Individualized Finger Prosthesis

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Abstract

As biomedical technology continues to develop, finger prostheses have become an increasingly available and popular solution for individuals that have suffered amputation of the phalanges. Prosthetic fingers can be either cosmetic, mechanical, or myoelectric; but current options rarely combine these aspects to provide a discreet and functional finger prosthesis. Therefore, this team is designing a financially reasonable and mechanically functional finger prosthesis without sacrificing aesthetics. In collaboration with the client, Mr. Gregory Gion, the team is working towards the integration of a compact mechanical unit into the existing, incredibly detailed silicone prostheses that are crafted by Mr. Gion at the Medical Art Prosthetics clinic. The most important aspect of this innovation requires the restoration of flexion and extension in a residual finger, capped by a finger socket provided by the prosthetist. The final design and prototype is a work in progress, and consists of a 3D printed opposing-motion link mechanical system and external casing, as well as a surgical plaster cast finger cap.

Introduction

Each year, around 61,000 Americans lose at least one finger in a partial hand or finger amputation [1]. The causes of these amputations are widespread, ranging from work-related accidents to cardiovascular diseases, infections, and nerve injuries [1]. Unfortunately, current partial phalange prosthetics on market either do not restore function of the lost fragment, or are bulky and undesirable to wear for affected individuals. Creating a prosthetic device that can restore some of the function of the lost phalange fragment while looking inconspicuous to the wandering eye is essential to help amputees return to a more normal hand function. Today, large prosthesis companies such as Medical Art Resources, Inc. produce cosmetic finger prosthesis composed of silicone that slides over the amputated phalange remnants. These prostheses are undetectable to the eye, but do not provide any additional function to the affected finger, causing awkward hand gestures in everyday life [3]. In contrast, more functional-based prosthesis companies, such as Naked Prosthetics, provide a more functional artificial phalange that is more tailored to the everyday tasks of individuals. However, these prosthesis are composed of carbon fiber or other highly functional material and look alien on the hands of patients [4]. There seems to be a gap in available products for individuals that want a bit of function out of their prosthetic finger without the noticeable aesthetics of a functional prosthetic.

Background

The complex and precise movement of the human fingers is regulated by muscles in the forearm and tendons in the hand that control the movement of each joint. Each of the fingers contains three tendons that each play a key role in flexion or extension. These tendons are the flexor digitorum superficialis, which flexes the middle phalanx, the flexor digitorum profundus, which flexes the distal phalanx, and the extensor digitorum communis which is the sole tendon responsible for extending the finger. As a team, it is our responsibility to first recreate the structure lost in an amputation and then try to replicate the function of these tendons.

Finger	tip – soft tissues of the tip of the distal phalanx (mm)	pd–distal phalanx (mm)	pm–medial phalanx (mm)	pp–proximal phalanx (mm)	m–metacarpal (mm)
Thumb	5.67±0.61	21.67±1.60		31.57±3.13	46.22±3.94
Index	3.84±0.59	15.82±2.26	22.38±2.51	39.78±4.94	68.12±6.27
Middle	3.95±0.61	17.40±1.85	26.33±3.00	44.63±3.81	64.60±5.38
Ring	3.95±0.60	17.30±2.22	25.65±3.29	41.37±3.87	58.00±5.06
Pinky	3.73±0.62	15.96±2.45	18.11±2.54	32.74±2.77	53.69±4.36

Table 1. This table shows the average phalanx and metacarpal lengths in the hand taken from the x-ray images of 66 undeformed hands. As found in [1], the data shown is in the form of average±1 standard deviation.

For our design to look as natural as possible, it also needed to be as anatomically correct as possible. Table 1 from Buryanov and Kotiuk [1] shows the average lengths of the phalanges and metacarpals located in the hand. This information proved useful during the preliminary design process, and will be even more useful as we look to finalize a design.

Mr. Greg Gion, our client and owner of Medical Art Prosthetics, tasked us with designing a functional skeletal structure that can be placed over the residuum of an amputated finger. Specializing in realistic cosmetic prosthetics, Mr. Gion desired something that could be covered with a silicone finger sleeve to create a final product that was not only functional, but appeared realistic as well. Aside from this, our client also wanted our design to be simple enough that specialized designs could be made for each customer and printed off in his lab. He also expected the device to last from three to five years, but no strenuous activity, such as weightlifting, to be placed onto the device. Further specifications for our design can be found in the PDS.

Preliminary designs

Design 1: The Links

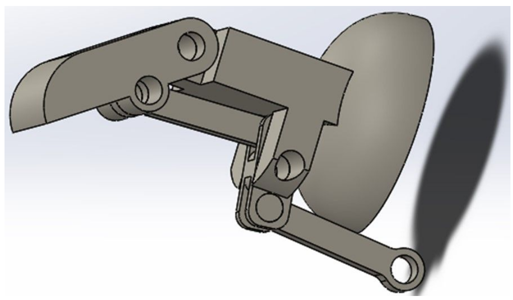


Figure 1. When a patient bends their finger, the rightmost link hits the distal phalanx and forces a bend in the prosthetic distal end. By manipulating the relative sizes of the links, our client can change the force necessary to initiate prosthetic movement and the range of motion achievable by the total finger system.

Design 2: Leverage Joint

Figure 2. The wires depicted in this design attaches to a ring just below the proximal joint of the residuum of the finger. The rod will be directly attached to a cap covering the residuum. As the proximal joint bends, the force from the wires creates a moment in the lever acting as the distal phalanx. This leverage causes the device to bend downward, and the subsequent extension of the proximal joint will in turn cause the lever to extend.

Design 3: Push/Pull

Figure 3. This design incorporates both a push/pull design centered on a ring the patient wears and a lever mechanism resting on the anterior surface of the amputated finger. By use of a moment arms the device will be able to flex based on the patient's articulation of their finger. The design features a built in spring to assist with extension of the finger following flexion.

Design 4: Levers

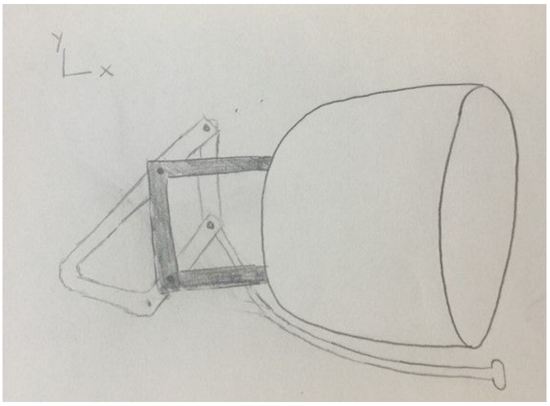


Figure 4. This design uses a push/pull system to control the flexion and extension of the prosthesis. As the lever on the bottom of the prosthesis is pushed to the left, it causes a moment imbalance at the two pins holding the mechanism onto the anchor frame. As the lever on the bottom is retracted back to the right, these moment imbalances reverse, causing extension of the joint.

Design 5: Gear System

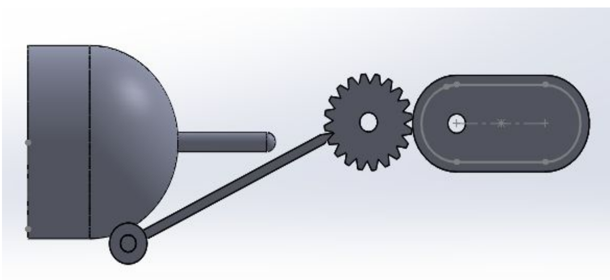


Figure 5. This design consists of a lever connected to the finger cap, and two fixed gears. When the residuum flexes, the extension on the tip of the the finger cap increases the moment arm, which pushes the lever in the downward direction, causing a counterclockwise rotation of the left gear. The left gear then causes the right gear to rotate clockwise about its fixed point. In this design, the left gear resembles the knuckle, and the rightmost gear mimics the distal portion of the index finger.

Preliminary Design Evaluations

Design Matrix

	Weight	Links		Two Bar Push / Pull		Leverage Joint	
Ease of fabrication	20	4/5	16	4/5	16	4/5	16
Functionality	20	4/5	16	4/5	16	3/5	12
Simplicity of design	15	4/5	12	3/5	9	4/5	12
Estimated lifespan	15	4/5	12	4/5	12	3/5	9
Weight	10	4/5	8	5/5	10	4/5	8
Safety	10	5/5	10	5/5	10	4/5	8
Cost	10	5/5	10	5/5	10	4/5	8
Total			84		83		73

Summary of Design Matrix

When choosing how to evaluate designs three fundamental questions arose: "Does the design work?", "How easily can it be fabricated?", and "Which design will benefit the patient the most?" With these guidelines in mind the above criteria and weighting scales were developed. The team individually assessed each design and data was collected on the averages. Due to the competitiveness of our designs, some design ideas were within fractions of a point from each other. In the interest of neater viewing, these fractions were rounded to the nearest integer in the table above. The proposed final design remained the same after rounding.

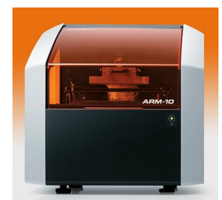
Proposed Final Design

Based on the evaluation of our design matrix and having fabricated a working prototype, the design “Links” was selected as the proposed final design.

Fabrication & Development

Materials

Mr. Gion has recently purchased an Arm-10 3D desktop printer. The Arm-10 3D printer uses a photo-curable resin, which quickly dries when exposed to the UV light source below the printing platform. The end product has the appearance of white translucent plastic.



The finger cap can be made out of PMMA or surgical plaster cast, although the plaster cast is highly preferable due to its low cost and ease of use. On the other hand, PMMA is an exothermic, biocompatible material that has a clay-like consistency for a few minutes before it hardens.

Methods

Both the mechanical element and the outer shell will modeled in SolidWorks for rapid prototyping via the Arm-10. This printer uses Digital Light Processing (DLP) stereolithography technology, which builds up the 3d object layer by layer.

Making the finger cap from surgical plaster casting is simple and efficient; once activated with water, the cast can be wrapped around the patient’s residuum and then dried within minutes. Modification is limited to a few holes that can be drilled into the end of cap, to which the mechanical element will attach.

Due to its exothermic nature, PMMA finger caps would require a finger mold instead of using the patient’s finger itself. While hardened PMMA can be easily drilled or threaded, this material is not ideal due to the extra steps and materials required to make the finger cap.

Future Work

Testing plan

The prosthesis will endure daily challenges over a long lifetime. To ensure that the product will hold up, the prototype will be subjected to different quantitative and qualitative tests. First, to test how the prototype will fair being inside the silicone sleeve in a moist, airtight environment, it will be placed in a humid and/or wet container for a long period of time. After certain time periods, it will be tested for strength using compression and tension tests. In addition, it must still have full range of motion, such that the material hasn't degraded or warped. To test this, goniometer readings will be taken and compared to existing finger readings.

It is important that the prosthesis is comfortable to the people that will be using it. To test this, qualitative surveys will be offered to our client's customers to see how the design could be altered and improved. Questions such as realism, comfort, practicality, and other categories will score overall design features.

Overall, the prototype will be considered successful if it can emulate the dexterity and realism of a real finger, even if the strength capabilities may suffer.

Manufacturability

Since our client will be 3D printing this device for each customer with more than one iteration likely, it must be easy to reproduce. Having designs that scale appropriately to different size fingers is essential to the realism of the prosthesis. By having parameters that are easily customizable, our client can have a well fitting mechanism inside his designed silicone sleeve for each unique customer.

Conclusion

Finger prostheses are provided for people who may have lost a finger due to amputation or accident. These products are forced into one of two categories: aesthetic and functional. This team was tasked with designing a product that can achieve both and, within a $10 budget, develop a process that can be reproducible for our client. Furthermore, the team was responsible for creating a test that would allow prosthesis properties to be evaluated against those of existing phalanges. Since our client will be 3D printing each prosthesis on a part by part basis we cannot change material, nor change manufacture accuracy. Upon testing of different 3d printed prototypes, a final design and work instruction will be provided to our client.

References

[1] A. Buryanov and V. Kotiuk, “Proportions of hand segments,” Int. J. Morphol., Kiev, Ukraine, Rep. 28(3):755-758, 2010.

[2] Amputee Coalition Organization. *Limb Loss Awareness Month*. Amputee Coalition, 2013. http://www.amputee-coalition.org/events-programs/limb-loss-awareness-month/

[3] Brown University Department of Biology and Medicine. *Statistics on Hand and Arm Loss*. Brown University, 2003. http://www.aboutonehandtyping.com/statistics.html

[4] Medical Art Resources, Inc. *Martin Defatte for Platypus Advertising Design*. Medical Art Resources, 2016. http://www.medicalartresources.com/services-directory/finger-toe-2/

[5] Naked Prosthetics, Inc. *It's All About Function*. Naked Prosthetics, 2016. http://www.npdevices.com/

From Appendix:

[6] Jan de Cubber, “Finger or Toe Prosthesis”, US Patent Application Publication, Patent# PCT/EP05/07503, PDF, 2007

Appendix

1. **Product Design Specifications**

Function:

Our client, Dr. Gregory Gion, has tasked us with the design and fabrication of a functional, cosmetic finger prosthesis to replace the distal joint of the index finger. The design should be useful for everyday tasks and small enough to be hidden beneath a cosmetic sleeve which is individually crafted by our client. The product should be completed by the end of the Fall 2016 semester.

Client requirements:

The client is looking to prototype a cosmetic finger prosthesis that possesses active function capabilities. This prosthesis has three main components working together to recreate flexion and extension, facilitated by the movement of a patient’s residuum. The base of the prosthesis, which is custom-made by the client, acts as a socket and anchors the prosthesis to the phalange of the patient. This base must then connect to a skeleton-like mechanism, which is the principal challenge of the design. This mechanical skeleton will therefore mimic the functionality and structure of the distal inter-phalangeal joint and its corresponding tendons and ligaments. Lastly, a cosmetic sleeve will slide over the mechanical unit of the prosthesis, making the artificial phalangeal segment appear natural. In addition, all three parts of the prosthesis must be easily reproduced within the client's laboratory.

Design requirements:

1. Physical and Operational Characteristics

a. *Performance requirements:* The device should be worn throughout the entire day, but must also be removable when desired. The prosthesis should be able to perform both passive and active functions of phalanges, including simple tasks such as picking up a coffee cup or handwriting. However, it is not expected to be used under severe stress, such as weightlifting.

b. *Safety:* Due to the prolonged contact with the skin, both the cosmetic sleeve and the finger cap must be biocompatible. In the past, Dr. Gion has used silicon for both solid and hollow prosthetic fingers and surgical plaster casts or PMMA for finger caps. These materials are already known to be biocompatible and durable, and therefore can be similarly used in the team's design. The mechanical element itself must be durable, non-porous, and non-corrosive to accommodate normal instances of stress while maintaining mechanical integrity during exposure to water or perspiration.

c. *Accuracy and Reliability:* The entire assembly should be easily duplicated to serve the needs of a variety of patients. After modeling the mechanical elements in SolidWorks, repeatability of fabrication is most easily achieved using 3D printer technology and ABS plastic. PMMA may also factor into the design, as it is a readily available and inexpensive biomaterial in Mr. Gion's supplies. Using anthropometry of the hand as a baseline, the length and diameter of the assembly can be tailored to an individual's particular phalange dimensions.

d. *Life in Service:* The prosthetic must continuously function for up to 16 hours a day under normal activity levels to provide the patient with proper flexion and extension. Service may include occasional cleaning or refitting of mechanical components. Ideally, the assembly will maintain mechanical integrity for at least 3-5 years.

e. *Shelf Life:* The product will be made to order and used immediately so there will be no pre-use storage requirements. As far as storage in between use, as long as the device is stored in a cool dry area, it will be able to last its full life in service.

f. *Operating Environment:* The product will not be exposed to many extreme circumstances. Daily activity may include manageable loads, low temperature (in the local area), and moisture. The latter being the most important; in accordance with the client's aesthetic cover, the product should hold up to repeated exposure to wetness. Additionally, it is important that the design be resistant to corrosion resulting from moisture and cleaning.

g. *Ergonomics:* The customer will likely use this product for everyday activities. Unlike strictly functional prostheses that are often attached with supports, the aim of this product is to use a suction cap at the end of the residual. This means that the user might not be able use quite the same amount of force. However, this shouldn't hinder them when performing basic biomechanical motions. The range of motion should be comparable to an existing finger. Additionally, the attachment should allow all day comfort, but is not expected to be used 24 hours per day.

h. *Size:* The size of the prosthesis should be small enough to be concealed underneath a cosmetic coating without looking too bulky or unnatural. Anthropometric data suggests that the length of female versus male phalanges are significantly different. Consequently, our design will be customizable to fit either. Measurements taken from the customers hands will be used to determine the length of different components. We aim to match the exact dimensions of any possible customer.

i. *Weight:* Keeping user comfort in mind, the weight of the assembly should be kept to a minimum. Using lightweight materials such as ABS plastic for the mechanical element would be ideal, to decrease additional strain in the knuckle from lifting the prosthetic.

j. *Materials:* Corroding metals should not be used for the purpose of creating a long lasting prosthesis. A durable, and easily machinable material must be chosen for the mechanical portion of the design. The material chosen for the mechanical portion of the prosthesis must be compatible with Dr. Gions existing materials which includes PMMA and silicone.

k. *Aesthetics*, *Appearance, and Finish:* Because the prosthesis will be covered by a sleeve, our aesthetic concern is the bulkiness of our design. The client described prosthetics as an "artform," so the mechanical element will be as thin as possible for optimal discretion.

2. Production Characteristics

a. *Quantity:* Our client has only requested one functional model to be used for the index or middle fingers. However, he has expressed interest in self manufacturing additional units, so process design is necessary. Being able to produce a large amount of units efficiently without error is a crucial concern.

b. *Target Product Cost:* As our client intends to produce this product in house, it is important that the costs be justifiable in terms of materials used. Valid tradeoffs include material strength, mechanical simplicity, and reproducibility. Our client stated that other functional prostheses may cost more than $10,000 and he would like to be extremely competitive. He has granted us a budget of $500 for the semester but we aim to limit the unit cost to $10 for 3d printing material.

3. Miscellaneous

a. *Standards and Specifications:* The prosthesis must comply with the beneficiary's requests, and instructions for fabrication, assembly, and operation will be provided.

b. *Customer:* Mr. Gion's clients are looking for finger replacements that are unnoticeable as well as functional. The client would like anatomic capabilities as possible, and resemble a human finger while flexing. For production, he would like something that can be replicated quickly (possibly by a 3D printer) in as little as a day.

c. *Patient - related concerns:* Our design is not intended to enter the body in any way, so sterilization should be of little issue. Mr. Gion sees patients with a wide range of injury, as well as finger length and diameter. With an internal, skeleton-like mechanism to provide flexion and extension, the team can devise an outer shell or filling that will maintain the finger's shape during movement. This outer component should therefore be highly customizable and easily manufactured in Mr. Gion's lab setting.

d. *Competition:* Upon searching through a patent application and publication database, a prosthetic finger similar to this design project was found. The prosthetic by Jan de Cubber is designed to replace the entire finger through an internal, skeleton-like structure. Her design incorporates a socket, bone anchor, and spring loaded joints in the fingers. Like ours, it can be covered with a cosmetic sleeve. However, the aforementioned prosthetic options in the general biomedical market do not commonly offer this combined mechanical and aesthetic solution. Therefore, Ms. Cubber's designs are worthy of inspiration towards the team's original approach toward the design of a prosthetic distal phalangeal segment [6].