure 1. However, at higher levels some of the control architectures might be not good enough or absent to control the artificial hand. For instance, elbow movements are absent in above-elbow and shoulder disarticulation, and some of the body motion if not all maybe insufficient to operate the prosthesis. At present, the most common bio-mechanical control source is the shoulder motion [17].

D. Clinical Significance

The final stage after laboratory testing and evaluations is the prescription of the devices in the sense of clinical use to patients. The prescription is in the means that they are purchased by patients, fitted with a training program and maintenance for its use. In short, the fore-mentioned points are clinical significance requirements for a prosthetic device to be legally recommended to patients.

Some difficulties come along with providing prostheses and developing their clinical significance. Artificial upper-limbs, BPs, and EPs have a low record of usage by patients due to several factors. Limbs may be rejected because of stigma and/or psychological trauma from amputation, too heavy, uncomfortable, and too unreliable to control. Whatever the rationale to the rejection may be, the solution is to emphasise a close interaction between engineers, patients, surgeons, prosthetists, and physical therapists in the design and development of prostheses devices. In other words, success with a prosthesis is most likely to occur when the clinical team

involved has many different types of professionals, depending on the person's needs. For more complicated cases, the team may include a psychiatrist, occupational therapist, social worker, psychologist, and family members. A prosthetist's expertise is to evaluate the amputee's(stump) overall functional capabilities and develop a prosthesis treatment plan (covering designing, fitting, fabricating), adjusting the prosthesis, providing lifetime follow-up care to maintain the prosthesis, and provide advice and instruction on care.

Prosthesis fitting requires is a specialised skill. It can be hard for people to make the physical and mental adjustments necessary to function with the prosthesis. Thus, the whole process of selecting and adjusting components and assessing the overall prosthesis function is challenging and takes significant time. Not all patients are candidates for all types of prostheses. Lastly, developing prosthetic devices for clinical use with commercial considerations is also a heavy task to be dealt with. The field for this kind of technology is limited and specialised. For instance, a large scale production means more of the products with higher capital investments that will end up not being utilised. Thus, in the present-day, the method of production and delivery is based on patient requests for the prostheses.

Privacy and legal concerns of the devices are such that the security personnel does not ask people to remove a prosthesis. Otherwise, a special place should be arranged for unfitting the device as some of the clothing has to be removed to unfit a prosthesis. It is recommended that a person writes a letter describing his prosthesis more especially when traveling by air. The evolution of robotic systems has formed highly specialised.

IV. BIO-MECHANICAL HAND DESIGNS

In this section of this research study we describe and formulate the architectures of our bio-mechanical robot as it is designed as a prosthetic device for amputees. Before that, it is the authors intention to highlight that the study will benchmark and improve the transmission, design methods and the aesthetics of the existing researches. Thus, rather than reinventing the wheel, these models will be the base for the designs.

Design objectives

- **Appearance** - should resemble the general form of the human hand
- **Control** - A simple voluntary closing mechanism to control the four fingers with less input force
- **Manufacturability** - Affordable low cost process and scalable for different patients as compared to other prostheses
- **Weight** - lighter in weight than current prosthetic hands

A. Fingers

Understanding the human arm was the starting point for the entire design process. We studied visually the handling and grasping process of a different object. The human hand was simply sketched to identify different locations of various joints and the possible range of motion. The fingers can be spread apart sideways and rolled slightly culminating in an impressively large amount of total degrees of freedom. Fortunately, to perform the majority of common gripping tasks, only a small amount of motion is required. When grasping, the human finger achieves a con-formal adaptive grip by bending the knuckles to enclose the object in between the fingers and the palm.

The implementation of the movements of the articulations in the arm is based on some mechanisms to flex, extend or fold fingers and other joints like wrist and/or elbow. Basically, the preferred ones are; bar-linkage transmission and/or tension cable transmission. Moreover, the mechanisms can optionally be fitted with spring or elastic rubber string return mechanism added to each articulation. The template is designed so that author affiliations are not repeated each time for multiple authors of the same affiliation. Please keep your affiliations as succinct as possible (for example, do not differentiate among departments of the same organisation). This template was designed for two affiliations.

1) *Bar-Linkage Mechanism*: If we study the finger anatomy from the fingertip to the last knuckle. That is, the joint between the metacarpals and proximal phalanges joint to the distal phalanges tip, it can be noticed that each finger has three links. Therefore, the first opportunity for simplification comes from treating the distal phalanges and intermediate phalanges as one fixed link as opposed to two separate links joined by the last knuckle. Looking at the hand from the side view, it can be noticed that the human finger rotates approximately 90° from full extension to full closure. Similarly, the second knuckle joint also rotates approximately 90° at this time. It was concluded that the two joints move approximately at the same rate in a 1:1 ratio. Therefore, that realisation opened up many mechanical possibilities for simple linkages which would allow for the base finger to be rotated actively while at the same time passively linked to the first joint.

2) *Cable transmission* : The idea of this mechanism is motivated by the human hand actuation mechanism. To achieve the grasping and releasing of objects, two pairs of systems must work together. It can either be tension cables with spring return, tension cables with elastic cord return or bidirectional tension cables for finger flexion and extension. The mechanism consists of force transmission cable inside a stationary hose. This mechanism reduces the weight of the hand and it's easy to implement.

B. Design Optimisation

As Childress has pointed out [17], positioning the prosthesis in the world space is the main goal to be achieved in prosthesis control . Designing and manufacturing artificial hand is not to duplicate the human hand but to have a device that enable the user to interact with the environment in the real world.

IV. RESULTS AND DISCUSSIONS

The results of this work have been encouraging. The bio-mechanical hand has satisfactory appearance and control. The movement of the fingers appears realistic and input force are minimised for ease control.



Figure 6: The prototype during experimental testing, grasping an object

IV. DISCUSSION AND CONCLUSIONS

The bio-mechanical hand is modelled from PLA, acrylic and wood that were selected based on weight, aesthetics and toughness. The material are light in weight and impose an aesthetically appealing appearance after finish. Using 3D printing manufacturing technology allows for easy product prototyping and inexpensive mass production for clinical fitting. Although the palm is made of wood, the device can be wholly 3D printed to give realistic appearance with rubberised soft 'skin', improve grip and avoiding the need for cosmetic glove.

The hand is compliant when under actuated and resembling the natural posture of the hand but becomes rigid when actuated. These results in a stiff and stable grip. All the fingers are actuated by a single tension cable (although more may extend their capabilities even further). Consequently, these allows the device to be a modular prosthetic terminal device which can be fitted to either a body- powered or externally-powered prosthesis.

Experiments to evaluate the performance of the body-powered prosthesis are discussed on the previous section. Although the designs closely resemble the human factor form, the designs can further be improved as in design and material selection for prototyping and manufacturing.

Although the design some how are close to resemble the human factor form, the design can be further improved as in design and material selection for manufacturing and

prototyping. The control for the artificial limb has to be smooth with low impedance. This is because the response of BP devices is determined by the mechanical impedance when interacting with objects in the surrounding. When grasping, the middle responds better than other fingers. This is because the tension cable mechanism align with the middle finger. With other fingers, there is slack within the finger tension cable and the fingers. Consequently, reducing performance of the overall prototype.

It further was noticed that the finger as well as the palm lack a firm grip. If the cabling mechanism is not pulled firm enough to grasp the object, it will fall. Comparing this to the human flesh, the PLA plastic used to manufacture the fingers is hard. When the object is held in the hand, the muscles deform and try to take the shape of the object. For this phenomenon to work in our model, a different filament is proposed. For instance, thermoplastic elastomers (TPE) are a typical materials that the author suggests. They have different range of flexibility, ranging from partially flexible like a car tire but others can be elastic and fully flexible like a rubber band.

Despite the limitations imposed by the hand, we believe that a prosthetic terminal device with design features of the artificial hand in this research paper has the potential to be used as a terminal device in many robotic manipulator system as well as prosthetic devices.

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