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Investigation on life-like 3D printed prosthetic hand

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ABSTRACT. *A prosthetic hand is an artificial device which is designed for disabled people who lose their hands through trauma or congenitally. In recent decades, unaffordable price, high weight and bad appearance of metal-based prosthetic hands cannot meet the requirement of customers. Owing to the development of 3D printing technology, designing sophisticated mechanisms for a life-like 3D printed prosthetic hand is meaningful. In this project, life-like appearance of prosthetic hand is produced by 3D scanning technology. And all the designs are done within the solid hand file generated by 3D scanning machine. Moreover, two prototypes which have four different mechanisms are printed from flexible materials-Tango Plus. Finally, analysis and improvements done on last prototype demonstrate a functional design.*

KEYWORDS*: 3D scanning, 3D printing, Prosthetic hand*

1. Introduction

As the development of 3D printing technology, it is possible to produce a customized prosthetic hand with fully 3D printed components for specific person. In recent decades, enormous researches and experiments have been done on prosthetic hand. Multi-DoF prosthetic hands such as I-limb hand, SmartHand and HIT/DLR hand have already been developed as commercial prosthetic hands. Nevertheless, the shortages of these metal-based hands cannot be ignored. Unaffordable price, high weight and bad appearance will ruin the user experience of these artificial hands. In this case, designing more sophisticated mechanisms to enhance the quality of a 3D printed prosthetic hand with low cost, low weight and life-like appearance is meaningful. In this project, three prototypes are built to seek the best mechanical structure of a prosthetic hand which can achieve all the project objectives. Problems

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occur in former prototype will be improved or eliminated in next prototype. As this process keep running, a relative sophisticated mechanism is established in last model.

2. Literature review

A prosthetic hand is an artificial device which is designed for disabled people who lose their hands through trauma or congenitally2. A desired prosthetic hand should have similar features and functions to real human hand10. Based on the performance of prosthetic hands, they can be divided into four kinds: cosmetic hand, body-powered hand, electromyography (EMG) prosthetic hand and anthropomorphic prosthetic hand with EMG control10. During the last decade, some multi-DoF (degree of freedom) prosthetic hands with similar functions to real human hand have been developed by some research institutions10. For example, i-limb hand from Touch Bionics has 5 fingers. Each finger is individually actuated by a micro motor which can provide precise direct current3. And these motors are controlled by simple open or close signals generated from two electrodes3. Moreover, a prosthetic hand with 5 actuators and 16 joints has been developed by researchers. The advantage of this kind of prosthetic hand is that it can provide 8 hand postures5. Furthermore, a robotic hand consists of 5 fingers, 16 degrees of freedoms and 40 sensors called SmartHand was designed and produced4. These 40 sensors form a bio-inspired sensory system which make it possible to deliver sensory feedback to customers4. Besides, the low weight (530g) and high reaction speed (closing time 0.5s) of SmartHand help it become a commercial prosthesis. In addition, the HIT/DLR prosthetic hand has numerous sensors fitted with 5 fingers actuated by 3 motors. Plenty of sensors give this artificial hand high capability of self-adaptation8. The prosthetic hands mentioned above all have similar features and performances to real human hand. On the other hand, all of the hands have been utilized as commercial products.

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3. Knowledge gap

Enormous researches have been done on the mechanism design of prosthetic hands. However, some apparent limitations and knowledge gaps cannot not be currently overcome.

For example, the weight of prosthetic hand is difficult to control due to the complex mechanical structures3. And material used to produce the 'skeleton' structure of prosthetic hand is Al alloy. Although 3D printing technology and polymer-based materials have been applied to fabricate modular components which help reducing the weight of prosthetic hand, some shortages will show up. The tolerance of 3D printed components is very low, and the non-isometric properties may limit its development2. Therefore, how to design more sophisticated mechanisms to enhance the quality of a 3D printed prosthetic hand with low cost, low weight and life-like appearance would be a knowledge gap2.

Moreover, choice of 3D printing materials would be another knowledge gap. Currently, the most commonly used materials are ABS and PLA. Nevertheless, some flexible polymer-based materials such as Tango Plus, Tango Plus FLX930 and Ninja Flex could be potential choices to print components of models. But which material is most suitable in this project is a knowledge gap.

4. Design process

4.1 3D scanned right hand

In order to gain the same appearance of real human hands. 3D scanning, a relatively novel technology has been used.

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Fig. 1 3D scanned human hand

A solid hand is shown in Fig. 1, which is a ‘copy’ of real human hand. The original version of this hand contains enormous holes, fracture facets and unconnected curve surface. After repairing operations through software, this virtual hand is ready for further design.

4.2 Curved fingertips

To simplify the mechanical structure of skeleton, every finger will contain two phalanges and two joints. Therefore, distal phalanges and distal joints should be vanished. To achieve this idea, finger tips are curved without destroying their bionic appearance. Plenty of experiments have been done on curve angles to balance the human like outlook and practicability. Finally, the curve angle of finger tips is set as 25 °. Sldprt file of hand with curved finger tips is displayed in Fig. 2.

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Fig. 2 Hand with finger tips curved

4.3 First prototype

Priority to design proper mechanisms for fingers, the hand is ‘cut’ from its centerline. This step makes it possible to modify two parts simultaneously without influencing each other. Which reduces the difficulty of editing changes in design. Fig. 3 shows the separated two parts.

Fig. 3 Front part and back part

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Because of the most cylindroid shape, middle finger is chosen as the testing finger. First of all, a cylindroid hollow with 14mm in diameter is digged inside the finger, which roughly limits the parameters of skeleton. And the skeleton of middle finger contains two phalanges (middle phalange & proximal phalange) and two flexure hinges (middle joint, palm joint). Components of first prototype will be discussed in following paragraphs.

4.3.1 Trapezoidal phalanges

The largest diameter of phalanges is pre-set as 14mm, which is same to the hollow. Considering the fact that machining tolerance of 3D printers will occur during printing process, size of phalanges should be reduced slightly to allow the exist of tolerance. Moreover, inspired by a commercial prosthetic hand in market, mechanical structures of middle phalange and proximal phalange is shown in Fig. 4.

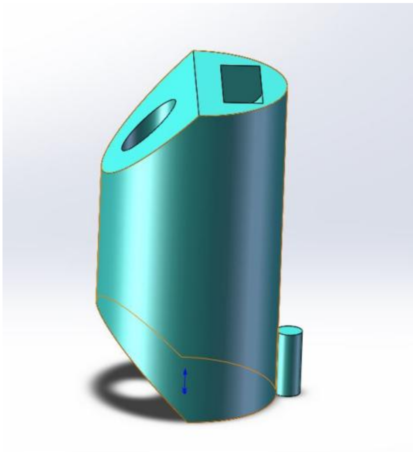

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Fig. 4 Middle phalange and proximal phalange of middle finger

As for eliminated distal phalange, it becomes a part of fingertip. The end of fingertip has similar trapezoidal structure to the other phalanges, which replace the function of distal phalange in initial design. These phalanges and fingertip will form two pair of ‘V’ shape slots after installing operation. And these slots not only ‘tell’ testing finger where to bend, but also indicate the position of joint parts. Besides, holes are drilled through one side of the phalanges to constrain the tendon (string) path. Furthermore, cylinders on the other side of phalanges are designed for assembling purpose. Inspired by snap fit (usually used in plastic products), there will be grooves on back part. So that these cylinders can slide into grooves to constrain the DOF (degree of freedom) of phalanges. Therefore, separated phalanges (middle phalange and proximal phalange) can be assembled easily and steady. Finally, grooves on the top and bottom of phalanges are designed to install reinforce joints. Both sides of reinforce joints are pushed inside the grooves. The Interference fit between reinforce joints and phalanges increase reliability of the whole mechanism.

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4.3.2 Reinforce joint

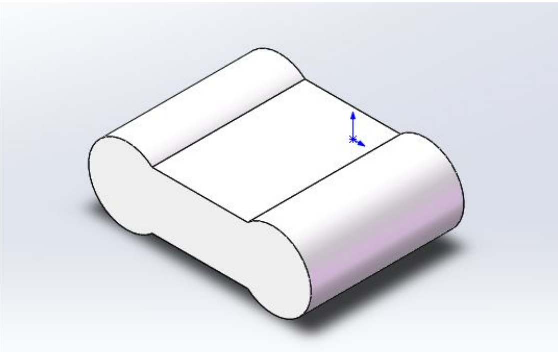
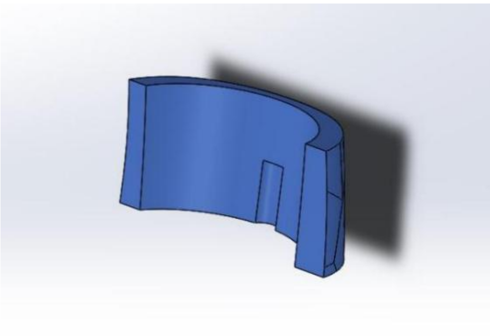


Fig. 5 Reinforce joint

Fig. 5 displays the reinforce joint that applied to connect phalanges. There are two reinforce joints in this design. And their main function is to help the finger rebound after bending motion. Although the flexible characteristic of raw material can achieve rebound movement, reinforce joints are still needed to increase response speed of this system.

4.3.3 Joint parts



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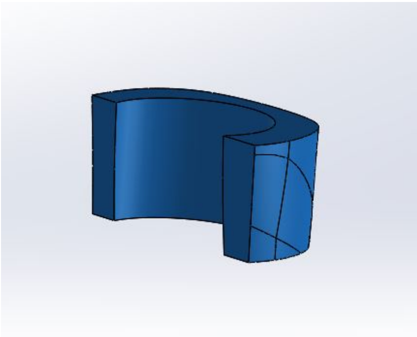

Fig. 6 Parts of first joint

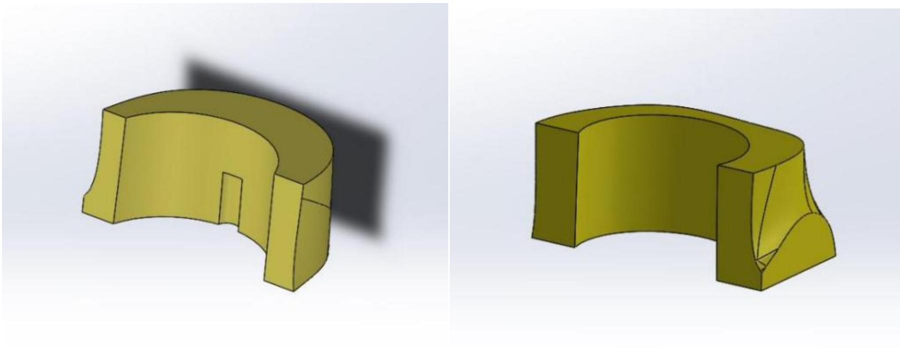

Fig. 7 Parts of second joint

Joint parts were part of middle finger (shown in Fig. 6 and Fig. 7). Due to the requirements of object printer (Objet Connex 350), they are cut off from the front part of hand and the back part of hand. As soon as the joint parts become separated body, they can be printed in material with different stiffness. Within the design of first prototype, joint parts are softer than other components, in which the joint parts of back part are softer than the joint parts of front part. This is because when the finger is bend, joint parts of back part will extend and joint parts of front part will shrink. In this case, material with lower stiffness but higher ductility is more practical for the joint parts of back part.

4.3.4 Files for printing

Only STL files can be recognized by the mating software (objet studio) of objet connex 350 printer. Thus, all the components are converted to STL format firstly. Then, reassemble those STL files based on mechanism design of first prototype in objet studio. Files belong to same assembly part will be allocated to one group. There are two groups (assembled back part, assembled front part) and four separate parts (middle phalange, proximal phalange, two reinforce joints) included in printing queues. Fig. 8 and Fig. 9 show the assembly groups of this model.

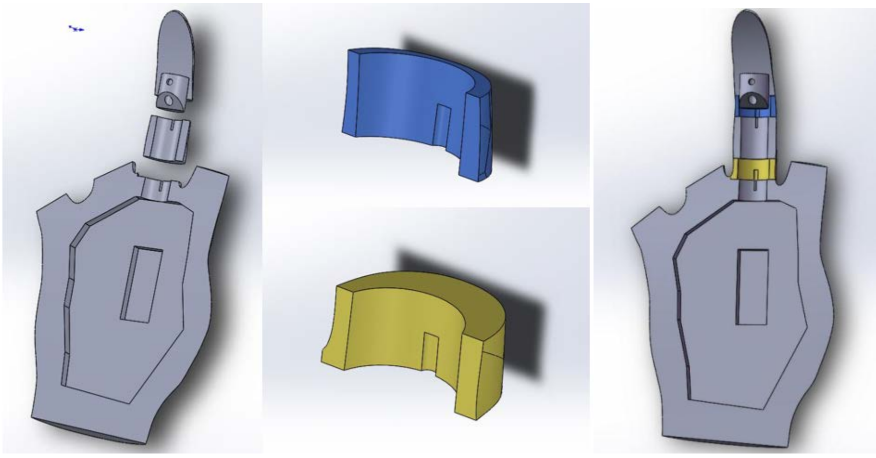

Fig. 8 Assembly group 1

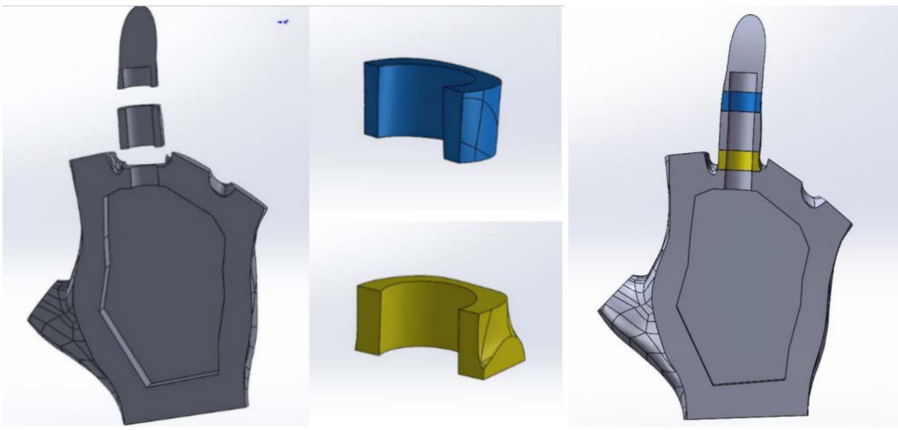

Fig. 9 Assembly group 2

Assigning of materials is done after assemble procedure. Table 1 lists the materials of every component.

Component name	*Material*
Back part	Tango Plus 85A
Front part	
Middle phalange	
Proximal phalange	
Reinforce joint	Tango Plus 70
First joint front part	
Second joint front part	
First joint back part	Tango Plus 50
Second joint back part	

Table. 1 Materials of components

As the number of Tango Plus material decrease, the hardness decrease.

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4.3.5 Outcomes of first prototype

Fig. 10 shows the printed assembly groups.

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Fig. 10 Printed front part and back part

The surface of these two parts is smooth. And there is no fractures or gaps between joint parts and main parts when they were printed out. Moreover, the tolerance of these parts is very low due to the high resolution of objet printer. Separated parts are displayed in Fig. 11.

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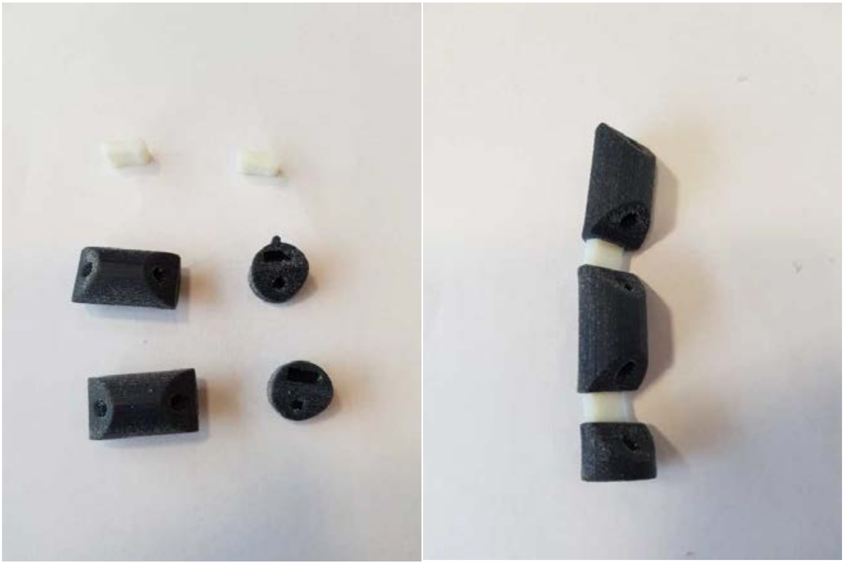

Fig. 11 Printed separated parts

Although the cylinders on phalanges do not look well, they can still be slid into the key grooves on back part. At the same time, reinforce joints are able to be installed between phalanges because of their flexible property. And string goes through all the phalanges and fasten on the end of fingertip. Finally, printed front part and back part are attached together by glue. Fig. 12 shows the hand with middle finger after assembling process.

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Fig. 12 Assembled hand

- However, problems appear during testing process:
- When pulling the string, middle finger does not bend as it supposed to be. Only the first joint bend slightly as the force applied on string. Friction at the connection face of front part and back part somehow stops the movement of middle finger.
- Glue cannot stick front part and back part tightly. When the string is pulled, gaps appear at connection face randomly.
- Fractures arise at the connection section of different materials rather than the middle of joint, short length of joint parts may contribute to the fractures.
- Phalanges cannot be installed on the back part tightly. Due to the tiny proportion of the interface between key and phalanges' main body, keys on the phalanges are easily to break.
- Reinforce joints are proved to be useless. The flexible characteristic of Tango Plus is capable to let the joint part rebound itself.

- Considering the problems occurred in first prototype, some changes in design are needed. And changes are used in second prototype.

4.4 Second prototype

In the second prototype, separated phalanges are eliminated due to the bad performance of first prototype. Skeleton is integrated within the finger itself, and four fingers with four different mechanisms are tested. Moreover, in order to fasten the string around fingertip without destroying its bionic appearance, bionic nails is introduced.

4.4.1 Bionic nails

Differ from the skin covered on hand, the toughness of nails is much higher. And their transparent appearances make them special. So that when inspecting a human hand visually, nails of real human hand can be regarded as separate parts. Relating to the mechanism design for second prototype, bionic nails could be a potential choice to tight the string. Well-designed ‘nails’ are shown in Fig. 13.

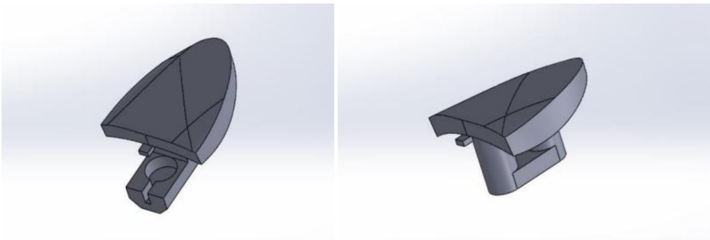

Fig. 13 Mechanical structure of nails

To install nails on fingertip, printed nails will be a little bit larger than the hollow reserved for nail. Therefore, the interference fit between nails and hollows makes the nail can be assembled by simply pushing into reserved hollow. Bionic nails not only solve the string attach problem, but also make the appearance of 3D printed prosthetic hand more realistic. Besides, this is a potential new market because nails can be sold as accessories. And with different colors, customers are more willing to purchase this hand.

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4.4.2 Mechanical structures of four fingers

To build skeletons for four fingers, hundreds of sketches and planes were created in the 3D modeling software. Based on the bending tests of the last prototypes, joint parts with 2mm thickness have good performance on bend and rebound motions. Thus, the thickness of joint parts in third prototype is pre-set as 2mm. Moreover, to overcome fracture issues occurred in first prototype, thickness of the whole back part of fingers is designed to be 2mm. So when fingers are bended, the whole back part can distribute the elongation ratio which was only carried by joint parts. Since the required elongation ration of joint parts is reduced, possibility of fracture happening is decreased. Due to the asymmetric shape of fingers, Extruded Cut and Swept Cut in Solidworks are not capable to cut hollows with complex structures. In this case, a sophisticated method called Lofted Cut is applied to dig hollows in third prototype. And this method will be fully illustrated in following paragraphs.

4.4.2.1 Inner V-cut forefinger

On account of the outcomes of the last prototypes, it seems that complex skeleton will make it hard to bend fingers. Thus, skeleton is eliminated in this mechanism. Mechanical structure of forefinger is displayed in Fig. 14.

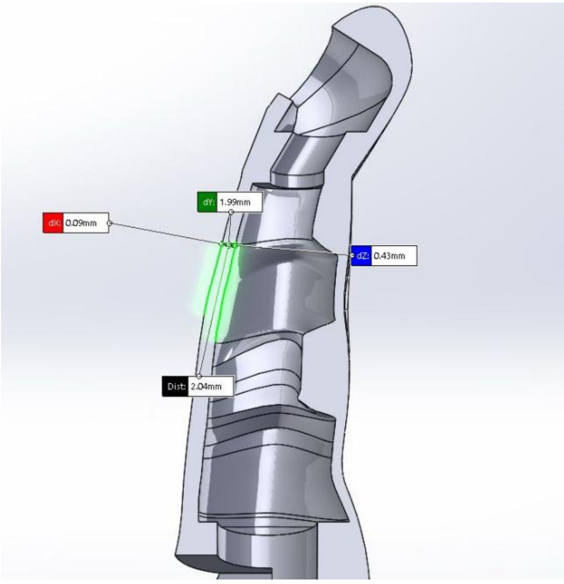

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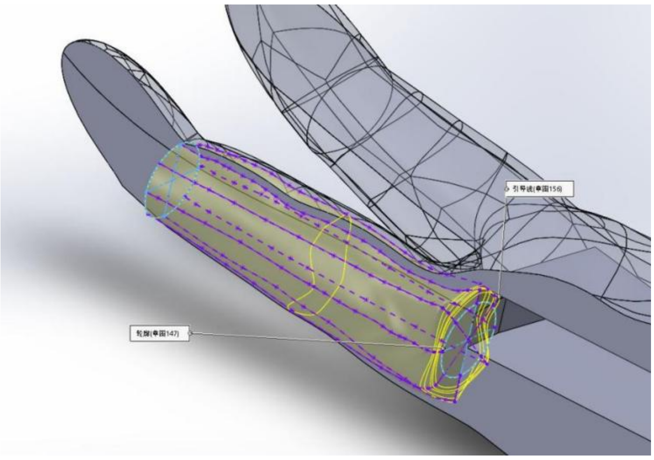
Fig. 14 Drawing of forefinger

Similar to the structure composed by phalanges and reinforce joints. In the front part of finger, the thickness at 'phalanges' positions is thicker than the thickness of joint parts. In this way, two V-shaped cuts are formed inside forefinger. And the difference in thickness will 'tell' the finger where to bend. Besides, the hollow built in fingertip reserves the space for installation of nail. Moreover, thickness of the back part of hand is designed as 2mm.

4.4.2.2 Middle finger with 'walls'

Middle finger is more like a shell, and the thickness is 2mm. Fig. 15 displays the mechanism of middle finger. Two 'walls' are created at the location of middle phalange and proximal phalange. Walls replace the function of phalanges by dividing the finger into partial solid-hollow pattern. Moreover, walls are smaller than phalanges, relatively larger gap between walls and hollow make middle finger easier to bend. Furthermore, simplified structure make string attaching task easier.



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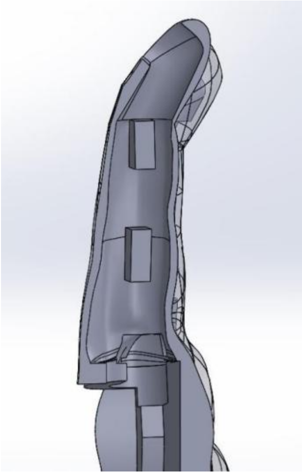

Fig. 15 Middle finger-Walls

4.4.2.3 Ring Finger-Phalanges

Finger with two phalanges and two joints is remained in ring finger. And the mechanical structure of ring finger is shown in Fig. 16.

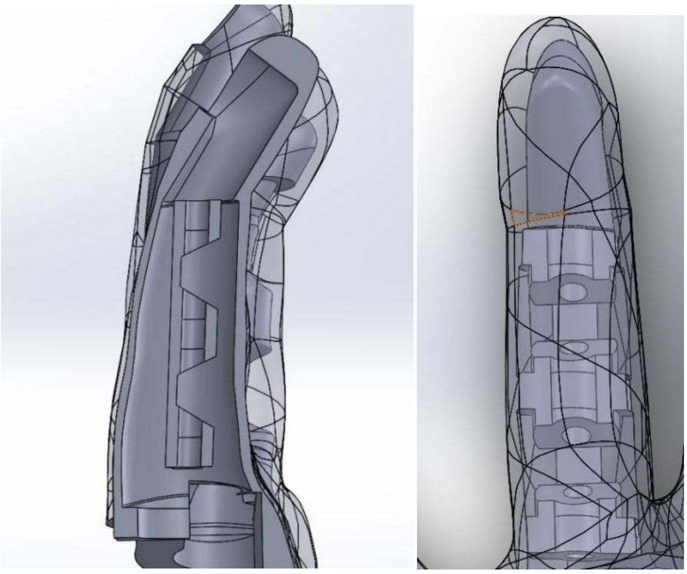

Fig. 16 Ring Finger-Phalanges

Using the same strategy applied in middle finger, ring finger is cut as a ‘shell’. Then phalanges are built based on the hollow. Compared with phalange systems in first prototype and second prototype, phalanges contained in ring finger is smaller. And the length of reinforce joints between phalanges is increased. Besides, since the average diameter of hollows in third prototype is bigger than that of last two prototypes, the distance between phalanges and hollow’s surface is increased. Therefore, when bending the ring finger, frictions between phalanges and hollow will not become a big issue. Furthermore, considering that support needs to be removed from hollow after printing, phalange parts are design in half-solid form.

4.4.2.4 Little finger-outer V-shaped cut

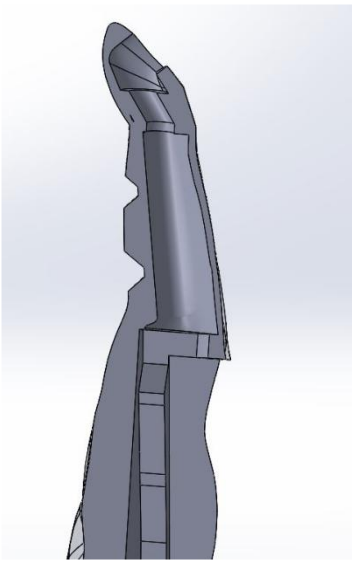

Fig. 17 Little finger-outer V-shaped cut

As displayed in Fig. 17, the mechanical structure of little finger is similar to that of forefinger. The only difference is V-shaped cut in little finger occur on the outer surface. Inspired by a prosthetic hand produced by Open Bionic, the initial idea is to

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remove some material from joint parts without destroying its appearance. So that the finger will bend at V-shaped cuts. Undergoing the same process, hollow is cut inside little finger.

4.4.2.5 File with four fingers

File with four fingers and separate back part is shown in Fig. 18.

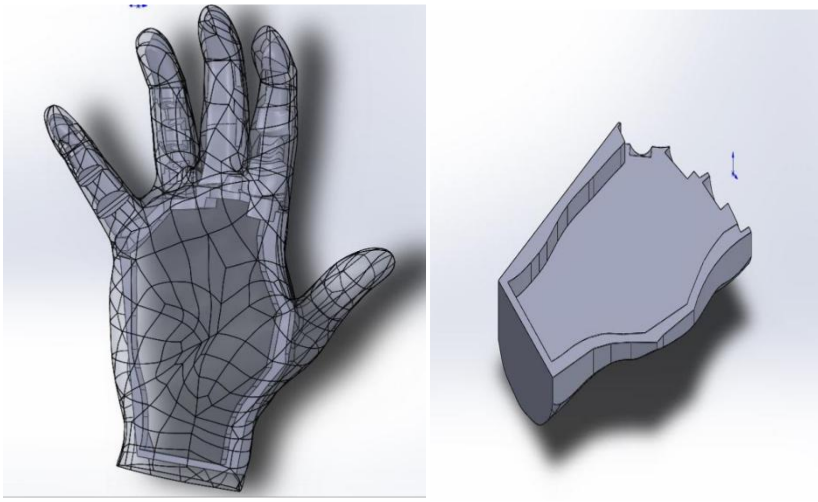

Fig. 18 Files for print

To investigate potential problems that may influence the bending movement of fingers, connection section between forefinger and middle finger is modified to a thin-wall. On the contrary, the rest connection sections between other fingers are solid. Comparison of different mechanisms will demonstrate which one is more practical. Moreover, there is a chamber inside palm. Electron components include motors, Arduino board and power supply will be installed in this chamber. The separate back part is cut off from the back part of the hand, and works as a cover. The softest material in Tango Plus Series-Tango Plus 30A-is the material used to print both the part with four fingers and separate back part.

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Furthermore, a new 3D printer called Zortax M200 is applied to print nails. Highest resolution (0.09mm) is used to earn the best appearances of nails. And the material of nails is ABS.

4.4.3 Outcomes

Printed hand and separate back part are displayed in Fig. 19.

Fig. 19 Printed hand and back part

The appearance of third prototype meet the requirement of this project. And the texture is very smooth. Separate back part can be easily installed on the front part. Fig. 20 displays the hand after assembling.

Fig. 20 Pictures of assembled hand

However, fractures can be seen by naked eyes. Actually, this model has been printed for three times. The hand shown in Fig. 20 is the third sample. For the other two, fingers were separated from palm. Fractures occur during cleaning process rather than printing process. Support structure inside fingers are removed manually, and tools with sharp edge are needed to clean the support from narrow corner. Although cleaning process has been operated carefully in third prototype, fractures at the connection section between fingers and palm are inevitable. There are two possible reasons:

Material itself could be a big problem. Within testing process, the bond between layers is weak. And the tensile strength of Tango Plus is too low, which cannot resist the force caused by manually operations.

The thickness at connection parts is too small. According to technician in laboratory, if the thickness can be increased to 3mm, fractures could be prohibited. Rubber-like characteristic of separate back part is very well, which proves that if fingers could become thicker, they will be more stable.

Printed nails are displayed in Fig. 21.

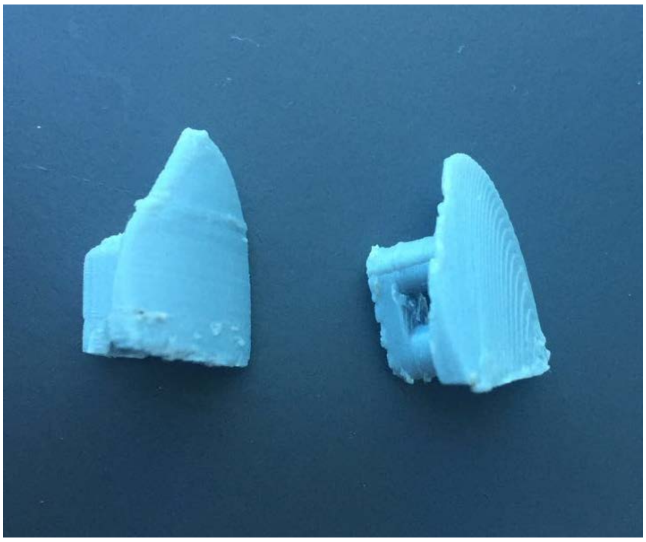

Fig. 21 ABS nails

Although the layer height is set as 0.09mm (smallest), surface of these nails is still rough. And some parts are broken when the nails are removed from platform. It might because the dimension of nails is too small which exceed the capability of Zotrax M200. Moreover, nails are too small to install on every fingertip. Thus, bending test cannot be held on this prototype.

Differ from the last prototype, every finger can be bended easily under the force applied on fingertip. In which forefinger (inner V-shaped cut) performs the best bend-rebound movement. However, fractures appear again when middle finger and ring finger repeat bending movements. Connection parts between ‘skeletons’ and hollows are broken due to the little thickness of hollows.

As a result, the size of nails should be amplified to make sure they can be installed on fingertip stably. And the thickness of fingers and palm need to be increased, so that fingers can resist the bending force without broken.

5. Conclusion

To draw a conclusion, two prototypes are produced by 3D printers in this project. All the inner mechanical structures are created based on a solid hand scanned by 3D scanning machine. Fingertips are curved to eliminate distal joints (refer to real human hand). As a result, all the fingers in these two prototypes only contain two joints. And this is the trend of prosthetic hand market. In first prototype, middle finger and palm are cut into half-half. Compositions of skeleton include two separate phalanges and two separated reinforce joints are designed to install on the back part of hand. String is fastened on the end of fingertip. However, when pulling the string, only middle joint bend slightly. Frictions between the two halves strongly obstruct the motion of middle finger. Thus, improvements on mechanisms are done in second prototype, in which forefinger with inner V-shaped cut is proved to be relatively best design. It not only reaches project objectives, but also achieves low weight and simpler mechanism. Combination of literature review and experimental testes in this project make the mechanical structure deign of prosthetic hand can be improved step by step. Although all the prototypes built in this project are still in the period of attempt, an applicable mechanism has been designed. After further improving, an affordable 3D printed prosthetic hand with appearance of real human hand could be a commercial product.

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