Rutgers Robohand

Kimberly Ding
dingkimberly@gmail.com

Daphne Kontogiorgos-Heintz
daphnekheintz@gmail.com

Wamia Siddiqui
wamiasiddiqui@gmail.com

Shayla Murray
shaylamurray7@gmail.com

Kasey McFadden
kaseysmcfadden@gmail.com

New Jersey Governor's School of Engineering and Technology

Abstract

Prosthetic hands today are not always accessible or affordable, especially for young children. Prostheses can cost thousands of dollars, and a child's growth rate would require a replacement every twelve months [1]. In this project, an affordable, safe, and functional prosthetic hand for a young girl was designed and assembled. The hand was created with computer-aided design programs, analyzed with stress simulation software, and 3D-printed. By describing the production process of an inexpensive prosthetic hand, this study sheds light on the specifics of the design and can serve as a guide for those intending to produce a similar prosthesis. Additionally, the study helps pinpoint weaknesses in prostheses for future reference. By indicating areas of decreased structural integrity that may need additional reinforcement, this study can lead to the development of stronger, more durable prostheses.

1. Introduction

Prosthetic limbs are capable of drastically improving the lives of people without functional limbs by increasing their mobility, independence, and self-esteem [2]. However, prostheses can be expensive to the point of impracticality. A passive, non-functional prosthetic arm can cost $5,000, while myoelectric prostheses cost upwards of $20,000 [3]. These high prices often prevent many amputees from obtaining a prosthesis. In particular, it is usually unfeasible for children, who rapidly outgrow their prosthetic devices, to purchase a new prosthesis as often as is required.

Other disadvantages of traditional prostheses include their excessive weight and necessary maintenance, which includes frequent check-ups and careful washing [4]. Consequently, there are low compliance rates: only twenty-five percent of upper-extremity amputees keep their prosthetic devices for more than a year [5].

3D printing offers an alternative to traditional prostheses. Inexpensive, lightweight, and customizable, 3D-printed prosthetic limbs are a practical choice for many amputees.

This project's primary objective is to use computer-aided design software to design an affordable, durable prosthetic hand that will enable a hypothetical four-year-old girl to write, draw, and perform other manual functions. Due to the fact that the prostheses of children at this age require annual replacement, a 3D-printed device is ideal.

2. Background

2.1 *Prostheses*

Prostheses vary in type and method of use and must be customized to fit a patient's specific needs. Certain types of prostheses are nonfunctional, serving only cosmetic purposes. Body-powered prostheses, such as a split hook (Figure 1a), are controlled by cables or elastic bands and powered by body motions. In contrast, myoelectric prostheses (Figure 1b) are controlled by nerve signals generated in muscles in the user's residual limb and are powered by an external force; these typically allow for a wider range of hand movements. Hybrid prostheses combine myoelectric and body-powered components [5]. Finally, advanced neuroprosthetic devices, such as the LUKE Arm, can be consciously controlled and allow the user to experience sensations in the area of the device, but cost approximately $100,000 [3].

(a) *Split hook* [6]

(b) *Myoelectric* [7]

Figure 1: *Split hook (a) and myoelectric (b) prostheses are types of conventional prosthetic hands.*

The design of a prosthetic limb depends on the level of its user's amputation. In the upper extremities, the more distal an amputation is from the shoulder, the more precise the motion can be. People in need of a prosthesis with a working wrist typically use a wrist-powered prosthetic device. When the wrist is disabled or absent but the amputation is below the elbow joint, a transradial prosthesis, powered by the movement of the elbow joint, is used. An amputation above the elbow that leaves only the shoulder joint requires a transhumeral prosthesis with limited mobility [8].

Regardless of their type, conventional prosthetic devices tend to be very expensive, with prices ranging from thousands to tens of thousands of dollars.

Although 3D-printed prostheses do not restore complete hand mobility, they typically enable grasping motions and limited finger movements. Their advantages lie in their easy customization and low cost, making them ideal for growing children and individuals who will need multiple prosthetic devices over a short period of time. 3D printing makes prostheses available to many individuals who would not otherwise have access to them.

2.2 *3D Printing*

Three-dimensional (3D) printing is a method of producing a 3D object by creating successive layers of material, with each layer being a cross-section of the object at a certain point.

Fused deposition modeling (Figure 2) is a fairly inexpensive and common method of 3D printing, involving the extrusion of a molten thermoplastic material from a nozzle or extruder. The plastic solidifies after leaving the nozzle, forming a single layer. The object is gradually printed layer-by-layer. Varying the layer heights and fill percentages can affect the strength and integrity of the material [9].

Several different materials can be used in 3D printing, including plastics, metals, and organic cells. Two of the most common materials are acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA). Both are thermoplastics, but ABS is stronger and more resistant to wear and heat deformation, while PLA is lustrous, sweet-smelling, and biodegradable. Additionally, PLA does not produce toxic fumes during the printing process or

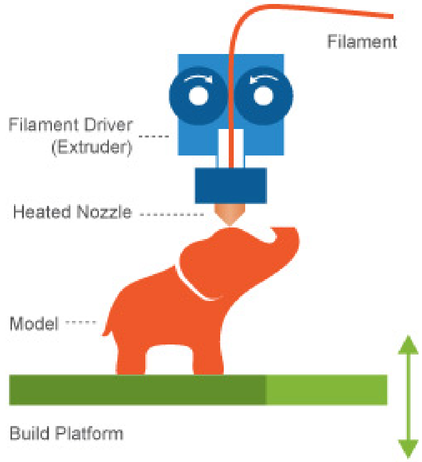


Figure 2: *During the process of fused deposition modeling, a nozzle extrudes molten thermoplastic to create an object.* [9]

release toxic chemicals as it wears down over time, unlike ABS [10].

2.3 *Computer-Aided Design*

Computer-aided design (CAD) is the use of software to construct designs. Several types of CAD software exist, each with different features. SOLIDWORKS [11] is a 3D modeling CAD software where a user typically begins the modeling process by creating a two-dimensional sketch before extruding it into three dimensions. Then, the piece can be molded or cut into virtually any design. Parts can then be assembled into a larger structure. SOLIDWORKS is a convenient platform on which to design a customized 3D-printable prosthesis, because of its intuitive interface, ease of use, and SimulationXpress program, which can simulate force against each part of the prosthesis to evaluate its performance. Blender [12], another CAD software, allows for easy visualization and scaling of CAD files.

2.4 *Amniotic Band Syndrome*

Amniotic band syndrome is a congenital disorder that occurs due to the presence of fibrous strands in the amniotic fluid entangling the fetus in utero. It can result in a wide range of fetal deformities, from band constriction to a lethal amputation, and can affect any portion of the body, though it often affects the limbs [13].

Amniotic band syndrome has an incidence of 1 out of every 11,200 live births [14], of which some cases affect the upper limbs and may lead to amputation. Treatments for amniotic band syndrome are individualized due to the rarity of the disorder and variations in its symptoms. When the disorder leads to acrosyndactyly (Figure 3) or amputation, a prosthesis can give the patient improved hand performance and higher quality of life.

While amniotic band syndrome does cause significant aesthetic defects, it leaves the patient with muscular functionality in the remaining portion of the body. This remaining functionality makes wrist-powered prosthetic devices useful for patients with amputations of the fingers or palm [15].

Figure 3: *Acrosyndactyly can result from amniotic band syndrome.* [16]

2.5 *e-NABLE*

Enabling the Future (e-NABLE) is a network of volunteers who create and publish 3D-printable designs for prosthetic hands and arms. Currently available designs are either wrist- or elbow-powered and typically use elastic cords that run through hinged fingers and produce a gripping motion when stretched. All designs are in the public domain and are often used to produce inexpensive prostheses for a variety of situations and specifications [17]. The Flexy Hand and Talon Hand are two of eight open-source wrist-powered prosthetic hand designs from e-NABLE [18].

2.6 *Hypothetical Case Study*

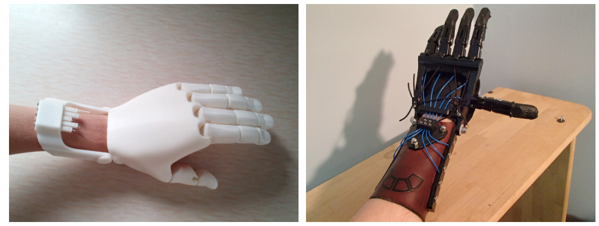
This project's hypothetical subject is Olivia, a four-year-old girl with amputated fingers on her right hand as a result of Amniotic Band Syndrome. She has a completely functional wrist and some remnants of her palm; however, she is unable to perform many tasks with her right hand. She previously has not used a prosthetic device because of the prohibitive cost but now wants to write, draw, and ride her bike. A customized, 3D-printed prosthetic device may change Olivia's life.

3. Hand Design & Assembly Process

3.1 *Preliminary Research*

Information was gathered on the various specifications for Olivia's case before a decision was made on the details of the prosthesis to be constructed. Olivia has a palm, functional wrist, and amputated fingers, making her a good candidate for a wrist-actuated prosthetic device. 3D-printing a prosthesis makes it possible to avoid the price, excessive weight, and difficult learning process of traditional prostheses, while still permitting Olivia to have most hand-based capabilities. In order to create a 3D-printed prosthetic hand that was fitted to Olivia's dimensions, each part was created in SOLIDWORKS and scaled to size in Blender.

The process of building Olivia's prosthetic device began with the measurements of the dimensions of an average four-year-old girl. After that, two existing e-NABLE hand designs, the Talon (Figure 4a) and the Flexy Hand (Figure 4b), were examined. These designs were chosen for their superior grip strength and aesthetic appeal, respectively. Olivia's customized design combined aspects of both designs and included new modifications in order to provide the most suitability and functionality.



***(a)** Talon* ***(b)** Flexy Hand*

Figure 4: *The Talon Hand (a) and Flexy Hand (b) are e-NABLE hand designs referenced in Olivia's hand design.* [20]

3.2 *Design*

The three dimensional design of the prosthetic device was created using CAD software. The palm piece was based on the Talon but modified so that the thumb sits at a 45-degree angle to the vertical instead of its original 90-degree angle, which is more functional and anatomically correct [19]. The gauntlet was modeled off of the gauntlet of the Flexy Hand, because it is simpler and better suited for a young child.

Each piece of the hand was either modeled after a piece from an e-NABLE design, modified from an e-NABLE design, or custom modeled. The cable guide was restructured in order to complement the sleek and simple aesthetic of the rest of the hand, and the distal interphalangeal joints were designed to be proportional to real fingers. The dimensions of the prosthesis were proportional to the measurements of the right hand of an average four-year-old girl, which had been previously researched. The SOLIDWORKS models were then visualized and measured in Blender, and each piece was transferred to Blender to ensure that they were correctly designed and would fit with the other pieces when fully assembled (Figure 5).

When the hand was initially designed, it was proportional to an adult's hand; as a result, it had to be scaled to fit Olivia. The average four-year-old

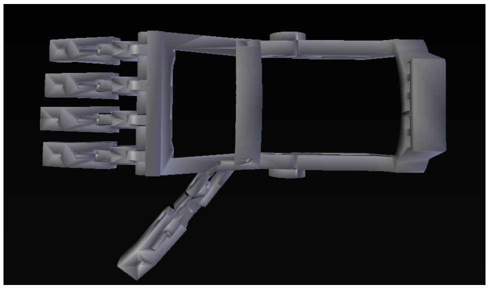


Figure 5: *The entire hand was fitted and resized in Blender.*

girl has a palm width of 5.2 cm, while the original Talon design has a palm width of 5.9 cm [20]. Based on these measurements, the prosthesis was scaled down by a factor of 0.88 along the frontal axis. Furthermore, the distance from the base of the palm to the distal tip of the middle finger, also known as the hand length, is 11.1 cm for the average four-year-old girl, while the Talon had a hand length of 13.7 cm, so the prosthesis was scaled down by a factor of 0.8 on the other two axes. The widths of the fingers were also adjusted to match the widths of the fingers of an average four-year-old girl (Table 1).

Table 1: *Finger dimensions of an average four-year-old girl [21]*

Finger	Width of distal phalanx (cm)
Thumb	1.3
Index	1.1
Middle	1.1
Ring	1.1
Little	1.0

In addition, a pencil-holding attachment to the prosthesis was designed (Figure 6), because the design of the prosthesis and its inherent capabilities do not provide sufficient grip strength and stability to handle an object as thin as a pencil. This task specific attachment is usable with most writing utensils and increases the device's capability to hold thin objects. The mechanism was designed as a circular pencil-holder connected to a hexagonal ring that would fit over the thumb.

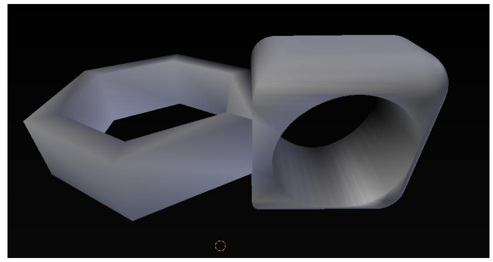


Figure 6: *The writing attachment enables the use of a pencil.*

3.3 *Printing & Assembly*

After the prosthetic device was designed, a 3D prototype was printed at Rutgers University Makerspace with a Lulzbot Mini printer (Figure 7). The set fill percentage was 30%, and the plastic used was 3 mm light blue PLA filament, which was selected for its durability, nontoxicity, appealing scent, biodegradability, and luster [10].

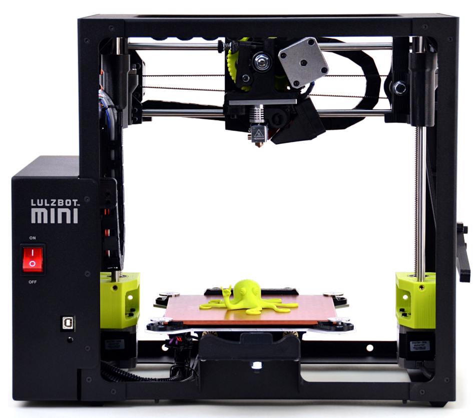


Figure 7: *The LulzBot Mini 3D printer has a bed size of 36 square inches.* [22]

In total, the hand weighed 71.6 grams and took seven hours and twenty minutes to print; at the organization's rate of 10 cents per gram, it cost $7.16 to print completely. After printing, pliers were used to remove the extraneous support structures. The pieces were then sanded down to smooth over any sharp edges, protruding parts, and remnants of support material.

It was necessary to file down each part to ensure smooth movement. For example, the proximal phalanx was filed at both ends because it is connected to the palm piece as well as the distal phalanx. In place of the screws that are typically used in the e-NABLE Talon, polydimethylsiloxane (PDMS), a flexible silicon polymer, was molded into tubes and inserted into the joints to connect pieces of the hand. The flexibility of PDMS decreases the possibility of cracking the prosthesis. PDMS was used to connect the distal phalanx with the proximal phalanx and to secure the completed finger to the palm piece.

Once all the fingers were attached, elastic string and fishing line were pulled through the appropriate holes. These strings attach to the gauntlet so that when the wrist is bent, the fingers flex downwards, and when the wrist returns to its normal position, the fingers revert back as well. The strings are pulled taut but loose enough so that they can return naturally to their original position. Epoxy was used to join the palm piece to the cable guide, and the strings were run through the cable guide to the gauntlet, finishing the assembly process (Figure 8).

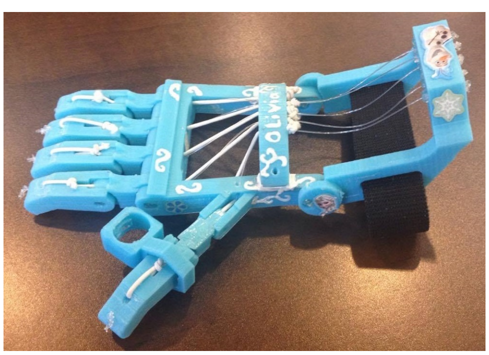
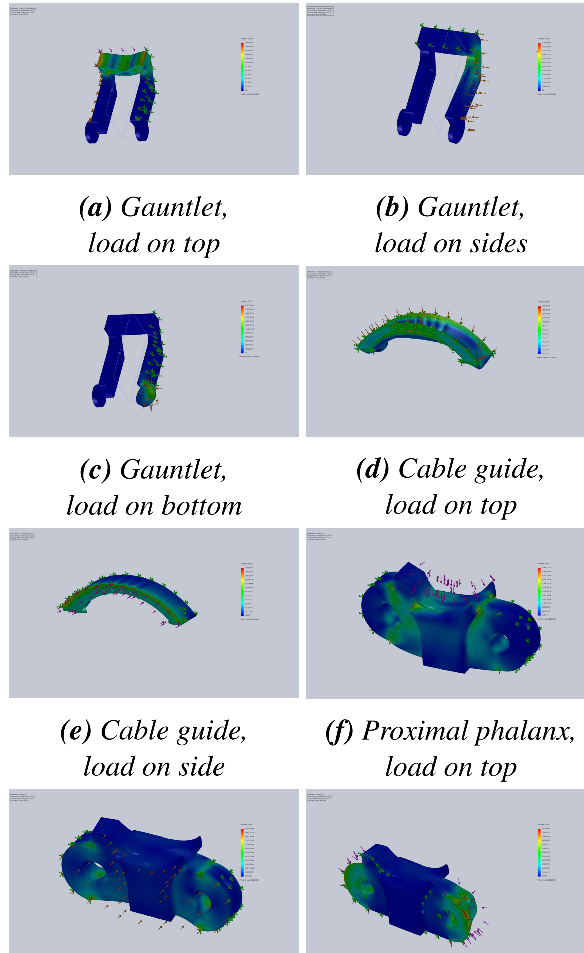


Figure 8: *The prosthetic hand (pictured with thumb attachment) was printed in light blue PLA, assembled, and decorated.*



(a) *Gauntlet, load on top*

(b) *Gauntlet, load on sides*

(c) *Gauntlet, load on bottom*

(d) *Cable guide, load on top*

(e) *Cable guide, load on side*

(f) *Proximal phalanx, load on top*

(g) *Proximal phalanx, load on side*

(h) *Proximal phalanx, load on joints*

Figure 9: *SOLIDWORKS SimulationXpress was used to conduct material part analysis of Olivia's hand.*

3.4 *Structural Analysis*

The fully assembled hand design was analyzed in SOLIDWORKS SimulationXpress to determine the strength of the PLA and its ability to avoid fractures (Figure 9). Each load-bearing piece received a simulated force of 178 newtons, the weight of an average four-year-old girl [23], in order to ensure that each individual part was constructed firmly enough to withstand Olivia's body weight if she were to fall on her prosthesis.

Each test resulted in a factor of safety, which is a number that indicates if the design will fail. A factor of safety that is less than one indicates that the design cannot withstand the simulated force. A factor of safety that equals one indicates that the design is close to failure. A factor of safety that is greater than one indicates that the design can successfully withstand the force. Most of the tests run on various parts of the prosthesis resulted in factors of safety that were greater than one (Table 2).

Table 2: *Results of simulated stress tests*

Part	Location	Factor of Safety
Gauntlet	Top	36.04
Gauntlet	Sides	0.82
Gauntlet	Bottom	2.99
Cable guide	Top	49.63
Cable guide	Side	35.53
Proximal phalanx	Top	1.25
Proximal phalanx	Side	0.73
Proximal phalanx	Joints	8.11

4. Results and Discussion

4.1 *Summary*

3D-printed prostheses are a sturdy, safe, and cost-efficient alternative to traditional prosthetic devices for children. A 3D-printed prosthesis provides the customization necessary to fit any subject, such as Olivia, a hypothetical four-year-old girl with amputated fingers, who requires a wrist-powered prosthetic device.

Olivia's prosthesis has an original design that fuses aspects of the e-NABLE Flexy Hand 2 with the e-NABLE Talon Hand 3 in order to create a more effective hybrid hand. The Flexy Hand and Talon Hand are two of eight open source wrist-powered prosthetic hand designs from e-NABLE. However, the two designs are extremely different. The Talon Hand has a significantly greater grip strength while the Flexy Hand is more flexible and features a more realistic thumb position.

SOLIDWORKS was used to create thirteen separate pieces that combine to form the gauntlet, palm, and fingers of the hand. The completed design was then converted to the dimensions of a four-year-old girl using Blender and printed with a LulzBot Mini 3D printer. Additionally, an attachment that allows Olivia to grip a pencil and write with ease was also designed and printed, because the hand has a limited range of motion.

4.2 *Analysis*

It was necessary to ensure that the prosthesis was safe and stable for a child. It was also necessary to ensure that it had the capability to withstand the forces applied on it from any angle, especially in the event of a fall. The fill percentage of the print was 30%, the strongest available option, and the material was PLA, which has a density of 1250 kilograms per cubic meter.

When the design was analyzed with SOLIDWORKS SimulationXpress, the results (Table 2) made it clear that the parts of the device could withstand large amounts of force. Only the proximal phalanx and the gauntlet parts failed the simulation when a force was exerted on their sides. All other parts of the hand passed the stress test, and are safe enough to bear Olivia's weight. Once the hand is assembled, the weight of a fall would be distributed across the entire device, decreasing the magnitude of force that each individual part would receive. Therefore, the complete hand would be able to successfully withstand Olivia's body weight.

In terms of cost, the price of a 3D-printed prosthetic is far less than that of any conventional prosthesis (Table 3). The overall cost of around $20 is clearly much lower than the thousands of dollars that conventional prostheses cost.

Table 3: Cost comparison between different types of protheses

Type of prosthesis	Cost
3D-printed	$20
Cosmetic	$5,000
Split hook	$10,000
Partial myoelectric	$18,000
Highly-advanced myoelectric	$100,000

4.3 *Shortcomings*

There are limits to the capabilities of the prosthesis, including its inability to have a stable grip on thin items, which allows certain objects, such as pencils or straws, to fall straight through the hand. Without a task-specific attachment, it is very difficult to firmly grip narrow items.

Aesthetically, a few modifications could be made to make the hand appear more realistic. The hand's current color is a child-friendly light blue, but could be made skin-colored to be more inconspicuous. The hand's shape could also be more rounded and personalized to the contours of the user's residual limb.

The device is also limited in its lack of versatility in motion and control. Currently, the hand can only make a simple grasping motion. More intricate movements, such as the movement of individual fingers, are not possible. In terms of functional changes, the greatest advancement that could possibly be made for improved control and coordination would be the use of electromyogram sensors, which would pick up nerve signals in the remnant limb and use them to move parts of the hand. The current design's range of movement is limited because it is body-powered; however, further research could be completed to investigate the potential of creating a reusable myoelectric component that could be transferred between 3D printed prosthetic models. This design would enable users to have the range of motion enabled by myoelectrics, but would not require growing children to continuously buy completely new prostheses as they grow. Another extremely useful modification would be the design of an opposable thumb, allowing for the hand to complete many more actions.

An additional shortcoming of the prosthesis is that it does not adhere to one of the basic tenets of creating wearable devices: that soft tissue should be covered with a hard surface and hard body parts should be covered with a soft surface [24]. Padding could be added to the inside of the prosthetic device to make it more comfortable, especially in the currently open palm area. The strings, which could be a hazard and easily snag, could also be covered.

5. Conclusions

Overall, the prosthetic device fulfilled the goals of being both affordable and suitable to Olivia's situation. CAD software was used to customize the device so that it fit Olivia's specific hand dimensions, and the device can be sized up or down to easily accommodate growing children. Additionally, the 3D-printed device costs much less than any type of conventional prostheses, which have prices ranging from thousands to tens of thousands of dollars. The device is also able to support the entire weight of the user.

The application of 3D printing in the manufacturing process of prosthetic devices can lower the costs of these devices by orders of magnitude, making them more readily available to growing children, patients of lower socioeconomic status, or patients without access to health-care facilities. 3D-printed prostheses are cost-effective, safe, and strong enough to bear large forces. As CAD software and 3D printers become increasingly accessible, a greater scope of people will have access to this option.

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