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A novel 3 -D printed wrist powered upper limb prosthesis using whippletree mechanism

K.P.L. Kumarage, W.H.S. Wickramarathan, V. Madhushan, V. Mugilgeethan, R. Neethan, T. Thanihaichelvan

Abstract- This study focuses on the development of a 3-D printed low-cost novel solution for upper limb amputees in Sri Lanka. Prosthetic devices available in Sri Lanka are declined by most patients with trans-metacarpal amputation due to the high cost and discomfort. Worldwide the 3-D printing technology has been recognized as a convenient solution for prostheses owing to its customizability and low cost. The adaptive grasp functionality in mechanical prostheses is important to effectively utilize the limited angle of the wrist. Wrist motion of healthy individuals and the limitations in wrist flexion occurring after amputation were studied. With the findings, a novel design was developed incorporating a modified whippletree mechanism. The prosthesis was printed and tested for adaptive grasp and comfort. In this testing, whippletree mechanism was used to improve the adaptive grasp through proper force distribution and a flexible material was introduced for wearable comfort. It was found that this kind of prosthetic hands will help the amputee to grasp complex shaped objects while providing good comfort.

Keywords: Trans-Metacarpal amputation, 3-D printing, Adaptive grasp, Whippletree mechanism, Prosthesis

1. Introduction

A prosthesis is an artificially made alternative for a limb lost through a congenital disability, accident, illness, or wartime injury. The primary function of a prosthetic device is to provide assistive support for patients with upper or lower limb amputation. The upper limb amputation can be categorized into seven levels based on the level of amputation [1]. They are partial hand amputation, metacarpal amputation, wrist disarticulation, below elbow amputation, elbow disarticulation, transhumeral amputation and shoulder disarticulation. In the northern part of Sri Lanka number of people suffer from upper limb amputation due to diabetes, birth defects and civil war [2]. Due to high initial cost and maintenance costs of advanced functional prosthesis amputees avoid their usages [3] [4]. One of the main prosthetic suppliers in the Northern Province is the Jaffna Jaipur Center for Disability Rehabilitation (JJCDR). JJCDR provides services and aesthetic prosthesis developed using Jaipur technology and polypropylene technology. From the time the organization was established in 1987, they have fitted 268 upper limb prosthesis and 6737 lower limb prosthesis for patients until May 2016 [2].

According to a study carried out involving American citizen, around 541,000 Americans suffer from upper limb amputations and this amount will be doubled by the end of 2050 [5]. Early methods of fabricating prosthesis limited its functionality and ability for customization. With the development of the rapid prototyping, specifically 3D printing in the last few decades the fabrication of prosthetics has become much more manageable. Three-dimensional printing is an additive manufacturing technique. Products are built up layer by layer instead of removing material from a large piece of material [6]. Using 3D printing made prosthetics customizable and lightweight while increasing functionality [7]. Additional to the advantages, there are also a few disadvantages of 3D printing as well, such as 3D printing is only possible with the limited number of materials. Acrylonitrile Butadiene Styrene (ABS) or Poly Lactic Acid (PLA) are considered as the most suitable material for 3D printing of prosthesis, focusing on the factors of cost and availability, toxicity, biodegradability and comfortability [8]. The functionality of the prosthetic hand is essential to the users to perform their day to day activities and their special requirements. Using a proper mechanism that can achieve the required functionality is one of the major concerns. The human hand is a unique tool, finding an alternative to it is very contrary.

Mr. K. P. L. Kumarage Undergraduate, Faculty of Engineering, University of Jaffna.

Mr. W. H. S. Wickramarathan Undergraduate, Faculty of Engineering, University of Jaffna.

Mr. V. Madhushan Undergraduate, Faculty of Engineering, University of Jaffna.

Mr. (Eng.). V. Mugilgeethan B.Sc. Eng. (Hons) (Ruhuna), Lecturer of Mechanical Engineering, Department of Interdisciplinary Studies, Faculty of Engineering, University of Jaffna.

Mr. (Eng.). R. Neethan B.Sc. Eng. (Hons) (Jaffna), Postgraduate student, The State University of New Jersey, USA.

Dr. (Mrs.) T. Thanihaichelvan B.Sc. (Hons) (Jaffna), Ph.D. (UM, Malaysia), Senior Lecturer, Department of Interdisciplinary Studies, Faculty of Engineering, University of Jaffna.

Prosthesis can be categorized into two types which are body powered and externally powered. A body-powered prosthesis uses a cable and harness system to transfer a patient's hand movement to the prosthesis. It requires a high muscle force to perform the tasks. The most affordable prosthesis are operated using string networks or using lever mechanisms. Common use is the string mechanism, which is less complicated, easy to repair and of less maintenance cost [9]. An externally powered prosthesis uses an external power source to activate the operating mechanism in the prosthesis. This reduces the use of the residual limb from exerting effort on the prosthesis to operate.

Commercially available prostheses lack certain features, like adaptive grasp and ability to wear without irritation for a long time (*i.e* comfort). Adaptive grasp is the ability to operate each independently with the other finger. In order to overcome these problems, 3D printing has shown a promising path in developing quick and customizable solutions using modern technology [10]. This research is mainly based on 3D printed prosthesis, where prosthesis can be improved with less complex parts to enhance the functionality while maintaining relatively low cost. In most 3D printed upper limb prosthesis where string mechanism is used, they do not have the ability to provide adaptive grasp which is very helpful when holding nonlinear objects like balls. The purpose of this study is to improve the adaptive grasp mechanism used in mechanical prosthesis to effectively utilize the limited angle of wrist to produce enough gripping force for better functionality. The typical angle of motion of the healthy person, the limitations, and complications occurring were found and the effects of trans-metacarpal amputation to the motion of the wrist were analyzed. According to the findings the design of the prosthesis was started using Computer Aided Designing (CAD) software and necessary improvements needed were taken into consideration during the design phase of the new prosthesis and the mechanism. The proper material was selected to be used in the 3D printer and the prosthesis was printed and tested for adaptive grasp and comfort. Whippletree mechanism was used to improve the adaptive grasp through proper force distribution. It was found that this kind of prosthetic hands will help the amputee to grasp complex shaped objects which cannot be grasped by some commercially available prosthetic devices.

2. Procedure

2.1. Materials

The prosthesis was printed by Ultimaker 3 Extended three-dimensional printer (Netherland) using fused deposition modelling (FDM) technology. According to the comfort and strength of the materials, various materials were used to print the distinct parts of the upper limb prosthesis. Polylactic acid (PLA) was used to print the palm part and fingers. PLA is relatively cheap, biodegradable and does not release harmful nanoparticles during printing [8]. Therefore, PLA was used in the palm part, fingers and hand socket. Due to the high strength in PLA, the structure can withstand any tensile stresses formed during the drop. As prosthesis tend to drop during handling or removing, so high impact strength is required. TPU 95A is a type of flexi material that was used to print the inner part of the hand socket. The TPU 95A has an exceptional wear and tear resistance, high impact strength and up to 580% of elongation at break [11]. This material has also good corrosion resistance to many industrial oils and chemicals. Nylon fishing lines of diameter 0.53 mm and 0.1 mm were used in the prosthesis for the force transfer from the wrist, where 0.1 mm nylon was used in fingers to allow high flexibility and 0.53 mm nylon was used to connect the palm to hand socket where higher force is necessary to transfer.

2.2. Prosthetic design

The most important part when designing a mechanical limb for the trans-metacarpal amputee is that their ability to use the wrist joint and musculature to be retained after the amputation.

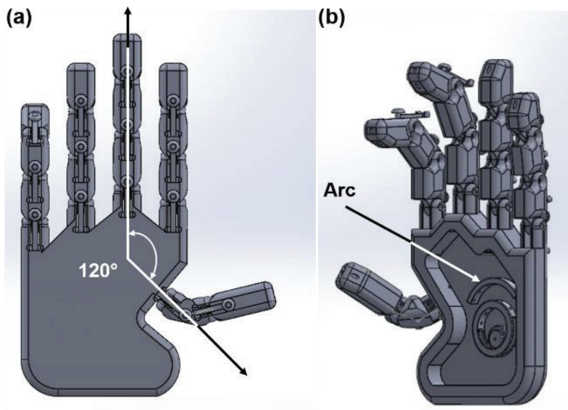

Figure 1: CAD design of (a) top view of the palm, and (b) palm side with proper working mechanism

Because this design mainly depends on the motion of the wrist for actuation. The preliminary CAD design is shown in figure 1, where the palm surface is flat. All four fingers except the thumb are positioned in the same plane, where the thumb is placed 120^0 apart from the plane of the other fingers. On the palm side, there is an arc with five holes to guide each thread from fingers to the mechanism. This also prevents the lateral movement of the mechanism. The attachment position of each finger is designed to imitate the human finger placement.

In the preliminary palm design, index finger, middle finger, ring finger and pinky finger have three segments which will give 3 degrees of freedom for each finger. The thumb has only two parts and gives 2 degrees of freedom to the system making of 14 degrees of freedom. An each finger segment has a small tip on the back that prevents the fingers from turning to the opposite side. Figure 2 shows the parts of the finger and the maximum flexion angle of an independent finger. There is a hole inside the finger segment to provide a path for the string and small headers are available on the top side to attach the elastic material. An each finger is designed to achieve a maximum flexion of 98^0 and operated only in one plane.

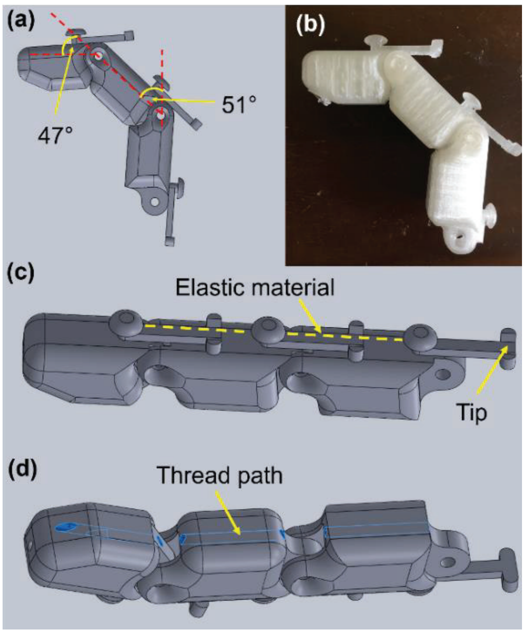

Figure 2: (a) CAD design of finger shows the finger flexion angle, (b) Fabricated finger, (c) CAD design of finger with elastic material fixtures, and (d) thread path

The hand socket is designed to accommodate the residual limb which shown in figure 3. It is equipped with a nylon thread fixture and a tension adjuster. In the tension adjuster, there is a plastic rod with a hexagonal head that helps to keep the turn angle constant at all times. In the front, there is a guide hole which is used to prevent damaging the thread from continues rubbing during continuous operation. It is also equipped with holes to accommodate the velcro straps which is used to tighten the prosthetic around the residual arm. There are two places to fix the palm to the socket using two pins (Figure 3(a)).

The design in figure 4 reveals the palm structure which has a socket to place the residual part of the hand. Here, the force distribution mechanism is located on the top side of the wrist socket. There is a thread guide to make sure that all the threads connected to the force distribution mechanism are parallel to each other. This design has 14 degrees of freedom as the preliminary design in figure 1. As the next part of the design improvement the pinky finger and the index fingers are allowed to rotate around their pivot points. This increases the total degrees of freedom to 16 while both fingers are allowed to move through an angle of 10^0 to each side.

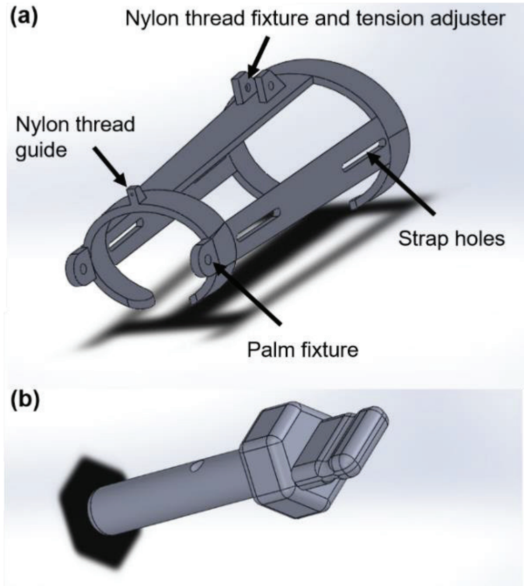

Figure 3: CAD design of (a) hand socket and (b) hexagonal tension adjuster

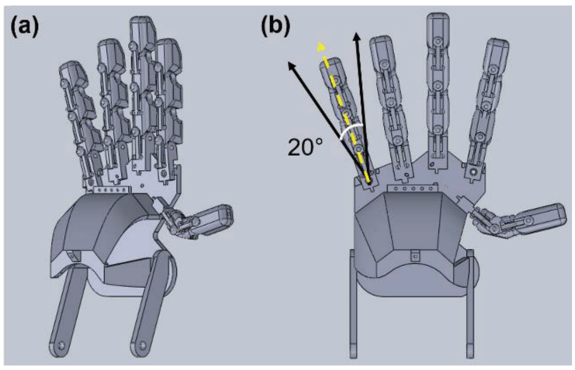

Figure 4: CAD design of (a) palm socket, and (b) lateral movement of fingers

As shown in figure 5(a), a whippletree mechanism modified into a ring and a disc to transfer the force from the wrist to the fingers. This is designed taking in to consideration that when an object under force is allowed to move in a constrained space will adjust itself to distribute supplied forces equally. Here the ring has five holes. An each hole is used to connect a finger to the wrist, where it is allowed only to have linear motion. The disc is designed to sit inside of the ring and is connected to the hand socket using a string. It is allowed only to have circular motion inside the ring. In the further modification process ring and disc whippletree mechanism was developed into half circular ring to allow consecutive fingers to connect together as shown in figure 5(b). This half circular whippletree mechanism part was further modified to a lever system as shown in figure 5(c), to allow further customization to the user. Although the operating mechanism is the same as in the design as mentioned earlier, this configuration enables the control over the force distributed over each finger based on the positioning of the holes for the string.

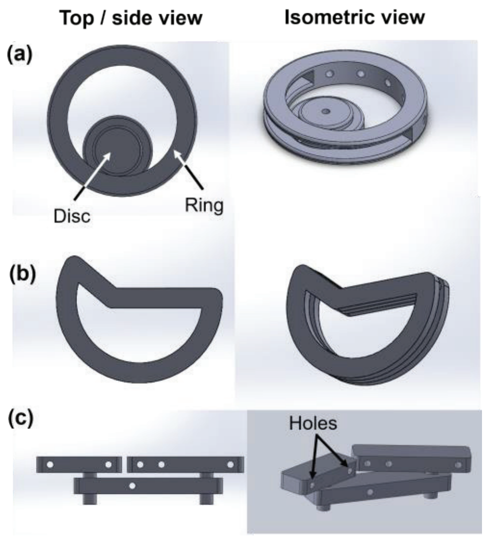

Figure 5: Different type of whippletree mechanism used for improving functionality (a) Ring and disc shaped, (b) Half circular ring, and (c) lever type

2.3. Characterization

2.3.1. Force Test

The first test was to measure the space needed inside the palm to fix the whippletree mechanism so that maximum flexion could be achieved. Therefore, the palm and fingers were first fabricated and assembled. Afterwards, a scale was drawn in millimeter was used to measure the length of string needed to move to gain maximum flexion. An each finger was operated using a spring balance to measure the force needed to fully achieve full flexion in the finger.

2.3.2. Adaptive Grasp Test

To test the adaptive grasp of the prosthesis, a set of different shaped objects were used. Each of these predefined shapes as shown in figure 6, were grabbed by the prosthesis. Then each shape was loaded with weights from 1 N to 20 N and the maximum weight the prosthesis could hold was measured for each shape to determine which shape can hold the highest weight. During this test it was also observed regarding which fingers receive the least force.

A - Wide Bar
B - Narrow Bar
C - Sphere shaped Bar
D - Variable width Bar
E - Constant width Bar

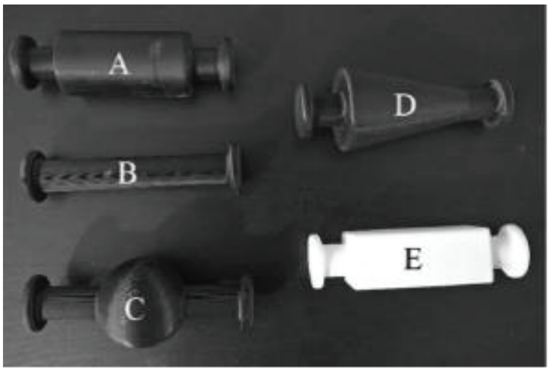

Figure 6: 3D printed test specimens

3. Results and Discussion

3.1. Design and Evolution

The overall design is a wrist controlled, body powered and voluntary open 3D printed prosthetic arm as shown in figure 7. The design resembles the approximate geometry of a human hand to reduce the gap in aesthetic differences. This was done as other designs with claws or fork segments instead of fingers could inconvenience the user and reduce the ability for adaptive grasping.

The user can open and close the entire hand by the transverse movement of the wrist. All the fingers in the prototype bend powering the grip by closing motion or turning motion of the wrist and are released by the unbending or releasing motion of the wrist. The power for the grip is transferred using a nylon thread running through the lower part of the finger segments which are designed with narrow pathways just enough to run the nylon thread and the grip is released by elastic material positioned at the upper part of finger segments. The tension of the elastic materials (rubber bands) can be adjusted by changing the material and the number of bands being used. The nylon thread used as the flexor in the prototype is of 0.1 mm diameter which can withstand 58 N of tension, and a rubber band of 1 mm diameter actuates the releasing mechanism of the grip, that finger is shown in the figure 2.

The designing process was done in three stages,

Stage 1- palm part

Stage 2- finger segments

Stage 3- arm socket

The geometry and dimensions were acquired by selecting an average built human hand. Those dimensions were used to develop the conceptual design into a 3D model using a Computer Aided Designing (CAD) software (SOLIDWORKS Education Edition 2014/2015). The individual designed 3D parts were sliced using a slicing software (Ultimaker CURA 4.1.0) to produce the G-Code file to be used in Ultimaker 3 Extended 3D printer and were fabricated using Polylactic Acid (PLA) filaments.

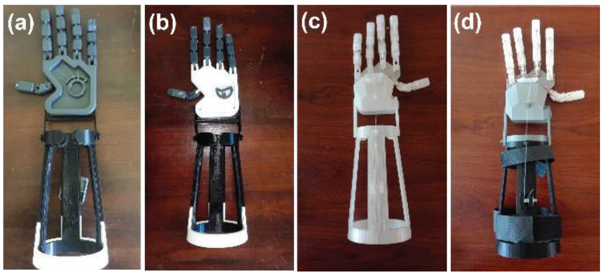

Figure 7: 3D printed upper limb prosthesis with various types of mechanism used (a) Preliminary prototype, (b) second prototype, (c) third prototype and (d) final product

The preliminary design (Figure 1) of the palm part was done by giving the priority to the actuating mechanism of the grip which in this case is the whippletree mechanism. After testing the reliability and the performance of the actuating mechanism, the palm part was remodified to facilitate a compartment to place the residual hand of the user. The hand of the prosthesis has five fingers. Among them, the thumb was designed as two segments which will finally give 2 degrees of freedom. The middle and the 4th finger were designed as three segments offering 3 degrees of freedom each and the index and 5th finger were designed as three segments giving 4 degrees of freedom each. The overall arm has totally 17 degrees of freedom with consideration of the wrist motion. After a few grasping tests, there was an immediate problem that could be noticed with the fingers. This was due to that they were moving in parallel planes. The human hand and fingers have the ability to rotate around pivotal points giving extra degrees of freedom to each finger. To incorporate this in the prototype we have provided this motion only to the pinky finger and index finger as a pivotal rotation of all fingers will compromise the rigidity of the grip. We also have made a small inclination angle between middle finger and ring finger to allow motion in an entirely different plane in a different angle. Thumb is positioned in 120^0 as shown in figure 1 to mimic the metacarpophalangeal joint of the thumb. This considerably improved the ability to grasp objects.

The final design can be rescaled approximately for each user based on measurements of the residual limb before printing.

3.2. Operating mechanism for adaptive grasp

Adaptive grasp is the automatically adaption of the fingers to the shape of different objects. To obtain this independent movement in each finger, the most suitable mechanism is the whippletree system. This is commonly used in horse carriages and windscreen wipers, to prevent resultant motion in a different direction rather than desired direction due to the difference in forces. A whippletree is a mechanism to distribute force evenly through linkages. It consists of a bar pivoted at or near the center, with force applied from one direction to the pivot and from the other direction to the tips.

Directly implementing this system on the prosthetic hand is not suitable because of the shape of the prosthetic and due to less availability of space. Therefore, a simplified whippletree mechanism was required to fit it on the prosthetic. As a result, the simplified whippletree mechanism was printed and as shown in figure 5(c).

This part was designed as three different parts, where it can be customizable according to the user's ability to bend the wrist. Because from the literature review, it was cleared that flexion of the wrist differs from user to user. All parts were printed using PRO® PLA. After fixing this part on to the prosthetic, we could achieve the whippletree effect. This design was able to withstand impulse motion and sudden drop of the prosthetic device and is easy to repair by the user. During the adaptive grasp test, it was found that the sphere-shaped bar was not able to be lifted by using the prosthesis. Main reason for not being able to lift was that the shape of the palm restricts it from grasping round shaped objects. There were also some difficulties in lifting the cone shaped bar mostly due to circular shape, but due to linear profile of the curved surface it was able to grasp it after a few tries. All other three bars were able to be grasped without any difficulties. At the end it was concluded that due to the flat surface of the palm round objects cannot to be grasped properly.

3.3. Thread placement

A connection of the nylon wires to the whippletree mechanism is very important in the prosthetic device because it decides the forces needed to operate. According to the previous studies conducted in the field of prosthetic devices, in order to operate the prosthetic device with less displacement, the low mechanical advantage pulley principle has to be used. In low mechanical advantage pulley system when a higher force with small displacement is given the resultant object will move twice the distance as the input force. Therefore, this method is used when connecting fingers to the whippletree mechanism. Thread placement is shown in the figure 8. In here two consecutive fingers were connected together. One connection is connected to the whippletree and it is sent to the finger and return back to the whippletree to connect the next finger. After modifying the ring and disc whippletree mechanism into lever mechanism incorporating this thread placement was extremely difficult for the amputee to operate. Therefore, single thread was used to connect the fingers.

4. Conclusions

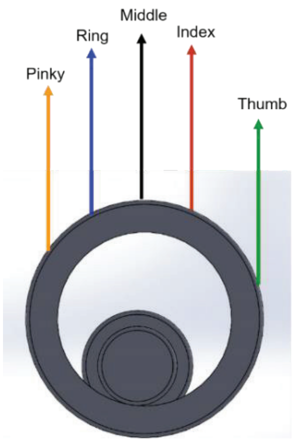

Figure 8: Thread connection in whippletree mechanism

The light weight and improved functionality of upper limb prosthesis was successfully developed by low cost 3D printing technology. PLA materials was used to fabricate the entire prosthesis. To incorporate adaptive grasp whippletree mechanism used as the fundamental theory to develop the lever type mechanism. As an overall manufactured prosthetic device is capable of achieving the proper flexion angle for better grasp of different shapes of objects including objects with non-linear surface profile. Tension adjuster was incorporated in the hand socket to adjust the tension of the operation cable according to the user’s preference. There is a limitation for this device as trans-metacarpal amputees can only wear it. Future work includes developing a prosthesis that can be used by metacarpal amputees.

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