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Optimizing 3D Printed Prosthetic Hand and Simulator

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Optimizing 3D Printed Prosthetic Hand and Simulator

by

Stephen Estelle

A thesis paper presented to the

Faculty of the Department of
Mechanical Engineering
Loyola Marymount University

In partial fulfillment of the
Requirements for the Degree
Master of Science in Mechanical Engineering

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Thank you to all.

Abstract

The purpose of this study is to examine the position and use of an upper extremity prosthetic simulator on non-amputees. To see how a 3D printed prosthetic simulator can be optimized to serve the user correctly and accurately. In addition, this study examines the improvement of the Hosmer 5X Prosthetic Hook with the addition of newly designed trusses on to the prosthetic, as well as utilizing a new manufacturing method known as 3D printing. These topics are important because there is no standardized prosthetic simulator for schools and research facilities to use. Off the shelf prosthetic simulator cost upwards of $2000, often too expensive for early stage research. By optimizing the Hosmer 5X Prosthetic Hook with 3D printing, this new opportunity could allow amputees, from a range of income classes, to have access to a wide variety of prosthetics that are strong enough to support everyday living activities. A low-cost prosthetic that is easily distributable and accessible can give people a chance to regain their independence by giving them different options of efficient prosthetic devices, without having to spend so much. The devices in this project were design and analyzed on SOLIDWORKS, 3D scanned on the Artec Space Spider, and surfaced on Geomagic Wrap. Key results include developing a low-cost, robust prosthetic simulator capable of operating a Hosmer 5X Prosthetic hook, as well as developing a lighter version of the Hosmer 5X Prosthetic Hook that is more cost efficient and easily obtainable to the population around the world.

1. Introduction

1.1 Background and Motivation

A prosthetic can be defined as an artificial substitution for a human body part (Disabled World). Some examples include legs, hands, eyes, and bone structures of the face (Disabled World). Prosthetic use can be traced back to more than two millennia. Currently, the oldest known prosthetic device dates back to 950-710 B.C.E. It was a prosthetic toe developed for an Egyptian noblewoman, seen in Figure 1 (Finch et al. 2012). A prosthetic toe, as small as it may be, played a significant role because it was necessary for the Egyptians to maintain physical wholeness (Mota 2017). The importance of a prosthetic toe in society is incredible, because it allows users to regain their independent mobility without the assistance from anyone else. Another historic prosthetic dates between 218-201 B.C.E. and belonged to a Roman general named Marcus Sergius who lost his hand in the Second Punic war (Zuo and Olson 2014). The prosthetic was an iron hand that resembled a gauntlet (Figure 2). It allowed the general to return to battle after losing his hand during the Siege of Landshut in Bavaria. This iron prosthetic had flexibility at the metacarpophalangeal, distal interphalangeal, and the proximal interphalangeal joints, allowing the general to hold weapons. The prosthetic was ultimately strapped to his armor via leather straps due to its heavy weight.

Prosthetics have been around to help aid humans, and even animals, who have experienced a traumatic event that left them without a limb, or part of a limb. When it comes to the upper limb specifically, the human hand is incredibly important because it allows the person to interact and operate with the environment around them sophisticatedly and intelligently; the hand and wrist alone give humans a total of 27 degrees of freedom (Cordella et al. 2016). When a person, or an animal, experiences the loss of an arm, limb, or a hand, restoring some of these capabilities gives them back a multitude amount of freedom to perform working and social tasks again (Cordella et al. 2016). Prosthetic ears are being 3D printed to be attached to humans because of an incident that left them without one (K Mills 2015). This prosthetic helps the human regain some hearing capability that was lost. Animals benefit from prosthetics, too, because prosthetics give the animal the ability to survive again in their environment. For example, an alligator was given the ability to swim again because of the addition of a 3D printed prosthetic tail (3DPrint.com). Without the tail, the animal lost the ability to swim and gather food. Now, the prosthetic allowed the animal to regain its ability to swim and thrive. The big toe that was made for the noblewoman in Egypt, as simple as it was, the prosthetic gave the women back her balance needed for walking, as well as the body limb needed to wear the Egyptian sandals (Finch et al. 2012).

Figure 1: A prosthetic big toe that dates back to the years 950-710. Fabricated out of cartonnage and covered in plaster, this prosthetic was created in Egypt for a noblewoman. Image retrieved from The University of Manchester <www.manchester.ac.uk/discover/news/egyptian-toes-likely-to-be-the-worlds-oldest-prosthetics/>

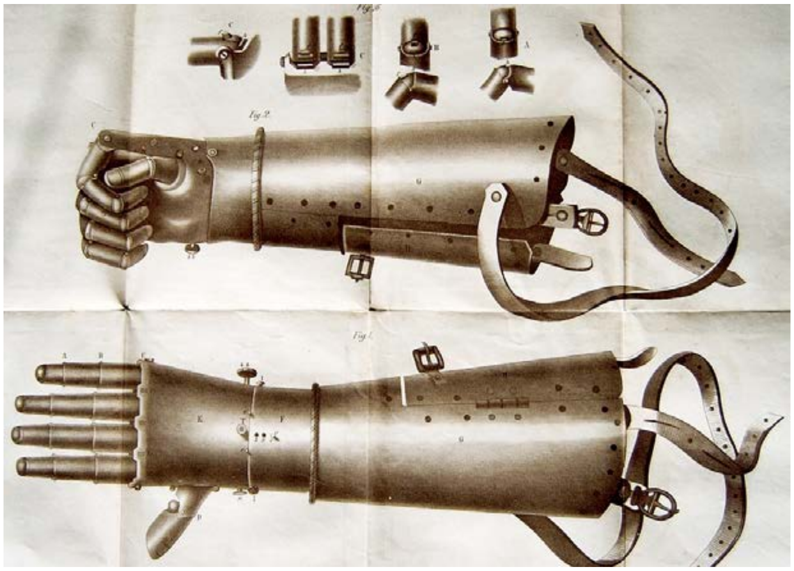


Figure 2: Iron prosthetic arm of general Marcus Sergius who lost his arm in the Second Punic war. The prosthetic had to be attached to his armor by leather straps due to its heavy weight. Image retrieved from The Collectors Weekly < https://www.collectorsweekly.com/articles/war-and-prosthetics/>

The development of prosthetics has given amputees a tool that can allow them to live their original life before their amputation. As the years move forward, the technology being applied to prosthetics is being accelerated incredibly. Advances in material, design, power, and assembling are areas where prosthetics have seen a rapid growth in its efficiency. Early prosthetics were made out of a variety of materials, including iron, wood, leather, bronze, glass, gold, and cartonnage (Mota 2017). The material was typically chosen based off obtainable resources and the prosthetic desired. Using an iron prosthetic arm that would be used for battle versus a wooden arm for less strenuous tasks is one example (Figure 2). This was because different prosthetics served different functions to the amputee that required different material characteristics in order to be successful.

The manufacturing of prosthetics in the past included the use of carved wood, leather straps, string, and textile (Mota 2017). Like the iron hand that was worn by Marcus Sergius after the second Punic War, past designs using similar material can lead to prosthetics that are heavy to wear (Zuo and Olson 2014). However, the prosthetic did give the user some ability back to where the limb used to be. Even with prosthetics not being as efficient as the original body part, prosthetics have contributed to giving the amputee some of their original functions back, giving the user a tool that would suffice (Mota 2017).

In the modern day, there are many causes of amputations, as well as a variety of classifications of prosthetics that help describe the location of where the prosthetics is applied. About 1.6 million people live with a loss of limb, with 54% due to vascular disease, 45% due to a trauma, and less than 2% due to cancer (Ziegler-Graham et al. 2008). There are four main types of artificial prosthetic limbs: transradial, transhumeral, transtibial, and transfemoral (Disabled World; Figure 3). A transradial prosthetic is a device that replaces an arm missing below the elbow. The Hosmer 5X Prosthetic Hook and the devices created in this study work around this kind of amputation.

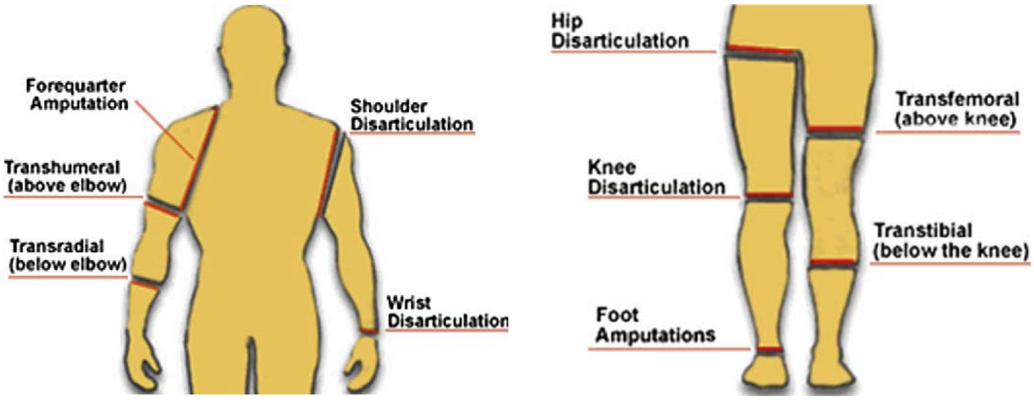


Figure 3: Locations of different amputations. Image retrieved from Semantic Scholar <https://www.semanticscholar.org/paper/Ideal-functional-outcomes-for-amputation-levels.-Meier-Melton/8a832a826762d371f3693704259f88f31ba21e64>

Modern day upper-limb prosthetics serve both passive and active roles (Biddiss and Chau 2007). A prosthetic is considered solely passive if its main intention is to simply look human, realistic, or otherwise appealing to the user, and if it serves no other function other than cosmetic. A prosthetic is considered active if it was design to be put to work under loads of force, moveable, or have functioning parts that allows the user to actively actuate the prosthetic. In addition, there are three main types of prosthetics that fit into these two roles. These three types of prosthetics are: cosmetic prosthetics, myoelectric prosthetics, and body powered prosthetics.

1.1.1 The Problems to Address

In the current medical market of prosthetics, there are a variety of challenges that still must be overcome in order to bring improvement to the quality of life of the prosthetic users. According to a study done by Brienne Phillips and her colleagues, the importance of introducing prosthetics to an amputee in the early months of amputation is essential. Early fitting and training with a prosthetic contribute to longer continuous use of the device. In their research, many services in urban areas lacked the ability to get access to large quantities of prosthetics for their amputees. The amputees, typically in labor-intensive occupations, were ultimately out of a job because they could not continue working without prosthetic assistance (Phillips et al. 2015). The fact that some amputees who are in dire need of prosthetics cannot even begin to learn and train with a prosthetic is a huge problem in lower income areas (Phillips et al. 2015). This issue alone leads to people's lives, and even their family's lives, being hindered because of the lack of resources accessible to them.

The use of prosthetics is important because it brings back a degree of independence to the user. Prosthetics allow amputees to not overexert their other limbs, and this, ultimately, can help avoid medical complications from over usage of other body part (Jones and Davidson 1999).

However, research found that fitting patients within the first 30 days after surgery was critical and had a rehabilitation success rate of 93%, while patients who were fitted 30 days or more after their surgery had a rehabilitation success rate of 42% (Malone et al. 1984). In a research led by Elizabeth Davies, they reported that the median prosthesis delivery and fitting time for upper-limb amputees was six months (Davies, Friz, and Clippinger 1970). Within those six months, the amputee ultimately becomes dependent on utilizing one hand, and the rate of successful rehabilitation with a prosthetic is lowered significantly. The need to deliver prosthetics within the first month to new amputees is imperative for success.

If an amputee does get a properly working prosthetic early on after their surgery, there are still other problems that arise that lead to the amputee abandoning their prosthetic. Wearing and using a prosthetic for typical daily tasks, for amputees, typically stop because of three core reasons: weight, discomfort, and limited usefulness (Datta, Selvarajah, and Davey 2004). These patterns of amputees not using their prosthetic for daily tasks occur throughout multiple studies and are said by amputees. By reducing the weight of the prosthetic device, the user will not need to exert as much effort to simply hold up their limb in place. A lighter prosthetic will increase the mobility for amputees, raise their endurance use with the device, as well as reduce any stress that is being created at the points of contact with the device (Amputee Coalition). Reducing forms of discomfort, such as any rashes and irritations caused by wearing the prosthetic, will allow the wearer to operate the prosthetic for longer periods of time without building up painful sores on the body (Amputee Coalition).

Lastly, usefulness of the prosthetic needs to be addressed because the amputee needs to know that the prosthetic device will operate as intended, and should live up to their expectation, especially when the prosthetic is used in sports (Radocy 1987). When prosthetic devices are created, they need to be designed for the amputee so that the amputee receives a device that is compatible with their lifestyle and daily agenda (Phillips et al. 2015). It is critical that the prosthetics are able to address and operate under the user's specific tasks. If a prosthetic device needs to be fixed, redesigned, or even calibrated in order to be more suited for the amputee, giving the amputee a more efficient and a more pleasant experience using said prosthetic, then the developers of the prosthetic devices need to be able to make these alterations and return a reliable prosthetic back to the amputee as swiftly as possible (Davidson 2002).

Making sure that the amputee continues to wear their prosthetic is an important problem to solve because the more an amputee wears their prosthetic, the more likely they are to be satisfied with their device. To improve these results, proper, often intensive training with the prosthetics is crucial so that the amputee will know how to use their device to its highest potential (Davidson 2002). To continue to raise prosthesis satisfaction, the professionals who are assisting the users with the prosthetics need to be able test, redesign, and optimize prosthetics for their clients (Davidson 2002). If issues arise for amputees, such as profuse sweating, and the working professionals had the most efficient technology, then they could bring new changes to the prosthetic as swiftly as possible. This is imperative so that the necessary changes to the devices can be made promptly, accurately, and correctly.

A survey of prosthetic users found that the priorities for prosthetic users are 1) increased functionality, 2) natural interaction with the environment, 3) reduced weight, 4) higher grasping speeds and forces, 5) low noise, and 6) better cosmetic appearance (Dalley et al. 2009). Using these claims as the backbone when designing new prosthetic hand devices for amputees to raise satisfaction can turn out to be beneficial (Dalley et al. 2009). Giving designers and professionals that work with amputees and prosthetics a new realm to work in to improve these important factors of prosthetics could leave an enormous impact on the amputee community. By giving these professionals additional tools to improve prosthetics and the important design factors that go with them, prosthetic abandonment could drop, time needed to improve prosthetics might decrease, and a raise in outputting more prosthetic resources to clinics and facilities could occur.

The body powered prosthesis is a device that is controlled using a cable that opens or closes the prosthetic with the use of tension. The cable system is controlled by the shoulder and wrist flexion of the wearer (Phillips et al. 2015). With there being a wide variety of prosthesis that used the body powered system, the potential users with transradial amputations have a large number of designs to choose from (Phillips et al. 2015). In addition, because body powered prosthesis typical have simple designs that are either 3D printed, injection molded, or assembled, prosthetist can be easily taught how to produce and repair them (Phillips et al. 2015).

1.1.2 Prosthetic Simulators

Body powered prosthetic hand simulators are important because they allow nonamputees to test hand prosthetic designs on larger populations as well as themselves. The use of a simulator gives researchers a tool to help develop more reliable prosthetics at a faster rate by increasing their feedback on their device they are developing (Gao and Kapp 2011). Currently, there is a small market and research being done with body powered prosthetic simulators; however, there are some design flaws and drawbacks to this. Examining the performance of the Hosmer 5XA Hook, the TRS Grip Hook 2S, and the Otto Bock VO hand was performed on a prosthetic simulator to determine which prosthetic delivered better results than others (Haverkate, Smit, and Plettenburg 2016). The simulator positioned all the prosthetics under and in front of the hand. Another study used a simulator of their own to determine if intermanual transfer effects can be detected after training with their myoelectric upper limb prosthesis simulator (S. Romkema, Bongers, and van der Sluis 2013). The simulator was position inline with the user's hand and placed the prosthetic directly in front of the hand. Last, another study used a simulator to look at bilateral transfer movement across limbs and to see if it effected a person's ability to learn how to use their prosthetic simulator (Weeks, Wallace, and Anderson 2003). The simulator also had the prosthetic positioned directly in front of the hand while being in line with the arm. The first issue to acknowledge is the position of the prosthetic on these simulators. The end of the prosthetic hand reaches further than the human hand operating the simulator. This is a crucial issue because the prosthetic should reach only as far as the human hand reaches, giving a more realistic use. Another concern is the price of some of the simulators. One prosthetic simulator can have a price of around $3,500 (TRS Prosthetics). Not all facilities can have access to these prosthetic simulators because of this cost (Figure 4). A more cost effective and accurate design of the prosthetic simulators need to be developed to help enhance our understanding of prosthetic hand designs. A prosthetic simulator was used as a body powered simulator and a myoelectric simulator to help determine the order of practice tests in the study that had the highest effect on using their upper-limb prosthetic simulator (Bouwsema, van der Sluis, and Bongers 2008; Figure 5). Making these simulators also easily accessible to researchers and prosthetist is key to help improve the trials and the redesigning process that goes in to improving prosthetic hands (Gao and Kapp 2011). Ultimately, by creating a universal standard for upper limb prosthetic simulators, schools and researchers can have simulators in house ready to use that they are confidence in to deliver accurate and reliable measurements. Research that focuses on optimizing a prosthetic simulator's position to deliver consistent results, can give users an authentic experience with the prosthetic and help lead to a universal standard for prosthetic simulators.

Figure 4: A body powered prosthetic simulator being used with a prosthetic hook. Image retrieved from TRS Prosthetics <https://www.trsprosthetics.com/product/body-powered-prosthetic-simulator/>

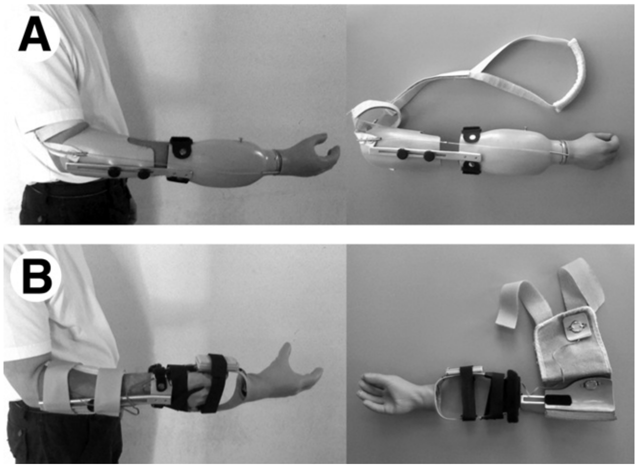


Figure 5: Two powered prosthetic simulators being powered through (A) the human body and (B) myoelectric simulators (Bouwsema, van der Sluis, and Bongers 2008).

1.1.3 Hosmer 5X Prosthetic Hook

The Hosmer 5X Prosthetic Hook was used in this research to perform the varying tests and analysis (Figure 6). The Hosmer 5X Prosthetic Hook is a voluntary opening, terminal device that is used as a body powered prosthetic. With a height of 4-7/8” (12.4cm) tall and a weight of

7.5oz (213g), this stainless-steel prosthetic with nitrile rubber covered tips has a simplistic, but yet multifunctional design that makes it a reliable terminal device for prosthetic users ("Hosmer Hooks Catalog" 2018). With the typical amount of rubber bands present on the prosthetic hook, the prosthetic hook applies a grip force at the tip of the hooks in between 45-70 N when grasping 1-3 cm objects, while the grip force can ultimately reach 140 N when grasping a 1cm object (Belter, Reynolds, and Dollar 2014). The hook gives the user not only the grasping function of opening and closing, the hook shape also allows users to successfully hang objects off of the prosthetic without worry of it slipping, as well as the ability to pull, too ("Hosmer Hooks Catalog" 2018). The clamps in the middle of the prosthetic that house the rubber band also can be used as a clamp to hold objects upright within the prosthetic ("Hosmer Hooks Catalog" 2018).

Figure 6: The Hosmer 5X Prosthetic Hook that was scanned and used for testing. This is a terminal device that is body powered operated. In the left image, the prosthetic hook is screwed in to the wrist attachment device.

The Hosmer Hook comes in a variety of different designs, sizes, and materials to support different amputees in different environments (Figure 7). Some hooks may be tailored towards more strenuous workloads, but may weigh and cost significantly more than other versions. In this study, the focus was on the Model 5X Hook because of ease of accessibility for the research study, its adult size, and the simplistic design. The 5X costs between $420.50 - $585.50 ("Amputee Store" 2018), and is usually worn with a wrist attachment and harness.

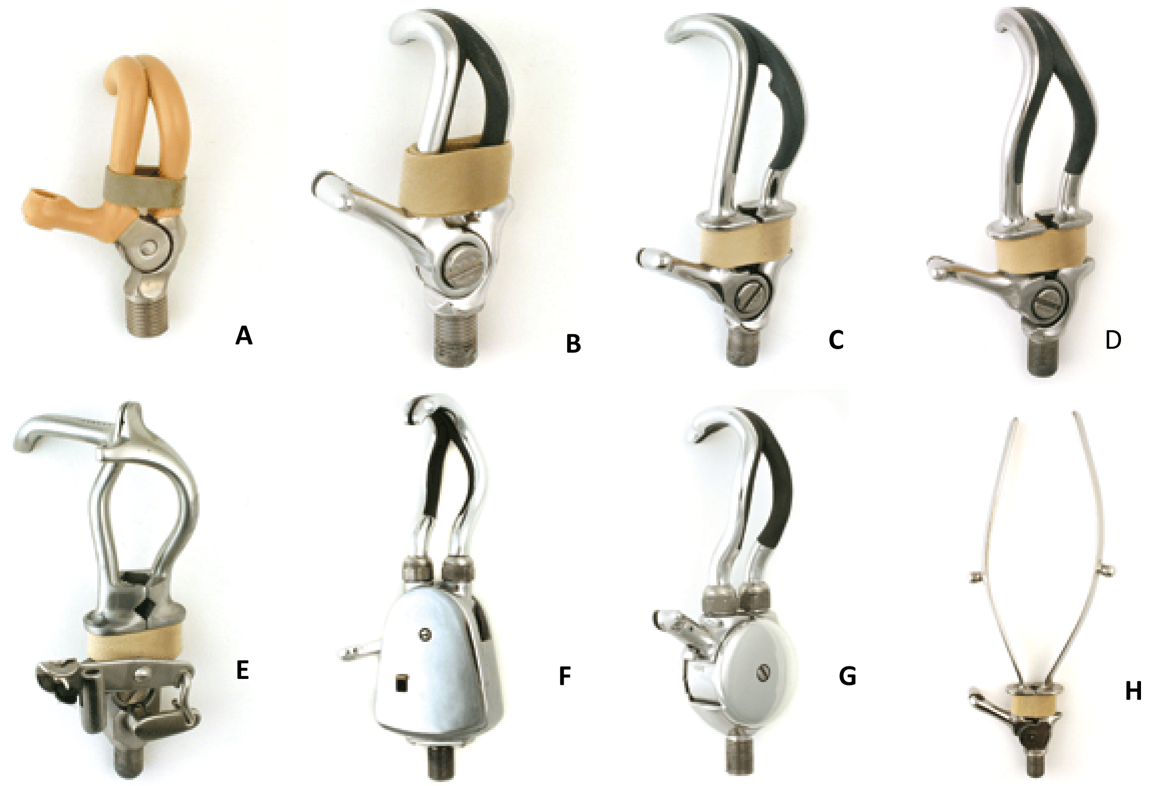


Figure 7: Some of the different designs of the Hosmer Hooks. **A**) Model 12P Hook – Child Size, Stainless Steel, **B**) Model 10X Hook – Child Size, Aluminum, **C**) Model 5X Hook – Adult Size, Stainless Steel, **D**) Model SS-555 Hook – Adult Size, Stainless Steel, **E**) Model 6 Work Hook – Adult Size, Stainless Steel, **F**) APRL Voluntary Closing Hook, Aluminum, **G**) Sierra 2 Load Voluntary Opening, Stainless Steel, **H**) Baseball Glove Attachment. Images retrieved from Hosmer <https://hosmer.com/products/hooks/>

1.2 3D Printed Prosthetic Hands

With the vast number of 3D printable hand prosthetics out there, a person with a 3D printer has a wide variety of choices to choose from if they wanted to 3D print one (Phillips et al. 2015). The prosthetics come in different shapes to fit specific needs, or in basic shapes to give the user a basic, easy-to-use hand (Phillips et al. 2015). Many of the 3D printed prosthetic need to be assembled, and require a harness to be purchased separately in order to operate the prosthetic. The rise of 3D printable prosthetics came about to help deliver a lower costing solution to people in need of a prosthetic in a wide area of places (Zuniga et al. 2015; R.Ishengoma and B. Mtaho 2014). Since prosthetic files for 3D printers can be delivered anywhere online, it is easy to get access to the designs for them. Some 3D printable prosthetics are made as myoelectric, and require some form of expertise to assemble the prosthetic correctly and to maintain it, while others are body powered and require only two parts to be printed with an easy assembling process (Phillips et al. 2015).

One 3D printed hand prosthetic example is the Cyborg Beast (Zuniga et al. 2015). This is a low-cost upper limb prosthetic that is 3D printable for children from PLA and ABS material (Figure 8). The goal of the prosthetic and the engineers who designed it were to create a prosthetic for children in low-income, developing countries with little to no health care assistance. The Cyborg Beast prosthetic costs about $50 for all the material and is currently free online to download for anyone to use. The Cyborg Beast is an active prosthesis that is body powered through wrist flexion (Zuniga et al. 2015). Currently, the model is being further examined in order to make it more durable, functional, and to improve the rejection rate (Zuniga et al. 2015). Plus, with the rise of 3D scanning, they plan to utilize a 3D scanner in the future to improve fitting (Zuniga et al. 2015; Dombroski, Balsdon, and Froats 2014; Doneus et al. 2014).

Figure 8: Cyborg Beast 3D printable prosthetic hand. A low-costing upper limb prosthetic design to fit children.

Other 3D printed prosthetics include The Trautman Hook and The OpenBionics Hand (Phillips et al. 2015; Figure 9). The Raptor Hook is an upper limb prosthetic that is fabricated from a metal 3D printer from stainless steel powder. Similar to the Hosmer Hooks, the Trautman Hook has two halves that are closed and open with the use of rubber bands and a wire. The total cost for this metal prosthetic to be made was $550; however, the design can be fabricated in less expensive material for a lower price on other printers. The OpenBionics Hand has 3D printed components and requires other materials found in hardware stores in order to be assembled. Powered by electricity, this prosthetic may require some expert help to connect it and get it functioning properly, and costs about $200 to be manufactured.

On the premise of 3D printed parts, this research will help determine the optimal position for prosthetic simulators. This research is focusing on answering how can a 3D printed prosthetic simulator be positioned appropriately, when attached to a prosthetic, to deliver consistent results. With a vast number of the currently made simulators being positioned in front of the user's hand, it is understood that numerous of groups have created their own prosthetic simulators (Sietske Romkema, Bongers, and van der Sluis 2017; Huinink et al. 2016; Sobuh et al. 2014;

Buckingham et al. 2018; Haverkate, Smit, and Plettenburg 2016; Weeks, Wallace, and Anderson 2003; Hackaday.io); however, creating a correct, universal prosthetic simulator that can be used to help deliver consistent results is the goal of the study. Ultimately, with the influence of 3D printing, an optimized simulator can be made easily, while being distributable to many.

Figure 9: The Trautman Hook (left) and the OpenBionics (right) both were made from 3D printing so that people can have easier accessibility to upper limb prosthetics (Phillips et al. 2015).

2. Development and Analysis of 3D Printed 5X Clone

2.1 Types of Hand Prostheses

The first type is cosmetic prosthetics (Figure 10). Cosmetic prosthetics play a passive role in prosthetic use. They are typically created to look realistic, and are made to give off a nice-looking appearance. Myoelectric prosthetics produce an active role in prosthetic use and are operated by electricity (Figure 11). The electrical signals are received from the user's muscles through EMG sensors and batteries are utilized in order to power the motors and any other electronics that are inside of the prosthetics. The last and final prosthetic is the body powered prosthetic (Figure 12). This active prosthetic uses no electricity. The movement of the prosthetic device comes from a combination of hinges and wires that move the prosthetic due to forces from body movement. These three types of upper-limb prosthetics all play a role in creating a satisfying device for amputees. They have their pros and cons for different scenarios that makes one type of prosthetic more ideal for different users based off their living conditions and life habits.

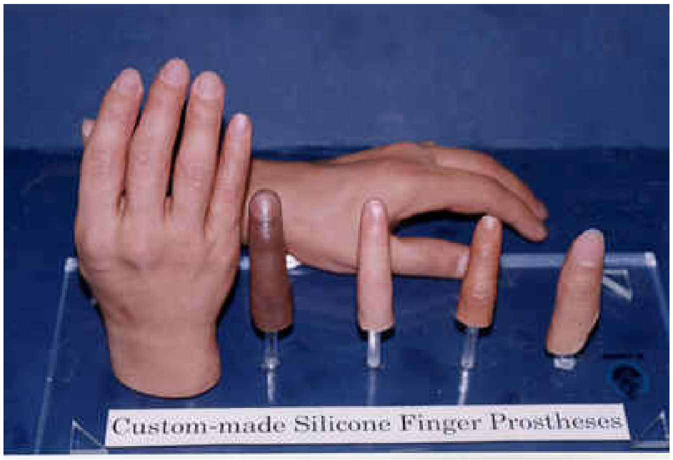


Figure 10: A set of silicon cosmetic prosthetic hands and fingers that were made for a specific client. Image retrieved from The National University Hospital <https://www.nuh.com.sg/uohc/patients-and-visitors/facilities/prosthetics-hand-clinic.html>

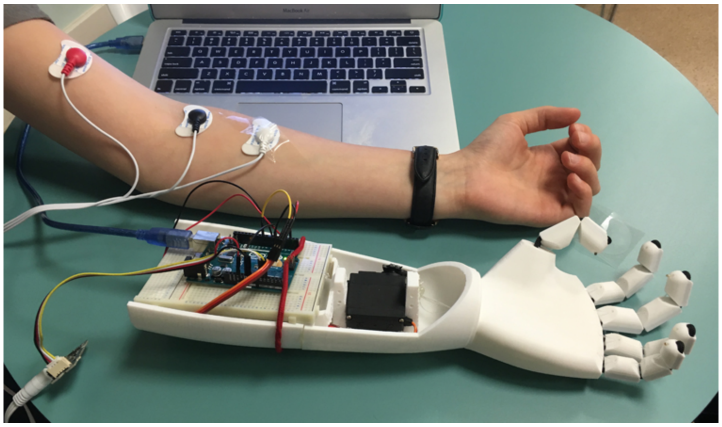


Figure 11: A myoelectric prosthetic that is hooked up to a person's arm. The electrical signals from the arm muscles sends information to the prosthetic to direct it how to move in specific positions. Image retrieved from The Perse School <https://www.perse.co.uk/news/2017/10/rouse-awards-chloe-curtis-smith/>

Figure 12: A body-powered prosthetic that uses a harness and a wire to connect the prosthetic hook to the body. Certain body movements then allow the prosthetic to open and close. Image retrieved from StudyLib <https://studylib.net/doc/5594843/file---a-transradial-prosthetic-arm>

Cosmetic prosthetics are typically the lightest prosthetic of the three. Reason being is that the cosmetic prosthetic does not require numerous mechanical properties. Typically, the prosthetic is made of silicon and fits on the amputee like a glove. The average price of a cosmetic prosthetic hand ranges from $3,000 to $5,000 (Strait, McGimpsey, and Bradford 2006). Even though the cosmetic prosthetic is the lightest and costs the least of the group, this type of prosthetic brings up some issues to its group of users. There are expressed heat problems with the socket that fits on the amputee, worn clothing issues, as well as problems with the wearable gloves (Kejlaa 1993).

Myoelectric prosthetics have the capability to use EMG sensors and batteries to move the prosthetic on the amputee. With the price of the myoelectric prosthetic hands costing between $20,000 to $100,000, this prosthetic is the most expensive of the three (Strait, McGimpsey, and Bradford 2006). The myoelectric prosthetic allows the amputee to move the prosthetic hand easily with slight muscle stimulation. This gives the user the capability to have control over the prosthetic without having to exert a tremendous amount of energy to do so. This ability also allows the user to move the prosthetic hand without having to rely on extending out their entire arm every time to retract a connected wire. As popular and advanced as these prosthetics are, they are reported to me a bit more fragile than the other two hand prostheses due to all the electrical components in its design, as well as the EMG sensors. This prosthetic has been noted to be heavier than the other two prosthetics due to many of its components, as well as being hotter. The myoelectric prosthetic also was shown to be slow moving due to its dependency on the batteries and the signals from the EMG sensors. The requirement for electricity means that the user must have access to electricity to recharge the prosthetic or have batteries to use (Phillips et al. 2015). There were other similar uncomfortable socket problems as well, just like the cosmetic prosthetic, and wearing out of clothing too. Lastly, a large key issue was that whenever a failure would occur, the user almost always had to consult the center they got the prosthetic from or their prosthetist in order to fix the electrical problem (Kejlaa 1993).

Body powered prosthetics, which utilize a wire to apply tension on to the prosthetic hand, are often favored because they typically can move and respond faster than the myoelectric prosthetics (Davidson 2002). This type of prosthetic is simpler, making it easier to fix if a problem occurs. The body powered prosthetic costs less than the myoelectric prosthetic as well, generally around $10,000 (Strait, McGimpsey, and Bradford 2006). Another benefit of the body powered prosthetic is that there is a high number of designs for long transradial amputations (Phillips et al. 2015). The body powered prosthetic; however, can have wire malfunctions such as slacking or breaking that could lead to issues. The wire that applies tension to the prosthetic can damage clothing from its movements when worn above the user’s shirt as well (Kejlaa 1993). The body is required to move a larger range of motion than the myoelectric prosthetic in order to get the body powered prosthetic to work. The arm would need to extend outward to activate the prosthetic hand, thus limiting the opening and closing position of the prosthetic hand. However, since the prosthetic gets its power from the body and tension being applied to it via rubber bands or a wire, the amount of force being delivered by these prosthetics to grasp items is great. Furthermore, the use of a body powered prosthetic typically requires utilizing a less cosmetic look, such as a hook for a prosthetic hand. In the study by Kejlaa, for people who did not rely heavily on the cosmetic look of their prosthetic, the body powered prosthetic was the most efficient choice for them because of weight, cost, independency from batteries and electricity, and speed (Kejlaa 1993).

Some prosthetic hands do utilize components from more than one type. For example, there are cosmetically realistic myoelectric prosthetic hands, as well as cosmetic hands that have a body powered hook built inside of the prosthetic (Figure 13). One example of a cosmetically realistic myoelectric prosthetics is the “i-limb quantum” that is compatible with covers that mimic the looks of human skin. The cosmetically realistic myoelectric prosthetic costs between $20,000 and $30,000 and some of the prosthetics have processors that can determine the amount of pressure it delivers on an object, as well as if the object is cold or hot (Strait, McGimpsey, and Bradford 2006). An example for a body powered cosmetic prosthetic is the “Otto Bock System Hand”. This has a grasping mechanism inside that is covered by a cosmetic glove to give the natural perception of a human hand. The shape, weight, and size of this prosthetic are the big factors that make this prosthetic different than the body powered prosthetic hooks. This prosthetic has extra mechanism inside in order to operate a couple of the fingers and to house the moving components inside.

Figure 13: The i-limb quantum (left), a cosmetic myoelectric terminal device, and The Ottobock System Hand terminal device (right), a cosmetic body powered prosthetic hand for amputees. Images retrieved from Ottobock <https://professionals.ottobockus.com/Prosthetics/Upper-Limb-Prosthetics/Body-Powered-Systems/Ottobock-System-Hands/Otto-Bock-System-Hand-passive/p/8K19> and Touch Bionics <http://touchbionics.com/products/i-limb-accessories>

2.1.1 Prosthetic Harness for Body Powered Prosthetics

The upper limb prosthetic harness and cable is what allows the body powered prosthetic to operate. In this study, the Hosmer Northwestern Ring Harness was used to conduct our tests. The harness is strapped on to the back of the user and the cable is ran along the arm towards the prosthetic (Figures 14, 15, and 16). The anchor ring on the harness must be located directly in the center of the user to insure proper stability of the harness. This is done by placing the anchor ring on top of the spine to center the prosthetic harness. A leather padding is strapped on to the user's triceps and the cable connects the leather padding to the strap that is connected to the anchor ring, as well as to the prosthetic.

Figure 14: Back view of the upper limb prosthetic harness and all of its components that connect the prosthetic hook.

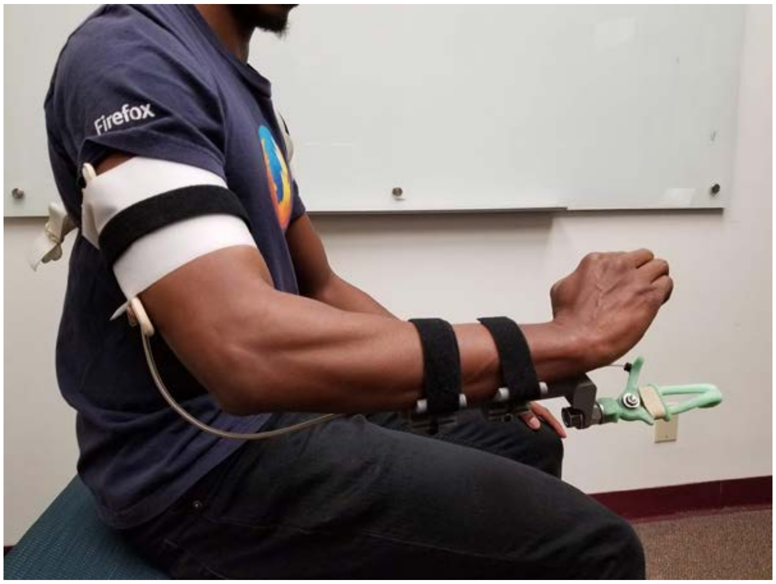


Figure 15: Side view of the upper limb prosthetic harness. The cable of the harness runs under the arm of the user towards the prosthetic.

Figure 16: Clear view of the front of the upper limb prosthetic harness.

When the cable is pulled upon, this causes the prosthetic to activate. Depending on the type of prosthetic that the user is wearing, this action can either open or close the prosthetic device. In this study, the prosthetic is a voluntary opening device, meaning it requires a force from the cable to open it. The other type of device is a voluntary closing prosthetic that requires action to close it. When the user does not move their arm and flexes their shoulders forward to activate the prosthetic, this movement is called scapular abduction. When the user extends their arm only and does not move their shoulders, that movement is glenohumeral extension. These types of movements are critical because depending on how far the user wants to reach with the prosthetic, they must switch off between these two movements. For example, to grab something close, the user may not want to extend their arm out far. At that point, they would use scapular abduction. When the user wants to grab an item from a distance, they want to extend their arm out and reach the object. That is when they would use glenohumeral extension.

2.1.2 3D Printing

As 3D printing continues to advance, companies, researchers, and engineers receive an incredible toolset that allows them to develop parts never created before in new ways. This new technology allows parts to be created in complex geometries while using strong material (Figure 17). Some geometries that are possible on 3D printers would be impossible on a more traditional route of manufacturing, such as using a Computer Numerical Control (CNC) Machine. Reason being is that 3D printing creates the parts layer by layer, allowing the machine to create interior features. On a CNC, multiple angles would be needed to get certain parts made; however, some interior features would simply be impossible to be created. 3D printing allows the user to create complex geometries without any additional costs to make the part. In addition, 3D printing allows manufacturers to create assemblies of multiple parts in to one conjoined piece. This ultimately saves the user time and money because some parts do not need to be assembled any more. This makes them lighter because only the material that is necessary is being used. By turning an assembly in to a single part, the need for screws, bolts, and other small parts to connect pieces together are no longer needed.

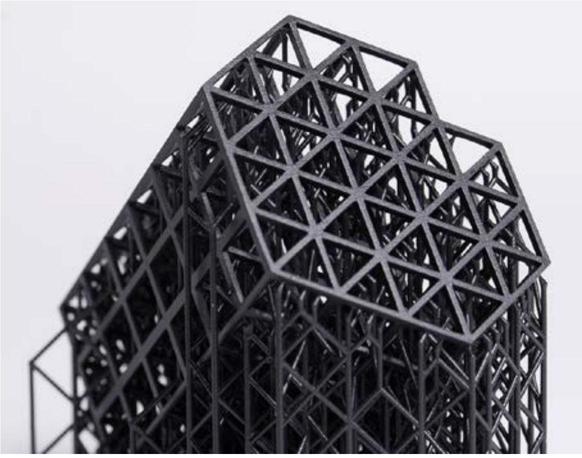


Figure 17: A 3D printed part that was fabricated in a single cycle. Models with complex interior geometries would be impossible to be made on other manufacturing machines. Image retrieved from 3D HUBS < https://www.3dhubs.com/knowledge-base/advantages-3d-printing>

In the 3D printing industry, there are many different types of 3D printers, each with a different method of fabricating a part and with different material chooses. Seven different 3D printer types include: Fused Deposition Modeling (FDM), Stereolithography (SLA), Digital Light Processing (DLP), Selective Laser Sintering (SLS), Selective Laser Melting (SLM), Laminated Object Manufacturing (LOM), and Electron Beam Melting (EBM) (Noorani 2006). The prototypes that were created in this study were all done on an FDM 3D printer because of the variety of material choices that could be utilized, the large build size, the lack of post processing needed, the low price to print a single model, as well as the speed to develop the prototypes. An FDM printer works by first feeding a spool of filament in to a heated extruder. Once the filament is inside the extruder and the 3D model is uploaded to the printer, the printer begins printing the part, layer by layer, starting from the bottom.

2.2.1 Material

For the FDM printer, material selection is continuously growing as the printers become more advanced. Material choice is important because it can determine the success of the part and how it functions. The most common materials for FDM printers are Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid (PLA) because of their durability and ease to print. Many of the prototypes in this study were printed in PLA material because of availability and strength of the material. NylonX is another material that can be used on an FDM printer. NylonX is a carbon fiber filament reinforced with nylon that is stronger than ABS and PLA. This material delivers high tensile strength and impact resistance. PolyFlex is another example of the variety of materials that can be printed on an FDM printer. PolyFlex is highly flexible filament that allows the user to print out elastic parts. If needed, there is also castable materials too for FDM printers called PolyCast. This material allows users to create metal castings of items if they need a new, quick alternative to creating cast moldings of parts.

2.2.2 Cost

The cost of 3D printing varies tremendously because of a wide variety of parameters. These variables include: the type of 3D printer you are using, the build volume of the printer, the material that can be used, the quality of the print, and the printing speed of the printer. For FDM printers specifically, these 3D printers come in a variety of price ranges as well. Some FDM printers have the capability to use two extruders. This feature allows users to design parts made out of two types of materials or colors. This is extremely useful when you need specific characteristics at specific areas of interest. For example, if you need a harder material on the outside for protection, and a softer material on the inside for a comfortable fit, like a helmet. Another common use of the dual extruder is using water soluble material in one of the extruders. By adding water-soluble material to your print job, the designer is able to dissolve away all the water-soluble support material that is used. This is beneficial because the water dissolves away any support material that is located in small, inconvenient crevices that would otherwise be difficult or impossible to pull out manually. Some FDM 3D printers have a heated build plate. This feature allows more complex materials to adhere to the build plate easier, as well as make the finish part that was built detach from the build plate quicker and cleaner. Other FDM 3D printers have an enclosed build compartment in order to keep the temperature inside the machine regulated to help the material's temperature stay consistent throughout the print. This is important because temperature plays a vital role in the success of a 3D print. The material must be kept at a consistent temperature to prevent any deformation of the part while it is being fabricated. There are FDM printers that have a large build volume of 12" x 12" x 24" while others have a small build volume of 4.7" x 4.7" x 4.7". The variety in 3D printers allows user to get the perfect printer for their personal or professional needs, making 3D printers accessible to a wide range of people (Figure 18).

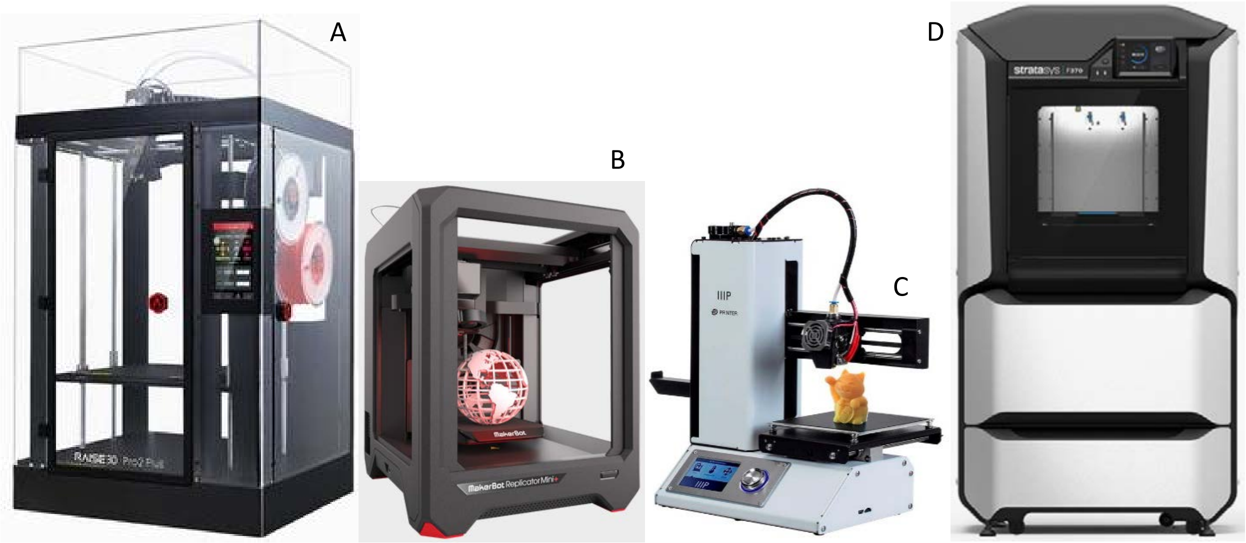


Figure 18: A) Raise 3D's Pro2 Plus 3D Printer that has a build volume of 12" x 12" x 24", dual extruder, layer resolution down to .01mm, a heated bed, can print in a large variety of materials, has an enclosed build compartment, and costs $5,999 (Raise 3D). B) MakerBot's Replicator Mini+ Compact 3D Printer has a build volume of 4" x 5" x 5", only has one extruder, layer resolution down to .1mm, and costs $1,299 (MakerBot). C) Monoprice's MP Select Mini 3D Printer V2 has a heated bed, single extruder, layer resolution of .1mm, a build volume of 4.7" x 4.7" x 4.7", and costs $189.99 (Monoprice). D) Stratasys' F123 Series 3D Printers have a build volume starting at 10" x 10" x 10", have an enclosed build compartment, can build prints with a layer thickness down to .127mm, and cost starts around $20,000 (Stratasys).

Material cost and the cost to create a part varies based off the type of material, the company, and the quality of the material. A kilogram spool of PLA or ABS material can range between \$20 and \$60, while half a kilogram of Nylon based material can cost about \$55. Better quality material typically delivers a cleaner finish for the 3D printed part. The surface finish of the higher quality material allows the filament to work more efficiently with the 3D printer, reducing the chance of clogging within the nozzles. The cost to create a 3D printed part depends on how much material is used for the part. This includes support material, a raft to build the part on, and a wipe tower for dual extruders to clean off the nozzle when switching between two nozzles. For example, to 3D print the Hosmer 5X Prosthetic Hook prototype in PLA material on a Raise 3D Pro2 Plus 3D Printer, the cost of material is estimated to be about \$1.00, and since it only takes about 31.1g of PLA material to make the prosthetic, about 32 Hosmer 5X Prosthetic Hooks can be printed from a single 1kg spool of PLA.

2.2.3 Accessibility

As mentioned before, because 3D printers come in a wide range of types and prices, consumers are able to purchase printers within their budget for under \$200. Some of the FDM 3D printers are compact enough that they can fit perfect on a desk with no need for special hook ups or safety requirements to house the small 3D printer. This portability allows the typical consumer to keep a 3D printer in their house if they please, giving them the capability to fabricate parts 1st handedly.

Another benefit is that the 3D printing files can be shared among people via the internet or USB drive. Stereolithography (.stl) files are the file format that most 3D printers use to fabricate the part desired. A .stl file is a 3D model that has been simplified and triangulated so that the 3D printer can interpret the shape of the model (Noorani 2006; Figure 19). These files can be emailed, downloaded from online, and are easily distributable among people to share designs and prototypes to communities across the globe. With the convenience that comes with 3D printers, as long as a consumer has electricity and internet, a person can 3D print an ever-expanding number of models and prototypes within their own household. 3D printers give designers accessibility to do rapid prototyping and shortens the time towards perfection of a given part.

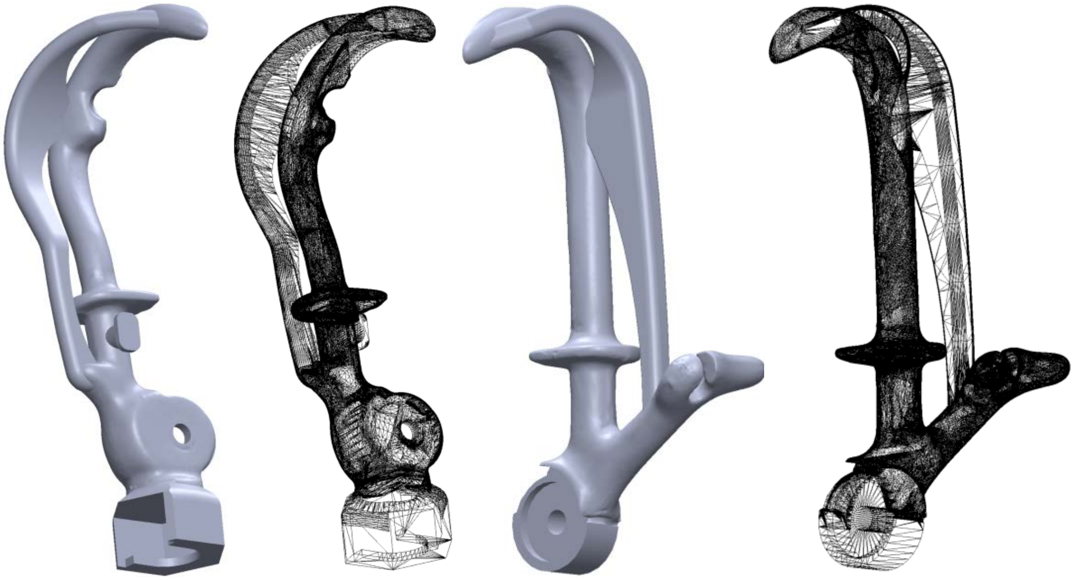


Figure 19: Halves of the Hosmer 5X Prosthetic Hook prototype in a Computer-Aided Design (CAD) file format, as well as a triangulated .stl file format that can be sent to 3D printers for fabrication.

2.3 Prototypes

Numerous iterations were done throughout this study in order to come to a complete design that can fulfill the actions required for the experiments. The Hosmer 3D prints went through tedious evaluation to determine what is needed versus what was unnecessary for the device.

2.3.1 3D Printed Hosmer 5X Prosthetic Hook

The redesigning of the Hosmer 5X Prosthetic Hook that was 3D printed went through a couple minor iteration to create a model that would work with the designed simulator, as well as the standard harness typically used for the original prosthetic. These two iterations included added a larger clearance of 1mm in between the rotating centers to provide smoother movement, and the addition of rubber tips (Figure 20). Before the addition of the rubber tips, the 3D printed material did not have the ability to grasp on to items efficiently. The slick surface profile of PLA material made it an extreme challenge. To combat this issue, a small cutout was design on the tips of the prosthetic models, and a rubber insert was then placed in the cutout to give the gripping capability to the models.

Figure 20: The first iteration of the 3D printed Hosmer 5X Prosthetic Hook (left, grey) and the final iteration of the Hosmer 5X Prosthetic Hook (right, green) with a M12-1.25 screw.

2.3.2 Added Trusses to Hosmer 5X Prosthetic Hook

The trusses on the side of the newly designed model of the Hosmer 5X Hook were inspired by bridges and the truss system used for them. The purpose of the truss is to reduce any form of displacement of the prosthetic hook, as well to disperse the stress and strain that the prosthetic encounters throughout the device more evenly. The truss was designed to reduce any bending or twisting moment due to a force on the tip of the hook. By doing so, the prosthetic is able to withstand higher forces and reduce the buildup of maximum stress in certain locations.

2.4 Methods

2.4.1 Finite Element Analysis

A Finite Element Analysis (FEA) was performed on the two sides of the replica prosthetic, as well as the modified prosthetic with trusses added. The redesigning and FEA was done in SOLDIWORKS 2017. An isolated, true point load of 3.3lbs of force was applied to the inside tip of the prosthetics, perpendicular to the surface, because that is the force calculated to open the hook with the standard rubber band used with the Hosmer hooks (Figure 21). The normal stress in the Z direction, due to the entire loading force, but just stress caused by the normal stress acting in the Z direction, was examined as well. For the screw-housing side, the model was given fixed constraints to the bottom surface of the screw housing. For the thumb side, the model was fixed about the inside surface of the bearing housing. In the FEA, PLA material was assigned to the model in order to calculate the appropriate stress and displacement of the models. The PLA material properties used were: elastic modulus of $2.79E^{10}$ N/m^2, shear modulus of $1.287E^9$ N/m^2, Poisson's ratio of .36, mass density of 1240 kg/m^3, tensile strength of $7.3E^7$ N/m^2, yield strength of $7E^7$ N/m^2, thermal conductivity of .2256 W/(m*k), and a specific heat of 1386 J/(kg*k).

2.4.2 Stress Test

A stress test was administered on the 3D printed prosthetic parts (Figure 22). The parts were tightened in to a vice and a 50lb spring scale was used to measure the amount of force needed to break each of the two pieces that compose the prosthetic. A ruler was used to measure the displacement of each piece right before breakage, with video recording allowing for the measurement to be taken retroactively. The pieces of the 3D printed prosthetic with and without the truss added all went through the test with PLA as the material of choice and the 50lb spring scale exhibiting the force on the tips of each half of the prosthetic.

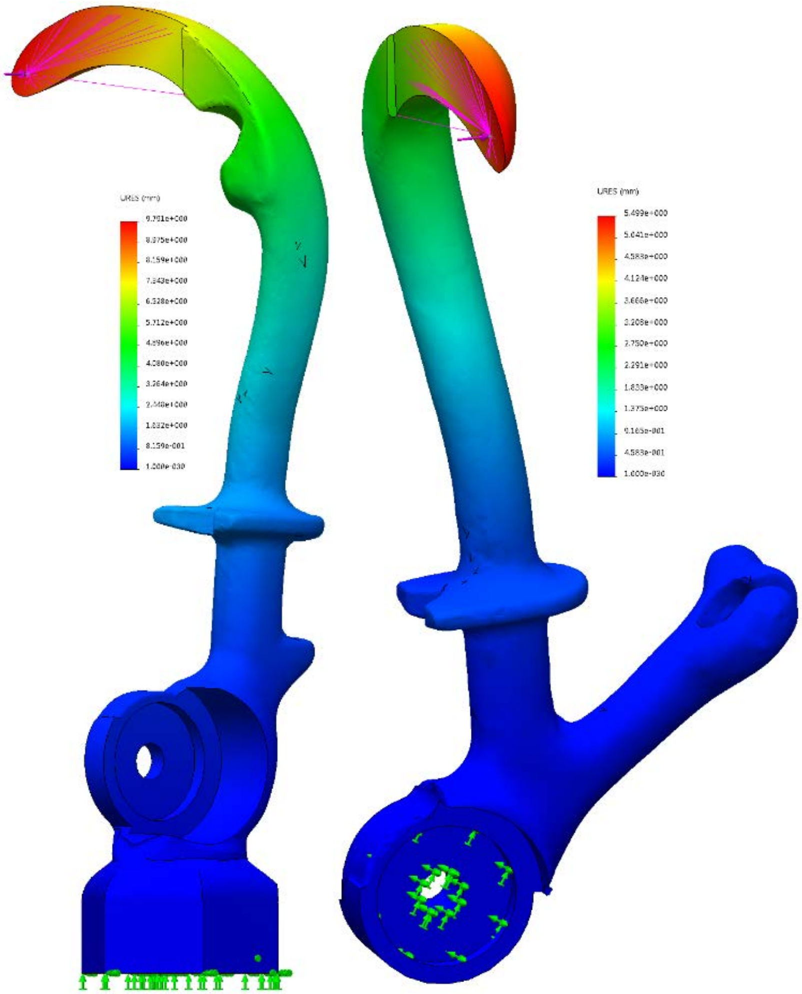


Figure 21: Displacement values of the screw-housing side (left) and the thumb side (right) of the prosthetic replica using PLA material properties.

Figure 22: Stress test being performed on screw-housing side of the 3D printed prosthetic without the added truss.

2.5 Results

2.5.1 Finite Element Analysis

A force of 3.3lbs, the force to open the prosthetic with one prosthetic sized rubber band, was performed on PLA material in the analysis. Consistently, the results showed an improvement on the thumb side and the screw-housing side of the prosthetic towards resistance to displacement and stress at the failure point (Table 1). The thumb side of the prosthetic showed that with the addition of a truss, the max displacement and the normal stress in the Z direction at the point of failure all decreased by 88% and 83% respectively. On the screw-housing side of the prosthetic, with the addition of the truss, the max displacement decreased by 23%, while the normal stress in the Z direction at the point of failure had a decrease in value by 57%. The data shows that the addition of the truss on the thumb side of the prosthetic showed a higher decrease in displacement and stress when compared to the screw-housing side.

Table 1: Comparison of the thumb and screw-housing sides, with the use of a truss and without the truss, in the finite element analysis.

	Thumb Side		Δ	Δ%	Screw-housing Side		Δ	Δ%
	No Truss	Truss			No Truss	Truss		
Max Displacement (mm)	5.499E+00	6.414E-01	-4.858E+00	-88%	9.791E+00	7.578E+00	-2.213E+00	-23%
Z Normal at the Failure Point (N/m^2)	6.559E+06	1.083E+06	-5.476E+06	-83%	8.641E+06	3.746E+06	-4.895E+06	-57%

2.5.2 *Stress Test*

The stress test that was performed on two 3D printed parts made out of PLA material showed that with the addition of a truss, the amount of force needed to break the part increased; however, the displacement of the tip of the prosthetic did not decrease for all the parts (Table 2).

Table 1: Force and displacement values of the 3D printed prosthetics in the stress test needed to break the part.

	Force (lbs)	Displacement (mm)	Notes
No Truss (thumb side)	8.5	22.5	Broke at the divot on the tip
Truss (thumb side)	20	15	Broke in the housing area
No Truss (screw-housing side)	12	80	Broke at the divot on the tip
Truss (screw-housing side)	13.5	90	Broke at bottom and at the divot on the tip

The thumb side of the prosthetic showed a significant improvement with the addition of the truss. With the addition of the truss, it was able to withstand more than double the amount of force than the prosthetic without the truss. The amount of displacement decreased by about 33% on the thumb side as well. The breaking point was different in these two parts, however. The thumb side, without the truss, broke in the divot on the tip, while the part with the truss broke around the bearing housing section. The screw-housing side of the 3D printed prosthetics showed slight improvements in the max force it could withstand. With the addition of the truss, the screw-housing side of the prosthetic was able to withstand an extra 1.5lbs of force, however, the displacement of the part actually increased. The part without the truss broke in the divot on the tip of the part, same as the thumb side, and the part with the truss broke in two places simultaneously, at the divot on the tip, as well as right above the housing unit for the screw.

2.6 Discussion

2.6.1 Finite Element Analysis

The finite element analysis showed that for the thumb side and the screw-housing side of the prosthetic, the addition of the truss greatly improves the performance of the part by lowering the max displacement and the stress at the point of failure that the part goes through.

The design of the truss on the thumb side of the prosthetic delivered better results to the part because it distributed the force of the weight better. On the screw-housing side, there was no "thumb" to distribute the forces to. This distribution of force is what sets apart these two halves of the same prosthetic. An additional part to help distribute the weight on the screw-housing side, like a new "thumb" part, could greatly influence the results of the data and produce a more efficient prosthetic.

2.6.2 Stress Test

The stress test showed a clear design flaw to the geometry of the 3D prosthetic designs. The corner on the tip of the prosthetic, where the rubber inserts were placed, is where improvements can be made. This corner was a stress concentration point and a majority of the parts broke at this location by delaminating the layers on either side of this corner. If this corner was rounded, the stress concentration may have been relaxed.

The addition of the truss on the thumb side showed greater improvement than the screw-housing side. It is interesting to note that with the addition of the truss on the screw-housing side, the stress test displayed an increase in displacement. This is due to the truss distributing the force to the lower portion of the prosthetic and allowing more bending to occur around the screw housing unit before breaking at the corner in the divot on the tip of the part. From the results in the finite element analysis and the stress test, the truss system on the screw-housing side of the 3D printed prosthetic needs to be reevaluated to produce a more efficient model.

2.6.3 Comparison

In the failure analysis, the normal stress from the loading force that was acting in the Z direction was looked at to see if this force contributed significantly to the location of failures in all of the prosthetic halves.

The thumb side of the prosthetic without a truss added showed that the max normal stress in the Z direction was located in the same area where the part broke in the stress test (Figure 23). However, when just looking at the von Mises stress, the max was not located in the area of failure during the stress test. The max normal stress in the Z normal direction could have led to delamination in that area, resulting in the part to fail in the corner on the tip, or areas of delamination, instead of at another location.

The other halves showed similar results (Figure 24, 25, and 26). The halves broke in the area where the max stress, due to the normal stress in the Z direction, was located, except for the screw-housing side with no truss added. The max stress from the Z normal stress for all the halves was in the direction to delaminate the layers in the 3D printed parts. The force required to delaminate the parts and break required less force, so when a large concentration of stress in the

Z normal direction was focused on a certain area, delamination occurred and failure came about in that vicinity first, than in the area of the max von Mises stress. For the screw-housing half that did not break in the area where the max Z normal stress occurred, the part still failed in the area where high concentration of the Z normal stress was located. The part must have just undergone delamination in that area first.

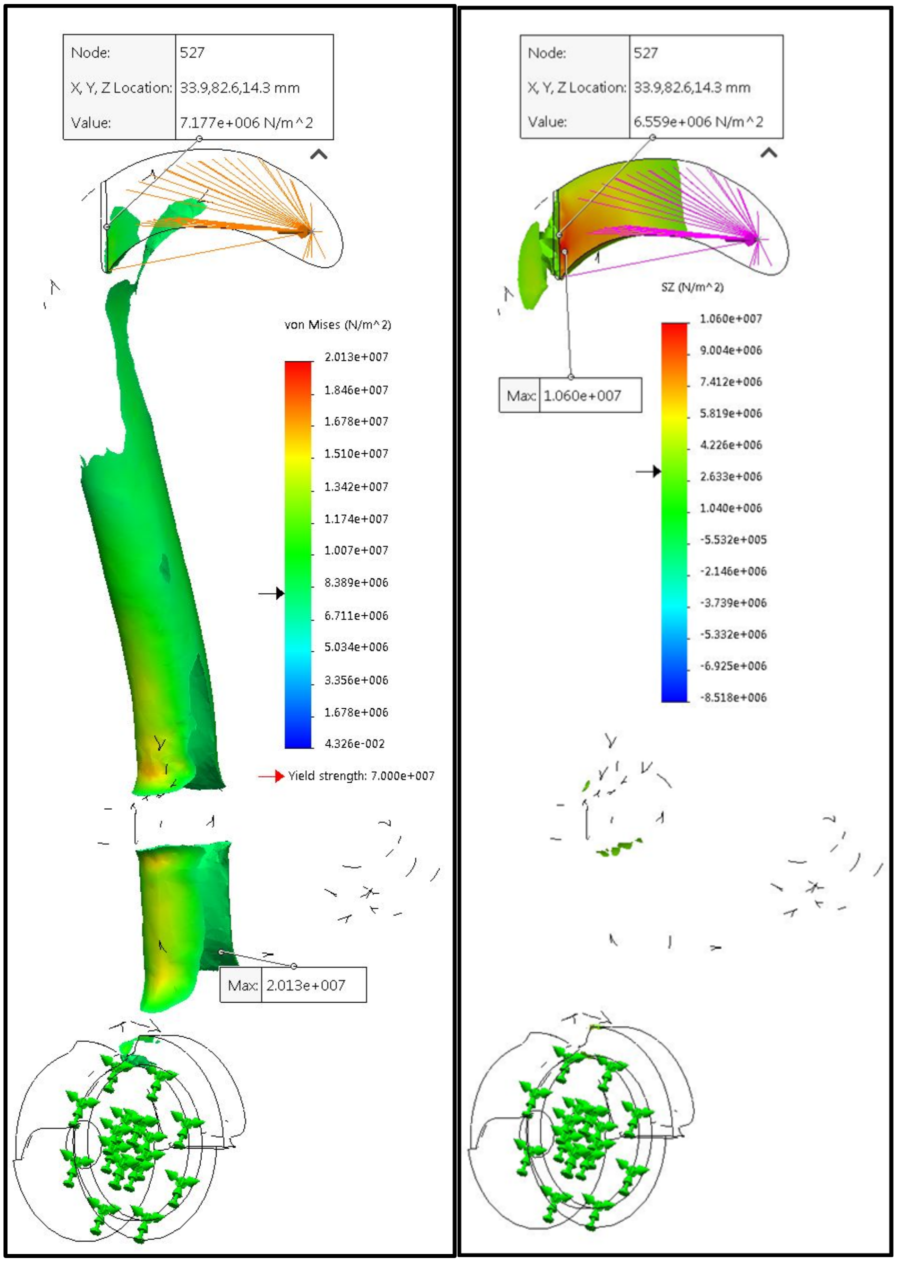
Looking at the system in the stress test, it works similarly to a spring. The expected displacement values from a force of 3.3lbs can be estimated for the parts in the stress test by utilizing the spring force equation:

$$Force = Stiffness \times Displacement$$

Table 3: Estimated displacement values from a force of 3.3lbs.

	Force (lbs)	Stiffness	Displacement (mm)	Estimated Displacement from force of 3.3lbs (mm)	FEA max displacement (mm)
No Truss (thumb side)	8.5	0.378	22.5	8.74	5.499
Truss (thumb side)	20	1.333	15	2.48	0.641
No Truss (screw-housing side)	12	0.15	80	22	9.791
Truss (screw-housing side)	13.5	0.15	90	22	7.578

The thumb side of the prosthetic showed similar displacement values when comparing the estimated displacement to the FEA displacement, while the screw-housing side shows a large difference between the two. As mentioned earlier, this difference in displacement, from a force of 3.3lbs, could be largely due to the truss distributing the force to a lower portion of the prosthetic, allowing more bending to come about before breaking at the corner. Lastly, the stiffness of the parts was calculated to be: .378 for the thumb side with no truss, 1.333 for the thumb side with a truss, and .15 for the screw-hosing side with and without the truss. Seeing an increase in the value for stiffness for the thumb side with the addition of the truss versus the consistent stiffness values in the screw-housing side delivers additional signs that improvements in the truss system for the screw-housing side of the prosthetic can be implemented.



Node: 527
X, Y, Z Location: 33.9,82.6,14.3 mm
Value: 7.177e+006 N/m^2

Max: 2.013e+007

Node: 527
X, Y, Z Location: 33.9,82.6,14.3 mm
Value: 6.559e+006 N/m^2

Max: 1.060e+007

Figure 23: Comparison of the max location between the normal stress in the Z direction (right) and the von Mises stress (left) on the tip of the thumb side of the prosthetic.

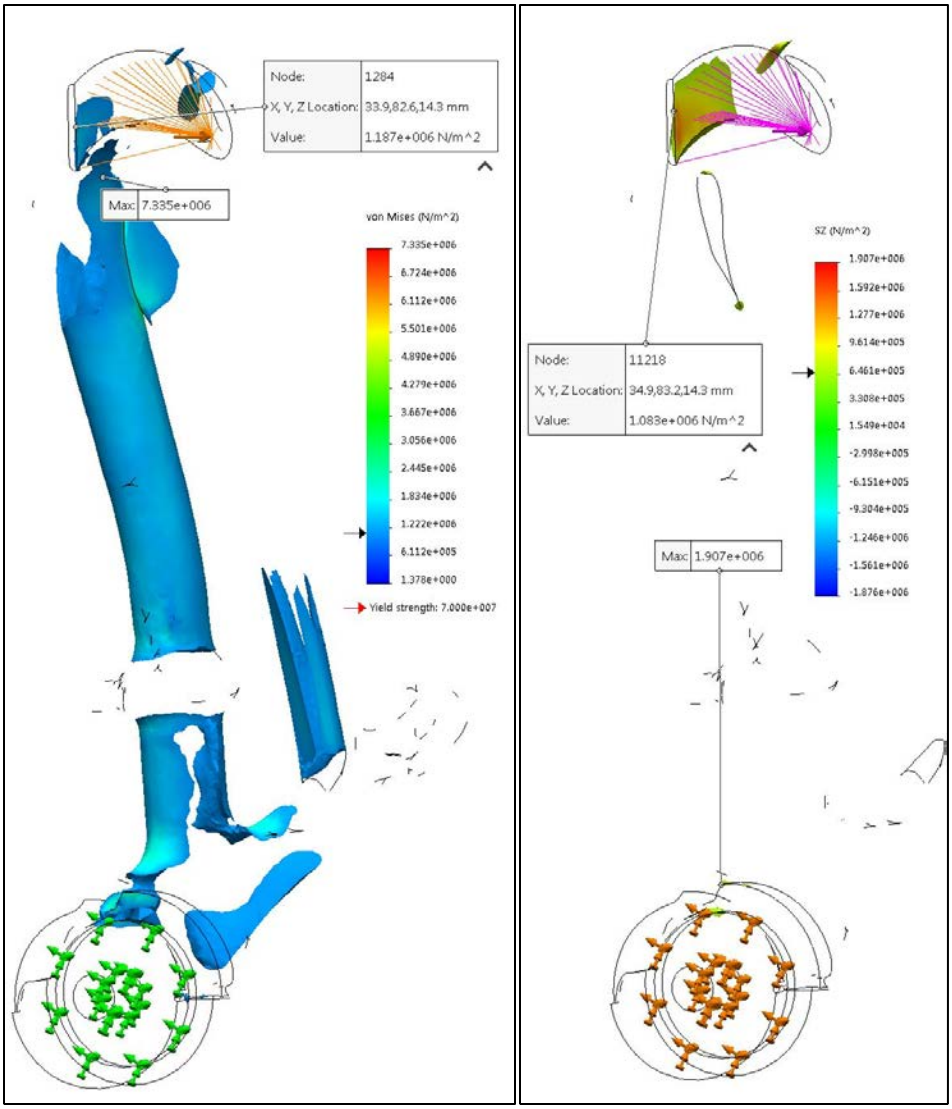


Figure 24: Comparison of the max location between the normal stress in the Z direction (right) and the von Mises stress (left) on the tip of the thumb side of the prosthetic with truss added.

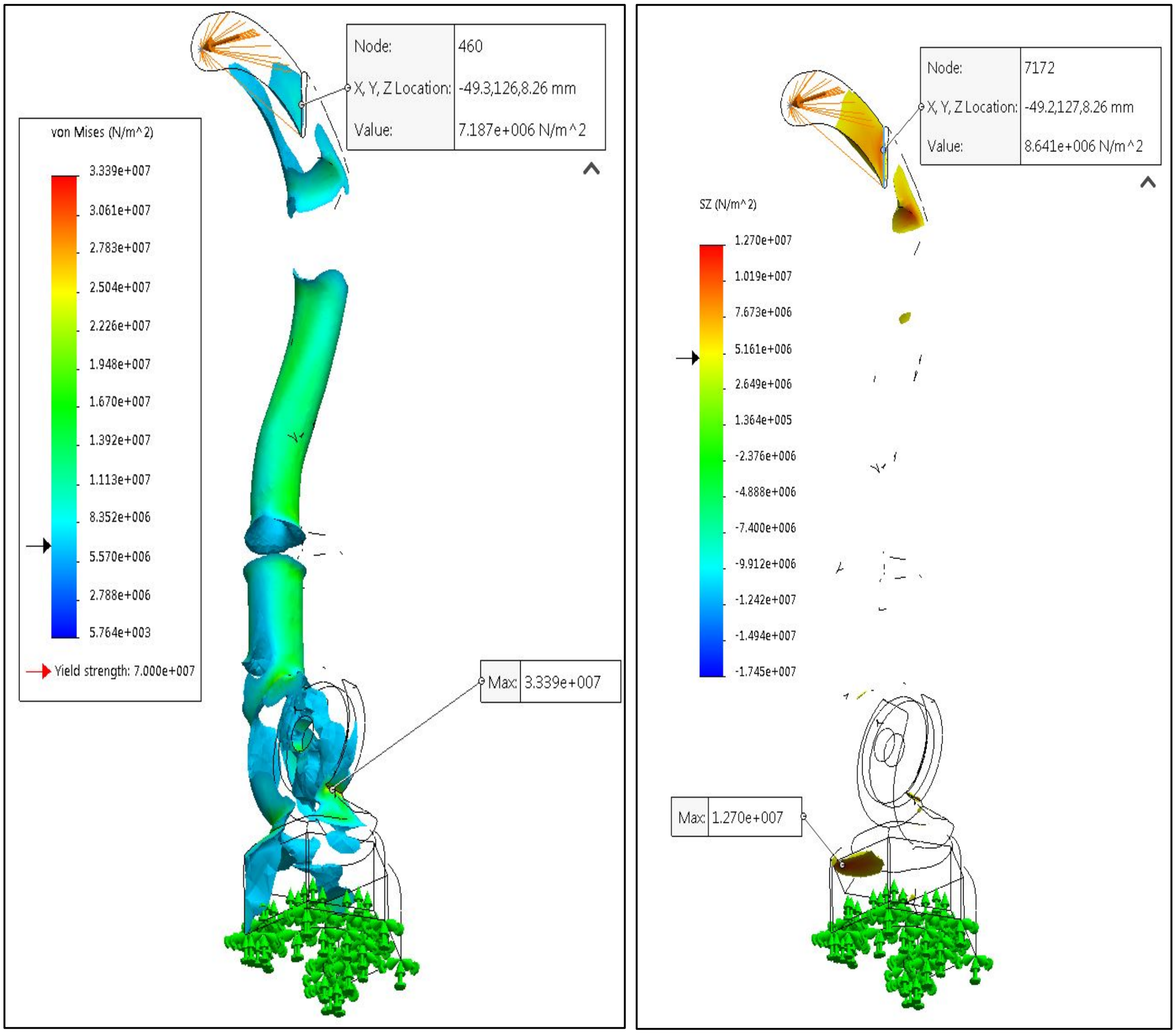
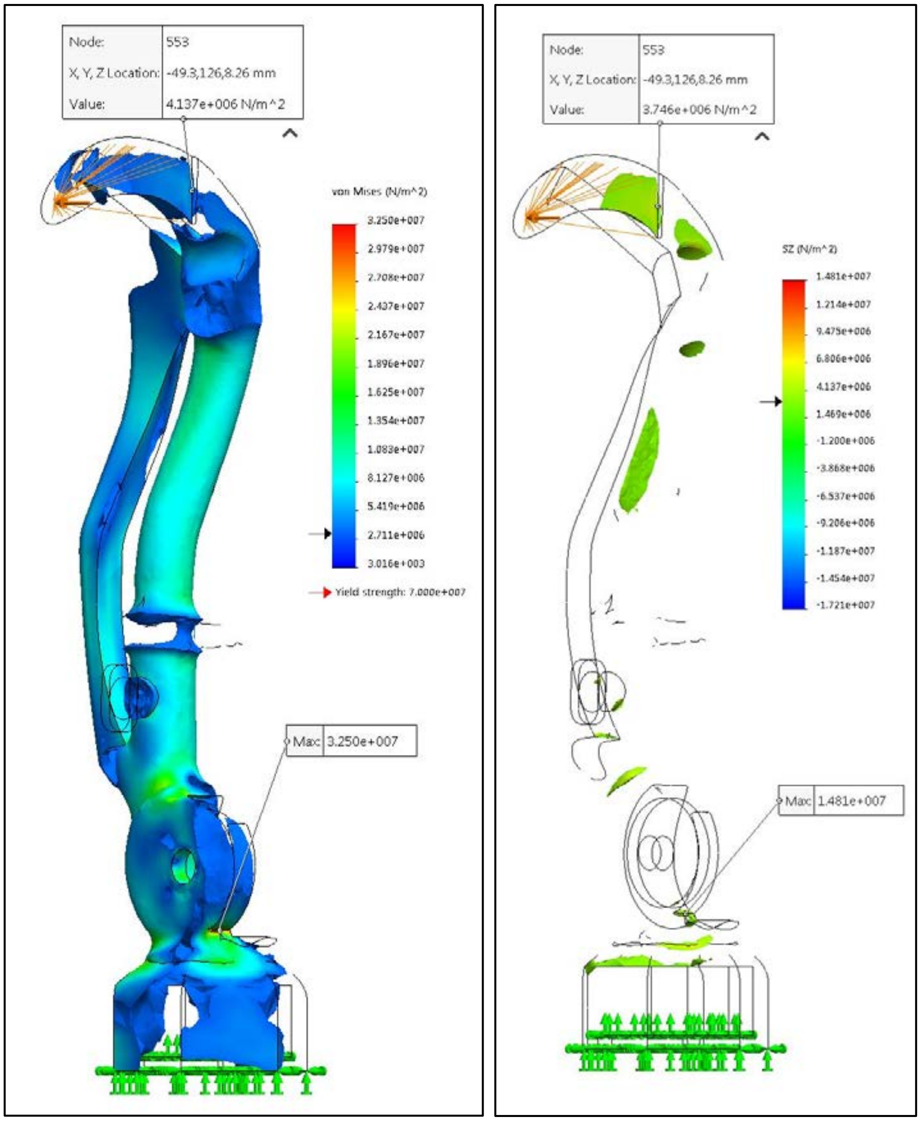


Figure 25: Comparison of the max location between the normal stress in the Z direction (right) and the von Mises stress (left) on the tip of the screw-housing side of the prosthetic.



Node: 553
X, Y, Z Location: -49.3,126,8.26 mm
Value: 4.137e+006 N/m^2

Max: 3.250e+007

Node: 553
X, Y, Z Location: -49.3,126,8.26 mm
Value: 3.746e+006 N/m^2

Max: 1.481e+007

Figure 26: Comparison of the max location between the normal stress in the Z direction (right) and the von Mises (left) on the tip of the screw-housing side of the prosthetic with truss.

3. Development of Hand Prosthesis Simulator

3.1 Prosthetic Simulator

The prosthetic simulator, when first designed, had an issue of being too bulky with an unnecessary amount of material present (Figure 23). The first prototype left no room for adjusting the position of where the Velcro straps can be independently strapped around the user's arm. The bottom of the simulator was flat, and was uncomfortable to the user as well. In the second iteration, a central pole was added so that ribs with the Velcro straps (Figure 24) can be slid on to the main body of the simulator to a comfortable distance. The connection point where the prosthetic is screwed in to place on the simulator was thinned down to an appropriate thickness and was turned to the side to see if the position served better for the user. Problems that arrived in the second iteration is that the sideways orientation to attach the prosthetic limited the space to open the prosthetic. It was a requirement of ours to have the prosthetic facing the same orientation as the hand because we wanted the user to use the prosthetic as if it were their original hand with as little alterations to the positioning as possible. Another error that came about was that we wanted the wrist of the users to play no role in altering or maneuvering the simulator in any way possible. This is was possible with the handle being attached. So, it was necessary for us to remove the handle to prevent any wrist action from intervening. Last, the circular rod that connected to the ribs allowed the ribs to slightly rotate about it because of its smooth surface. To combat this dilemma, the circular rod was turned in to a hexagonal rod to prevent any rotation about it. In the final iteration, we made an above-arm simulator and a below-arm simulator because we wanted to test out the benefits of using a prosthetic below the hand, versus in front of the hand. The rod was also shortened because in the previous iteration, the rod was too long for some people. Before, the simulator was capable of holding three ribs, in the final version, it was design to only hold two ribs.

Figure 27: The prosthetic simulator iterations. The first being on the left, and the final above-arm and below-arm simulators on the right. The second iteration is the part second from the left.

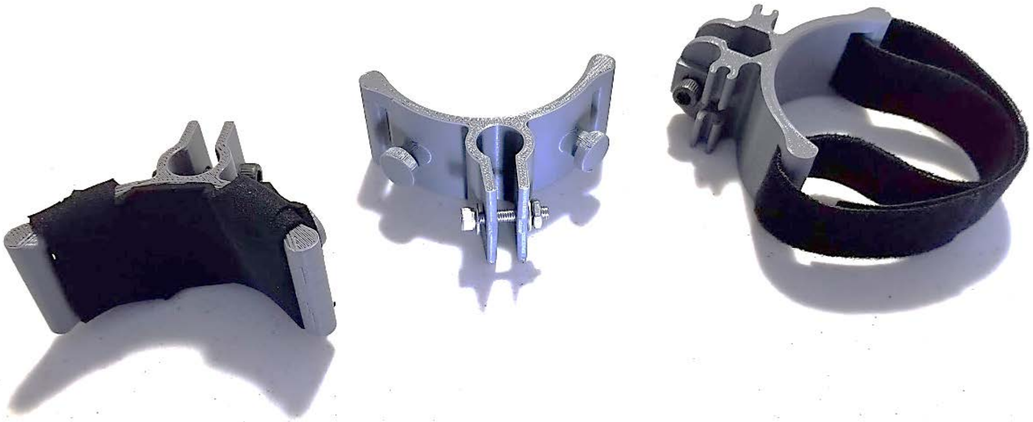


Figure 28: The prosthetic simulator rib iterations. The left two are the first iterations, while the right rib is the final iteration.

3.2 Ribs

The ribs went through smaller iterations, mainly focusing on minimizing the size, making it comfortable, and allowing it to attach to the entire prosthetic setup. The first prototype of the rib was made to fit the circular rod on the main body of the simulator. Screw holes were made above the hole that slid over the pole so that a screw can be placed in to tighten the rib around the pole of the simulator. Fabric holders were placed on each side of the rib in order to hold on to a piece of scuba diving fabric. The scuba diving fabric was placed to give comfort to the user and to reduce friction between the device and skin. The rib's shape was modeled to form a nice arch over the user's arm. This was an improvement over the flat surface on the first iteration of the prosthetic simulator. Channels were then inserted on the side of the ribs to allow a 1-inch width Velcro strap through to tighten on to the user's arm. In the final iteration of the ribs, the fabric holders were removed because the smooth surface of the 3D printed PLA material was smooth enough and did not cause any friction or pain against the skin of the user. The circle was changed to a hexagon to prevent any form of rotation about the pole of the simulator. The portion above the hexagon was shortened in height, rounded on the top corners, and had extra thickness added to the area that the screw is placed to add more reinforcements and a flat surface to the area of stress. The ribs were made symmetrical so that it would not matter which way you put on the ribs, and a small wire clip was created on both sides of the hexagonal hole so that the wire connected to the harness has a place to rest on the prosthetic simulator assembly.

4. Human Subject Trials with Prosthetic Simulator

4.1 Background

It is hypothesized that if the Hosmer 5X Prosthetic Hook is positioned below the user's hand instead of in front of the hand, while on the simulator, then the user will perform quicker and more accurately with the simulator and the Hosmer prosthetic. That the under-arm position better emulates the prosthetic use and will lead to better dexterity than the in front position. Hand-eye recalibration, readjustment of posture, and incorrect position of the prosthesis are some expected shortcomings of the commonly used in front configuration. This is why the Box and Blocks Test is being utilized - to measure the dexterity of the user and to help measure the performance of the simulators.

4.2 Methods

A small sample population of 4 participants participated in this study. The ages of the participants were 22, 23, 23, and 27, and all were male. All participants provided written informed consent prior to participation, and all methods were approved by the Institutional Review Board of Loyola Marymount University. The Box and Blocks Test used in this study works by testing a user's manual dexterity (Mathiowetz and Weber 1985). Typically used for handicapped individuals, the test delivers a score for the users who perform the test. Within a set time limit, the participant moves small blocks, from one side of the box to the other. They must only pick up one block at a time, and they must move the block over the small divider that separates the two sides of the box.

The 3D printed prosthetics and the simulators were printed off the Stratasys F270 and the MakerBot Replicator in PLA material. Two prosthetic positions for the simulator and two different prosthetics were used in randomized order. The two simulator positions were in front of the hand and below the hand, while the two different prosthetics were the original stainless-steel Hosmer 5X Prosthetic Hook and a PLA 3D printed replica. The two prosthetics weighed 5.5oz and 2.5oz respectively, and the only difference being the material and the additional M12-1.25 hex screw connected to the 3D printed replica. The four testing groups were: (1) in front of the hand with the original prosthetic, (2) below the hand with the original prosthetic, (3) in front of the hand with the replica, and (4) below the hand with the replica. During these tests, the position of the box and blocks were positioned closer to the subject, as well as eight inches away from the subject on a table. The three experimental conditions were: the prosthetic material, the prosthetic position, and the box position. The prosthetic material was analyzed to see if the weight difference played a large role in the success of the test; or if the 3D printed replica model performs better or worse than the original. The prosthetic positions were evaluated to see if the position directly below the hand delivered better scores than the in front position. The box position was looked at so that there was a wider range of subject workspace to analyze, to see if there were benefits of a near or far box when testing prosthetic position and material. As mentioned before, participants were assigned to these groups randomly to help balance a learning effect. As people go through the Box and Blocks Test, they naturally become more familiarized with the prosthetic simulators and start to get more skilled at the device. In addition to the random assignment, before each participant started, a training period was administered to further reduce any learning effect from skewing the data.

The participants in this test had an 3D printed PLA prosthetic simulator, that was design for this experiment, Velcro strapped on to their dominant forearm. A Hosmer 5X Prosthetic Hook will be connected to the 3D printed simulator in the distal direction. From there, the Hosmer Northwestern Ring Harness is connected to the prosthetic, fastened on to the back of the individual, and the wire is inserted in to the grooves on the prosthetic simulator (Figure 25). The Hosmer 5X Prosthetic Hook was 3D scanned with the Artec Space Spider, surfaced on Geomagic Wrap, and redesigned in SOLIDWORKS in order to create the 3D printed replica and a new 3D printed prototype.

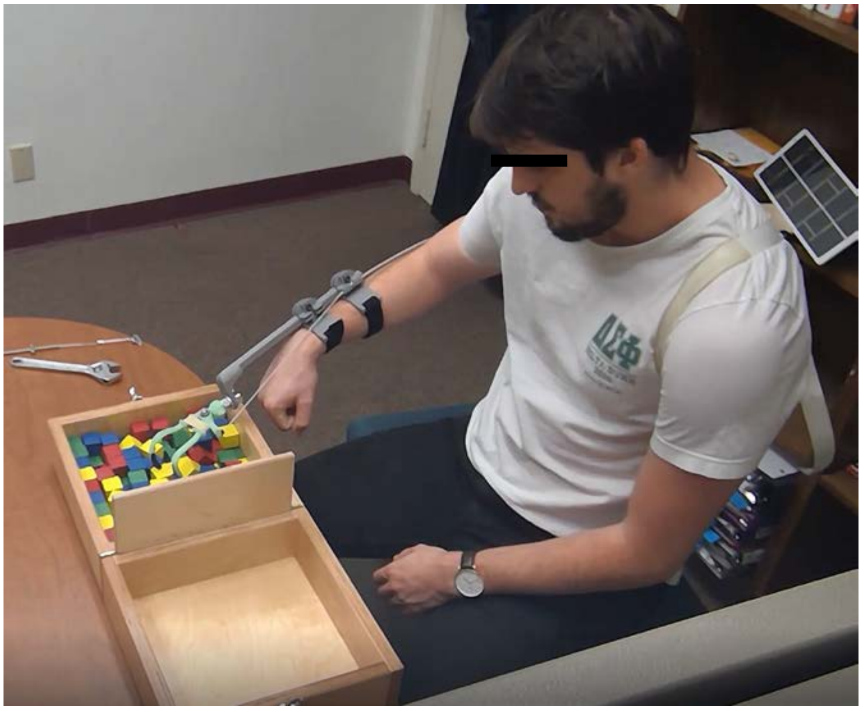


Figure 29: The Box and Blocks Test being performed with the above-arm simulator and the plastic prosthetic.

Last, the number of blocks that were moved in a set time limit of 60 seconds were measured to calculate the performance of the individual. The current test results were developed as preliminary tests. In future trials, the individuals will perform the Box and Blocks Test while the user's arm positions are tracked and calculated. The participants movements will be calculated on Qualisys Track Manager software, with a nine-camera tracking system, and a camera sample rate of 240Hz.

4.3 Results

4.3.1 Box and Blocks Test

During the Box and Blocks Test, all the participants completed all of the tasks asked of them (Table 3). Looking at the average scores of all the participants, there was a small learning effect in play as the trials progressed through the study, despite there being a training period of about 1 minute at the beginning of each study right before they started using the simulator (Figure 26). The largest learning effect was displayed after trial number 2. Trial number B1 and B2 were the box and blocks assessment trials when the participants used no simulator or prosthetic and performed the tasks with their dominant hand.

The scores from the two simulator positions were averaged together to look at the performance of the front position versus the bottom position. These score averages were taken from trial number 1 through 8 (Figure 27), as well as from trial number 3 through 6 (Figure 28) to see if the absence of the learning effect affected the results. For trials 1 through 8, the front simulator position had an average score of 19.5 ± 3.8, while the bottom position had an average score of 20.625 ± 2.9. For trials 3 through 6, the front position had an average score of 21 ± 2.4, while the bottom position had a score of 20.125 ± 2.48. The same analysis was performed for the effect of prosthetic material. Again, these averages of these two variables were taken from trial 1 through 8 (Figure 29), and also from trial 3 through 6 when learning had minimal impact (Figure 30). For trials 1 through 8, the plastic material received an average score of 20.19 ± 3.6, while the metal material received a score of 19.9 ± 3.28. For trials 3 through 6, the plastic material had a score of 21 ± 2.45 and the metal material had a score of 20 ± 2.39.

Table 4: Scores of the four participants in the Box and Blocks Test. Darker rows indicate the rows used to remove the learning effect.

Task	Prosthetic	Simulator
Near = 1	Metal = 1	Front = 1
Far = 0	Plastic = 0	Bottom = 0

Subject S33	Task	Prosthetic	Simulator	Score	Trial #	Subject S35	Task	Prosthetic	Simulator	Score	Trial #
	1	-	-	59	B1		1	-	-	59	B1
	0	-	-	66	B2		0	-	-	64	B2
	1	0	0	20	1		1	0	1	13	1
	0	0	0	17	2		0	0	1	17	2
	1	1	0	17	3		1	1	1	22	3
	0	1	0	18	4		0	1	1	23	4
	1	0	1	19	5		1	0	0	21	5
	0	0	1	24	6		0	0	0	22	6
	1	1	1	18	7		1	1	0	23	7
	0	1	1	16	8		0	1	0	25	8
Subject S34	Task	Prosthetic	Simulator	Score	Trial #	Subject S36	Task	Prosthetic	Simulator	Score	Trial #
	1	-	-	67	B1		1	-	-	54	B1
	0	-	-	63	B2		0	-	-	58	B2
	1	1	0	21	1		1	1	1	16	1
	0	1	0	25	2		0	1	1	15	2
	1	0	0	24	3		1	0	1	18	3
	0	0	0	22	4		0	0	1	18	4
	1	1	1	23	5		1	1	0	19	5
	0	1	1	20	6		0	1	0	18	6
	1	0	1	27	7		1	0	0	16	7
	0	0	1	23	8		0	0	0	22	8

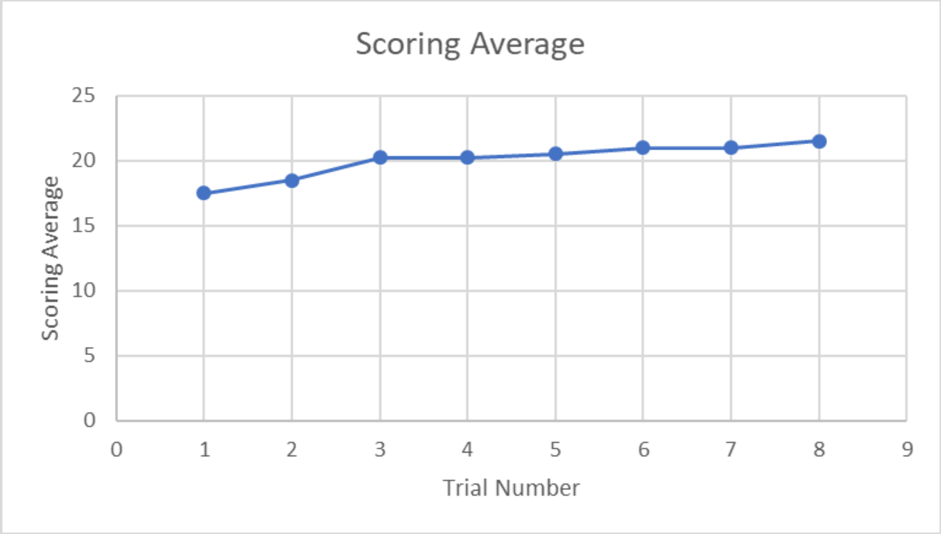


Figure 30: Summation of the scoring averages of all the participants for every simulator trial.

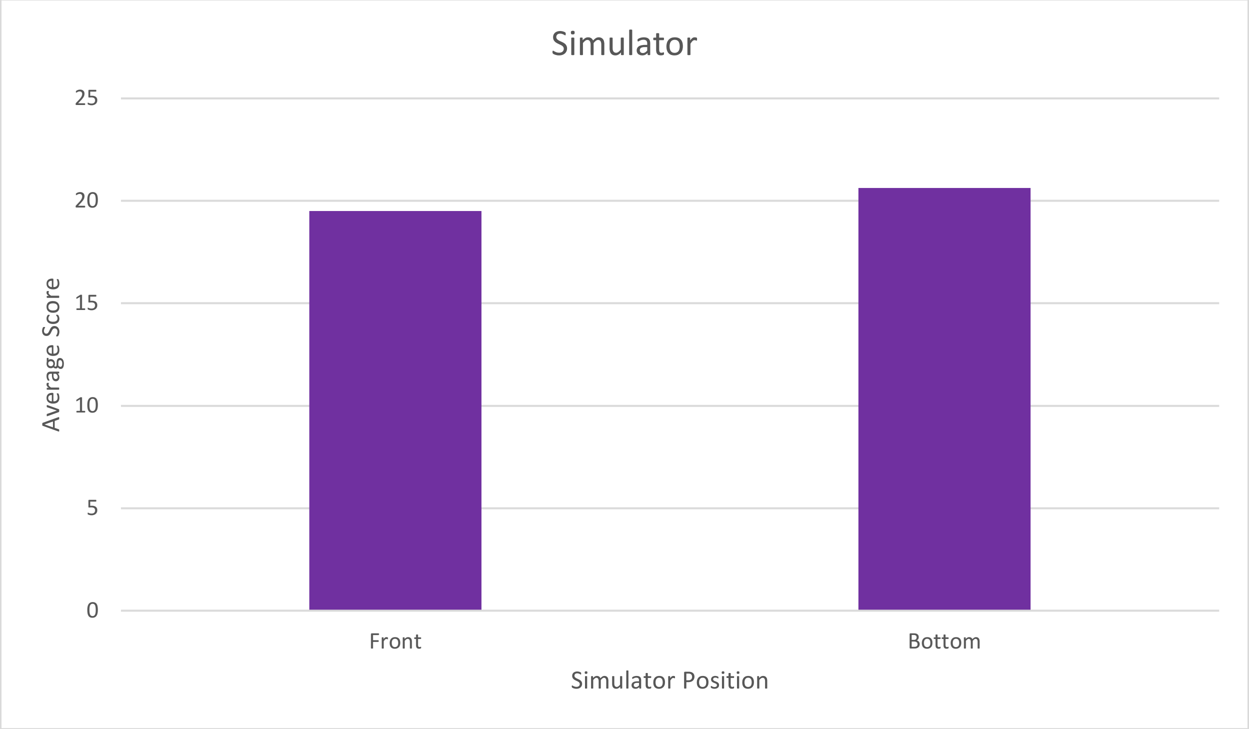


Figure 31: Average scores for the simulator positions.

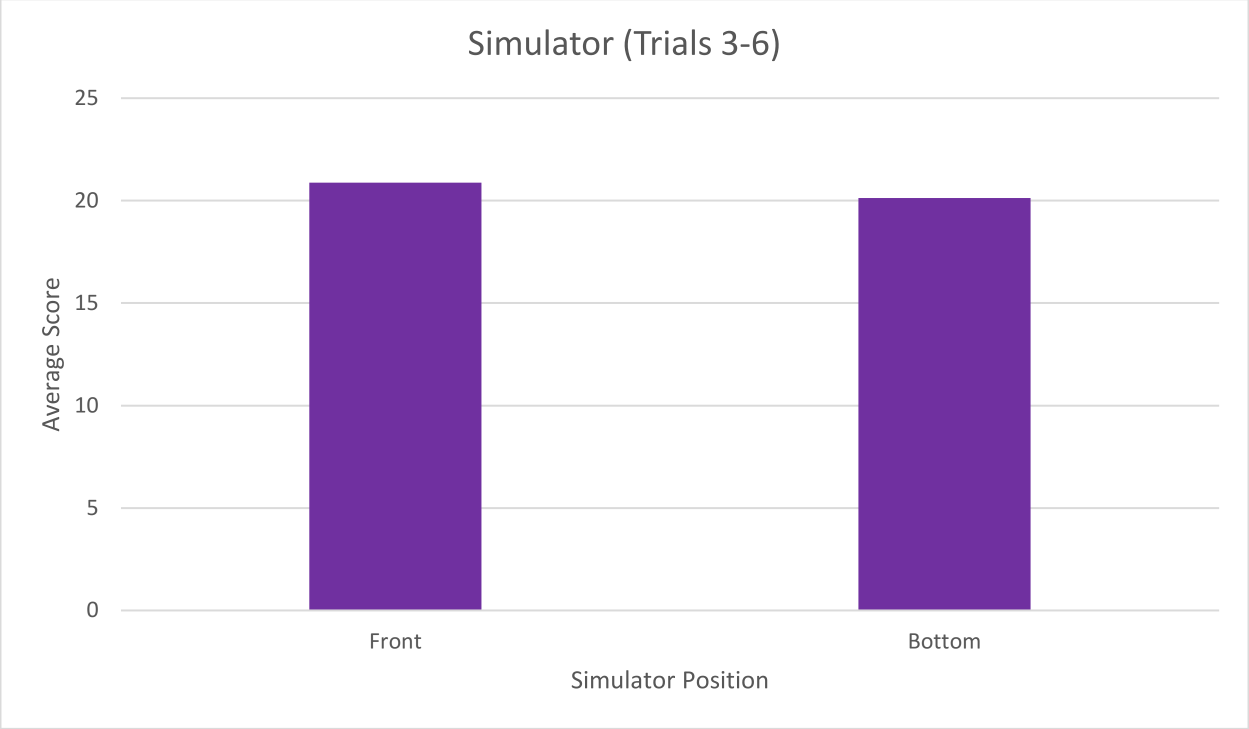


Figure 32: Average scores of the simulator positions where the learning effect is less present.

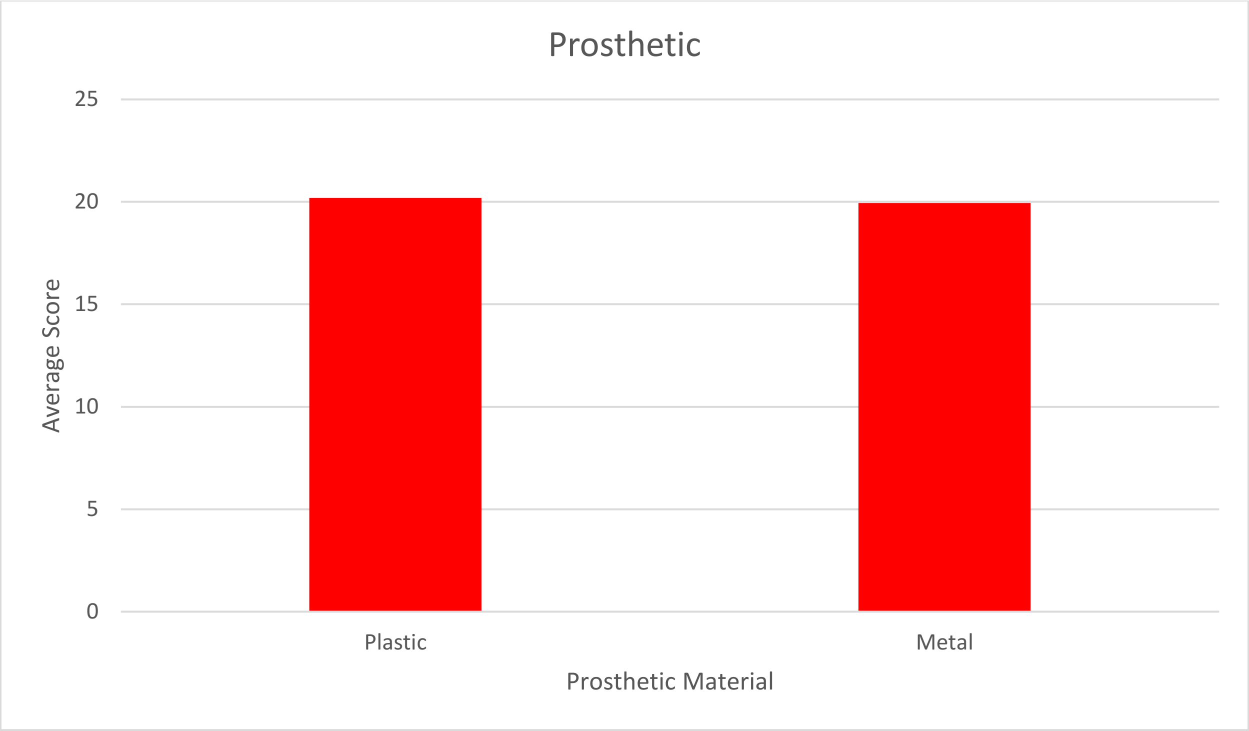


Figure 33: Average scores of the prosthetic material.

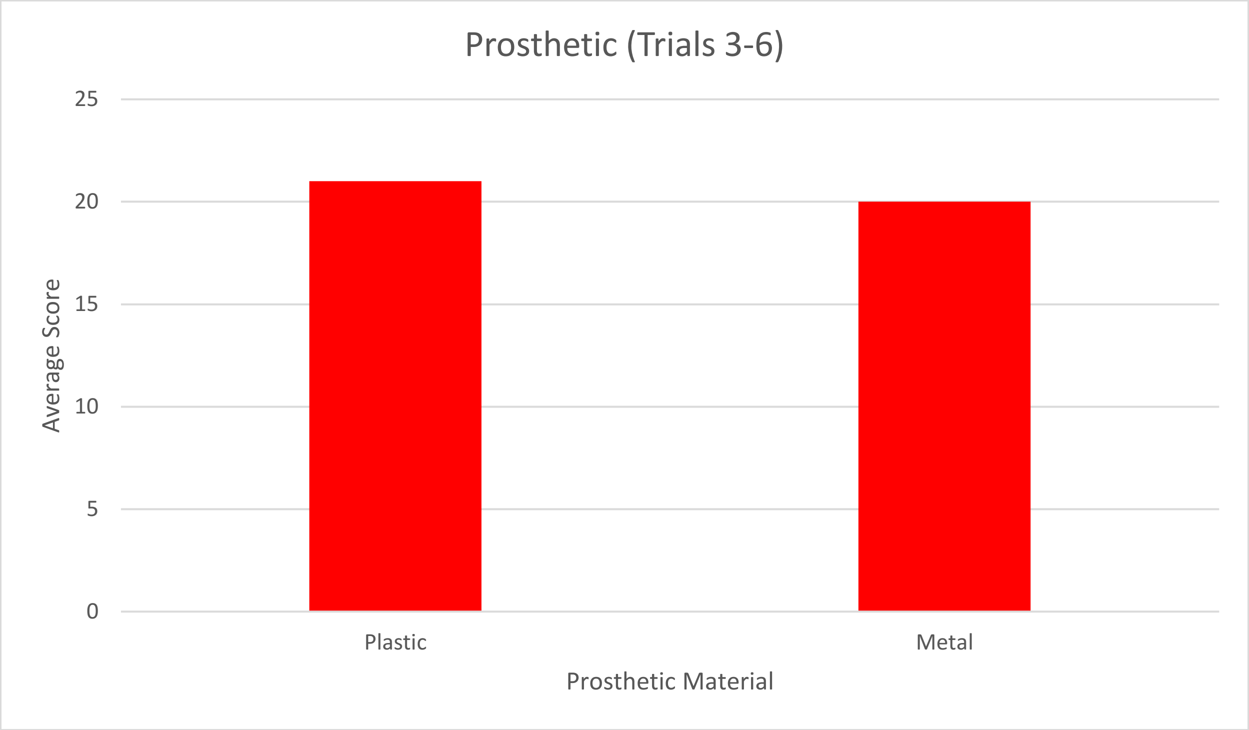


Figure 34: Average scores of the prosthetic material where the learning effect is less present.

4.4 Discussion

The entire results from the Box and Blocks Test suggested that there is a minor performance enhancement when utilizing the prosthetic simulator in the bottom position as well as using the plastic prosthetic.

The effect of material could have arisen from the difference in weight between the prosthetic. The lighter weight of the plastic prosthetic could have allowed the user to move more swiftly throughout the study. The metal prosthetic's weight may have tired the user's arm slightly faster, making them fatigue and less accurate. This is important because it speculates that all the weight in the metal prosthetic is overbearing. The user may only need a light prosthetic to get simple tasks done, while also being able to minimize the number of pounds they must lift with their arm.

The bottom prosthetic position could have allowed the participant to reach the item quicker, thus leading to a slightly higher score. By positioning the prosthetic simulator on the bottom, the user was able to position the prosthetic in a similar location as their actual human hand. This position could have given them better hand-eye coordination because the prosthetic is closer to where their real hand is located, limiting any need for hand-eye calibration. However, with the simulator being below the hand, the user could have had a disadvantage by having limited eye sight of the prosthetic because of their hand getting in the way of their vision. The front simulator position could have impeded the subjects' dexterity because it effectively lengthened their forearm, requiring them to readjust their posture to grab blocks at closer distances. Ultimately, the bottom simulator still can mimic the common angles that humans encounter in motor movement because it is a simple offset of the joint angle. The simulator position in front of the hand is not a common experience when grabbing ahold of items, and this results in new motor movement to compensate for this new position. Lastly, the in-line simulator could have made it easier for the participant to get over the divider in the Box and Blocks Test since the prosthetic was in line with the user's arm. For the most part, if their real hand made it over the divider, then the prosthetic makes it across too, while for the under-arm prosthetic there is still room for hitting the divider, even if their human hand makes it over.

There seems to still be a learning effect even after the short training the users received before the first trial with the prosthetic simulator. This effect appears to mostly level out after trial 2. In future experiments, the results could be better isolated from learning effects by adding two full trials prior to the main set of 8 trials. In particular, it may be advantageous if trials 1 and 2 were repeated before moving on to the remaining 6 trials. Then the data from trials 1 and 2 could be used to measure the learning effect, and the data from the new trials 3 and 4 (the repeat of trials 1 and 2) could be compared with the remaining 6 trials to measure the effects of simulator position and material, with a reduced impact of learning.

The effects of prosthetic position and material were also measured across trials 3 through 6 during which the learning effect was not as great. It is interesting to see that the in-line position had a slightly better score than the bottom position when only these trials were considered. The plastic material still led to a higher score than the metal. If the learning effect was eliminated, it is assumed that these results would reappear, with the top simulator and the plastic material having higher scores; however, it is impossible to tell which position led to better scores without a larger sample size. It is interesting to note that the participants who used the front position simulator first had a more dramatic learning effect over the first three trials. As more data is collected, it will be intriguing to identify if this phenomenon means that the bottom position has a quicker learning period, while the in-front position has a longer learning period, or was it just those subjects in particular.

5. Conclusion

It was hypothesized that by locating the prosthetic simulator under the user's hand, then the user would have better results in the Box and Blocks Test. This hypothesis was shown to be true; however, there are still many other variables to look at that could change the results. Since, on average, the user's performed better with the above-arm simulator when looking at trials 3 through 6, this shows that the learning effect needs to be dealt with at a greater scale. To completely assess the hypothesis, a larger sample size will be needed to do so.

These preliminary tests that were done in this study not only gave us insight on the prosthetic simulator position and the material choice for the prosthetic, it also gave us a better understanding on performing more accurate and reliable tests as we move forward and continue with this study. In the upcoming trials, the addition of a tracking system will be added to help us understand the body movements that go along with the simulator positions and the prosthetics being used. The additional tracking system in the upcoming tests will give us a more in-depth view on how the user behaves when they are grabbing an item in a location that is not close to their original hand position. The tests in this study also exposed better approaches to drastically remove the learning effect when the study is running in the future with the tracking system and a larger population. When running the study, trial 1 and 2 will be repeated for a second time in a row to help towards eliminating any learning effect.

In terms of improving the Hosmer 5X Prosthetic Hook by adding a truss system, we learned that if a truss system from the thumb side of the prosthetic was used on the screw-housing side of the prosthetic, then the prosthetic can be evenly improved to perform basic human tasks, as well as withstand greater forces as well. In addition to that, completely removing the divot on the tip of the prosthetic can insure a better distribution of force throughout the prosthetic parts.

As we move forward and continue with the study, as mentioned before, the first thing we will be looking in to is improving the format of test to ensure that the data delivers more impactful results. The population will be larger, more diverse, while the tracking system and a greater reduction of the learning effect will improve our results. For the prosthetic simulator and the prosthetic, it will be interesting to work with stronger 3D printing materials, such as NylonX, to figure out how to further optimize the models. Diving deeper in to the printing orientation, as well, will give us insight on optimizing the prints and making them as durable as possible in areas of high loading. The results from the test show that utilizing the replica prosthetic hook for heavy duty tasks would be detrimental. Tasks that require strenuous manual labor, like operating tools and machinery, may result in to a loading stress too high for the hook to handle, resulting in the prosthetic breaking.

Creating an easily accessible, cost efficient simulator that works consistently and reliably for schools and labs is the goal. By having a standardized simulator for schools and laboratories to use, any imbalance in simulators can potentially be removed, leading to more consistent results in tests and studies. For prosthetic users, they can receive prosthetics that can go through more rigorous testing because researchers can utilize a standardized simulator to test prosthetics on a wider population of nonamputees. In addition, delivering a 3D printable prosthetic that can withstand the use of daily living, weigh less than the original, be more cost effective, and also be easily distributed is an important task as well. With the average delivery time for a prosthetic being 6 months, and the critical time to teach an amputee how to use their prosthetic being the first 30 days after amputation, delivering a solution to the individual quickly is critically important and finding a solution to this issue seems beneficial to the success of the amputee and their device (Malone et al. 1984; Davies, Friz, and Clippinger 1970).

References

“A Body Powered Actuation System for Prosthetic Hands.” 2018. 2018. <https://hackaday.io/project/4745-openbionics-affordable-prosthetic-hands/log/27117-body-powered-actuation-system-for-prosthetic-hands>

“Amputee Store.” 2018. 2018. https://amputeestore.com/collections/all/products/hosmer-model-5x-prosthetic-hook.

Belter, Joseph T., Bo C. Reynolds, and Aaron M. Dollar. 2014. “Grasp and Force Based Taxonomy of Split-Hook Prosthetic Terminal Devices.” *2014 36th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBC 2014*, 6613–18. https://doi.org/10.1109/EMBC.2014.6945144.

Biddiss, Elaine, and Tom Chau. 2007. “Upper Limb Prosthesis Use and Abandonment: A Survey of the Last 25 Years.” *Prosthetics and Orthotics International* 31 (3): 236–57. https://doi.org/10.1080/03093640600994581.

"Body Powered Prosthetic Simulator." 2018. 2018. https://www.trsprosthetics.com/product/body-powered-prosthetic-simulator/.

Bouwsema, Hanneke, Corry K. van der Sluis, and Raoul M. Bongers. 2008. “The Role of Order of Practice in Learning to Handle an Upper-Limb Prosthesis.” *Archives of Physical Medicine and Rehabilitation* 89 (9): 1759–64. https://doi.org/10.1016/j.apmr.2007.12.046.

Buckingham, Gavin, Johnny Parr, Greg Wood, Samuel Vine, Pan Dimitriou, and Sarah Day. 2018. “The Impact of Using an Upper-Limb Prosthesis on the Perception of Real and Illusory Weight Differences.” *Psychonomic Bulletin and Review* 25 (4): 1507–16. https://doi.org/10.3758/s13423-017-1425-2.

Cordella, Francesca, Anna Lisa Ciancio, Rinaldo Sacchetti, Angelo Davalli, Andrea Giovanni Cutti, Eugenio Guglielmelli, and Loredana Zollo. 2016. “Literature Review on Needs of Upper Limb Prosthesis Users.” *Frontiers in Neuroscience* 10 (MAY): 1–14. https://doi.org/10.3389/fnins.2016.00209.

Dalley, Skyler A., Tuomas E. Wiste, Thomas J. Withrow, and Michael Goldfarb. 2009. “Design of a Multifunctional Anthropomorphic Prosthetic Hand with Extrinsic Actuation.” *IEEE/ASME Transactions on Mechatronics* 14 (6): 699–706. https://doi.org/10.1109/TMECH.2009.2033113.

Datta, Dipak, Kanther Selvarajah, and Nicola Davey. 2004. “Functional Outcome of Patients with Proximal Upper Limb Deficiency–acquired and Congenital.” *Clinical Rehabilitation*

18 (2): 172–77. https://doi.org/10.1191/0269215504cr716oa.

Davidson, Judith. 2002. "A Survey of the Satisfaction of Upper Limb Amputees with Their Prostheses, Their Lifestyles, and Their Abilities." *Journal of Hand Therapy* 15 (1): 62–70. https://doi.org/10.1053/hanthe.2002.v15.01562.

Davies, Elizabeth J., Barbara R. Friz, and Frank W. Clippinger. 1970. "Amputees and Their Prostheses." *Artificial Limbs* 14 (2): 19–48.

Disabled World. (2018-08-18). Prostheses and Prosthetics: Artificial Limbs News and Information. Retrieved 2018-09-29, from https://www.disabled-world.com/assistivedevices/prostheses/Finch, Jacqueline Louise, Glyn Harvey Heath, Ann Rosalie David, and Jai Kulkarni. 2012. "To the History of Prosthetics."

Dombroski, Colin E., Megan E R Balsdon, and Adam Froats. 2014. "The Use of a Low Cost 3D Scanning and Printing Tool in the Manufacture of Custom-Made Foot Orthoses: A Preliminary Study." *BMC Research Notes* 7 (1): 2–5. https://doi.org/10.1186/1756-0500-7-443.

Doneus, Michael, Geert Verhoeven, Clement Atzberger, Michael Wess, and Michal Rusˇ. 2014. "New Ways to Extract Archaeological Information from Hyperspectral Pixels." *Journal of Archaeological Science* 52: 84–96. https://doi.org/10.1016/j.jas.2014.08.023.

Finch, Jacqueline Louise, Glyn Harvey Heath, Ann Rosalie David, and Jai Kulkarni. 2012. "To the History of Prosthetics."

Gao, Fan, and Susan Kapp. 2011. "A BODY-POWERED UPPER LIMB PROSTHETIC SIMULATOR American Academy of Orthotists & Prosthetists 37 Th Academy Annual Meeting And," 2011.

Haverkate, Liz, Gerwin Smit, and DIck H. Plettenburg. 2016. "Assessment of Body-Powered Upper Limb Prostheses by Able-Bodied Subjects, Using the Box and Blocks Test and the Nine-Hole Peg Test." *Prosthetics and Orthotics International* 40 (1): 109–16. https://doi.org/10.1177/0309364614554030.

"Hosmer Hooks Catalog." 2018. 2018. https://hosmer.com/products/hooks/.

"i-limb quantum." 2018. 2018. http://touchbionics.com/products/i-limb-accessories.

Huinink, Laura H.B., Hanneke Bouwsema, Dick H. Plettenburg, Corry K. Van der Sluis, and Raoul M. Bongers. 2016. "Learning to Use a Body-Powered Prosthesis: Changes in Functionality and Kinematics." *Journal of NeuroEngineering and Rehabilitation* 13 (1): 1–12. https://doi.org/10.1186/s12984-016-0197-7.

Jones, L. E, and J. H Davidson. 1999. "Save That Arm : A Study of Problems in the Remaining Arm of Unilateral Upper Limb Amputees." *Prosthetics and Orthotics International* 23 (1): 55–58. https://doi.org/10.3109/03093649909071611.

K Mills, David. 2015. "Future Medicine: The Impact of 3D Printing." *Journal of Nanomaterials & Molecular Nanotechnology* 04 (03). https://doi.org/10.4172/2324-8777.1000163.

Kejlaa, G. H. 1993. “Consumer Concerns and the Functional Value of Prostheses to Upper Limb Amputees.” *Prosthetics and Orthotics International* 17 (3): 157–63. https://doi.org/10.3109/03093649309164376.

“MakerBot Replicator Mini+ Compact 3D Printer.” 2018. 2018. https://store.makerbot.com/printers/replicator-mini/.

Malone, J M, L L Fleming, J Roberson, T E Whitesides, J M Leal, J U Poole, and R S Grodin. 1984. “Immediate, Early, and Late Postsurgical Management of Upper-Limb Amputation.” *Journal Of Rehabilitation Research And Development* 21 (1): 33–41. http://www.ncbi.nlm.nih.gov/pubmed/6527288.

Mathiowetz, Virgil, and Karen Weber. 1985. “Adult Norms for the Box and Block Test of Manual Dexterity.” *The American Journal of Ocupational Therapy* 39 (6): 387–91.

“Monoprice MP Select Mini 3D Printer V2.” 2018. 2018. https://www.monoprice.com/product?p_id=21711.

Mota, Anissa. 2017. “Materials of Prosthetic Limbs,” 7. https://broncoscholar.library.cpp.edu/bitstream/handle/10211.3/193171/MotaAnissa_LibraryResearchPaper2017.pdf?sequence=1.

“NylonX Carbon Fiber Filament.” 2018. 2018. https://www.matterhackers.com/store/3d-printer-filament/nylonx-carbon-fiber-nylon-filament-1.75mm?gclid=Cj0KCQiAlIXfBRCpARIsAKvManyoOJ99V2p0ouP-UMncTFUrMg56gSjJ2lovgCeeQ6RxzdOTV6kGxDoaAnz2EALw_wcB.

“Older Adults Can Thrive as Prosthesis Users” 2018. 2018. https://www.amputee-coalition.org/resources/thrive-as-prosthesis-users/

Phillips, Brienna, Gabrielle Zingalis, Sarah Ritter, and Khanjan Mehta. 2015. “A Review of Current Upper-Limb Prostheses for Resource Constrained Settings.” *Proceedings of the 5th IEEE Global Humanitarian Technology Conference, GHTC 2015*, no. December: 52–58. https://doi.org/10.1109/GHTC.2015.7343954.

R.Ishengoma, Fredrick, and Adam B. Mtaho. 2014. “3D Printing: Developing Countries Perspectives.” *International Journal of Computer Applications* 104 (11): 30–34. https://doi.org/10.5120/18249-9329.

Radocy, By Bob. 1987. “Upper-Extremity Prosthetics : Considerations and Designs for Sports and Recreation.” *Clinical Prothetics and Orthotics* 11 (3): 131–53. http://www.oandplibrary.org/cpo/pdf/1987_03_131.pdf.

“PolyCast.” 2018. 2018. http://www.polymaker.com/shop/polycast-4/.

“PolyFlex.” 2018. 2018. http://www.polymaker.com/shop/polyflex/.

“Raise 3D Pro2 Plus 3D Printer.” 2018. 2018. https://www.raise3d.com/products/pro2-plus-3d-printer.

Rafiq, Noorani. 2006. *Rapid Prototyping: Principles and Applications*.

Romkema, S., R. M. Bongers, and C. K. van der Sluis. 2013. “Intermanual Transfer in Training

With an Upper-Limb Myoelectric Prosthesis Simulator: A Mechanistic, Randomized, Pretest-Posttest Study.” *Physical Therapy* 93 (1): 22–31. https://doi.org/10.2522/ptj.20120058.

Romkema, Sietske, Raoul M. Bongers, and Corry K. van der Sluis. 2017. “Influence of the Type of Training Task on Intermanual Transfer Effects in Upper-Limb Prosthesis Training: A Randomized Pre-Posttest Study.” *PloS One* 12 (11): e0188362. https://doi.org/10.1371/journal.pone.0188362.

Sobuh, Mohammad M D, Laurence P J Kenney, Adam J. Galpin, Sibylle B. Thies, Jane McLaughlin, Jai Kulkarni, and Peter Kyberd. 2014. “Visuomotor Behaviours When Using a Myoelectric Prosthesis.” *Journal of NeuroEngineering and Rehabilitation* 11 (1): 1–11. https://doi.org/10.1186/1743-0003-11-72.

Strait, Erin, Grant McGimpsey, and Tc Bradford. 2006. “Limb Prosthetics Services and Devices.” *White Paper*, no. January: 1–35. http://www.glb.nist.gov/tip/wp/pswp/upload/239_limb_prosthetics_services_devices.pdf%5Cnhttps://notendur.hi.is/ats9/Prosthetics in DevelopingCountries.pdf.

“Stratasys F123 Series Printers.” 2018. 2018. http://www.stratasys.com/3d-printers/f123.

"The advantages of 3D printing." 2019. 2018. https://www.3dhubs.com/knowledge-base/advantages-3d-printing

Weeks, Douglas L., Stephen A. Wallace, and David I. Anderson. 2003. “Training with an Upper-Limb Prosthetic Simulator to Enhance Transfer of Skill across Limbs.” *Archives of Physical Medicine and Rehabilitation* 84 (3 SUPPL. 1): 437–43. https://doi.org/10.1053/apmr.2003.50014.

Ziegler-Graham, Kathryn, Ellen J. MacKenzie, Patti L. Ephraim, Thomas G. Travison, and Ron Brookmeyer. 2008. “Estimating the Prevalence of Limb Loss in the United States: 2005 to 2050.” *Archives of Physical Medicine and Rehabilitation* 89 (3): 422–29. https://doi.org/10.1016/j.apmr.2007.11.005.

Zuniga, Jorge, Dimitrios Katsavelis, Jean Peck, John Stollberg, Marc Petrykowski, Adam Carson, and Cristina Fernandez. 2015. “Cyborg Beast: A Low-Cost 3d-Printed Prosthetic Hand for Children with Upper-Limb Differences.” *BMC Research Notes* 8 (1). https://doi.org/10.1186/s13104-015-0971-9.

Zuo, Kevin J., and Jaret L. Olson. 2014. “The Evolution of Functional Hand Replacement: From Iron Prostheses to Hand Transplantation.” *Canadian Journal of Plastic Surgery* 22 (1): 44–51. https://doi.org/10.1177/229255031402200111.

“3D Printing helps Mr. Stubbs the Alligator get a new Tail” 2018. 2018. https://3dprint.com/221027/3d-printed-alligator-tail/

Appendices

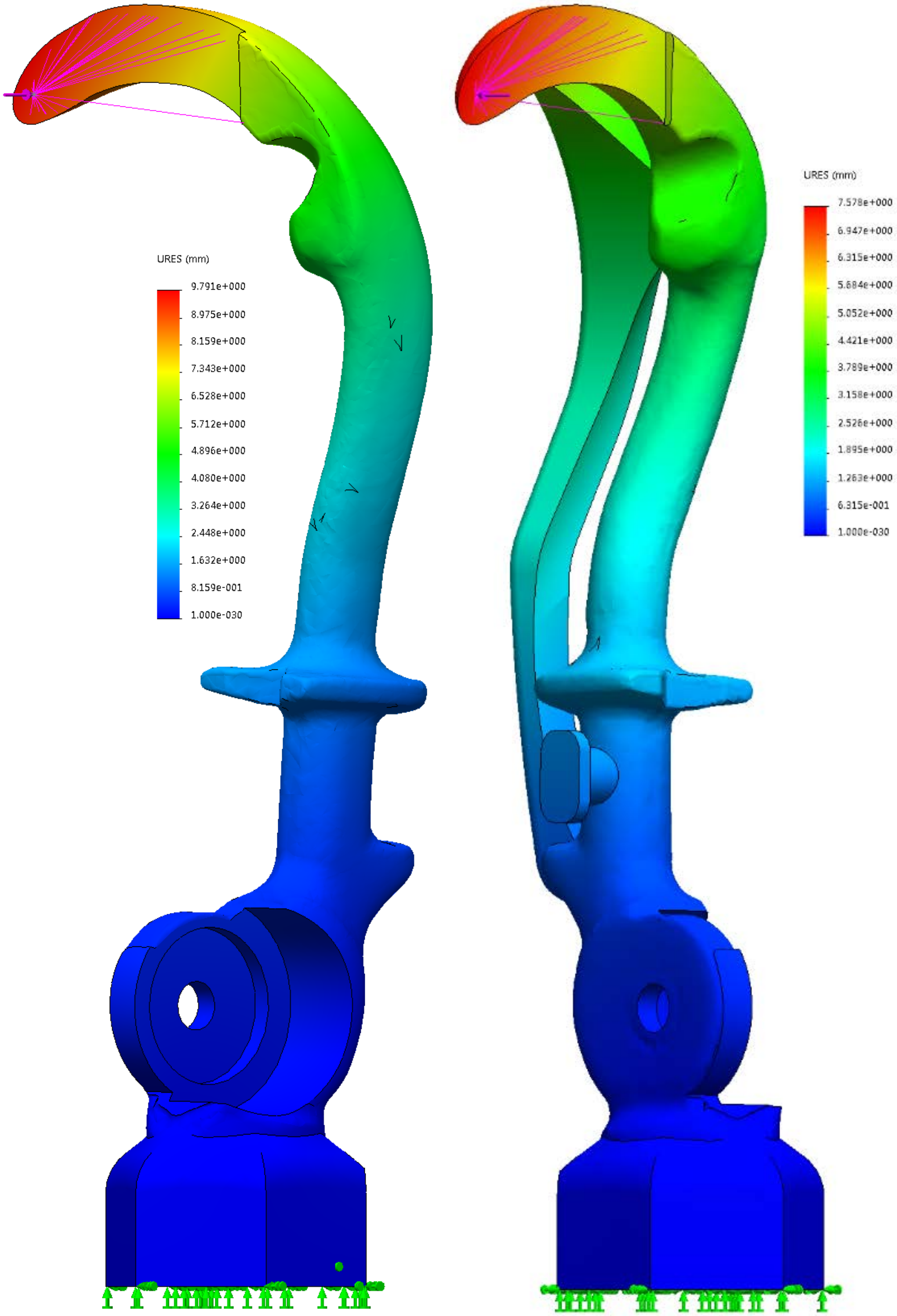


Figure 35: Displacement values of the screw-housing side of the prosthetic with no truss (left) and with truss (right) using PLA properties.

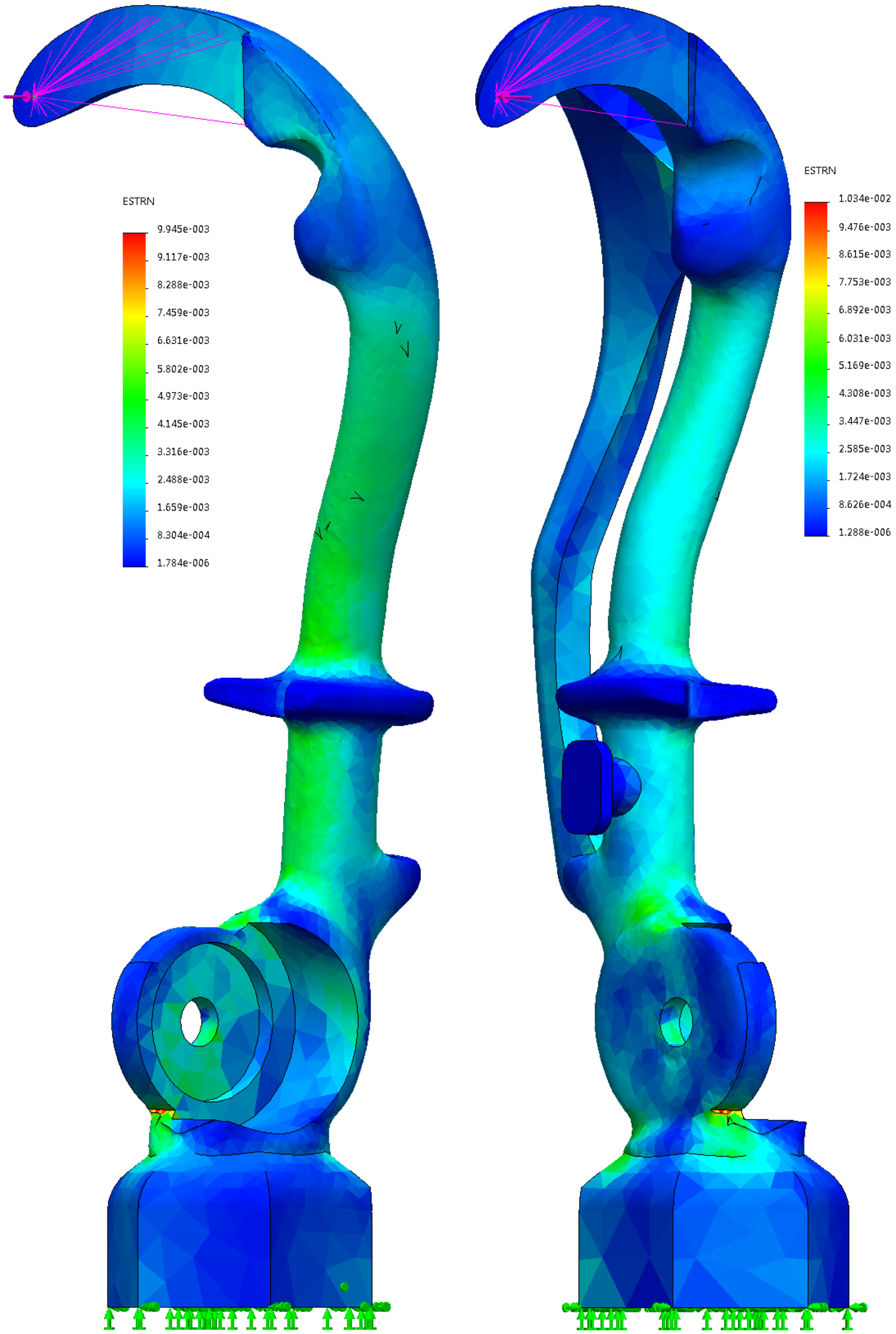


Figure 36: Strain values of the screw-housing side of the prosthetic with no truss (left) and with truss (right) using PLA properties.

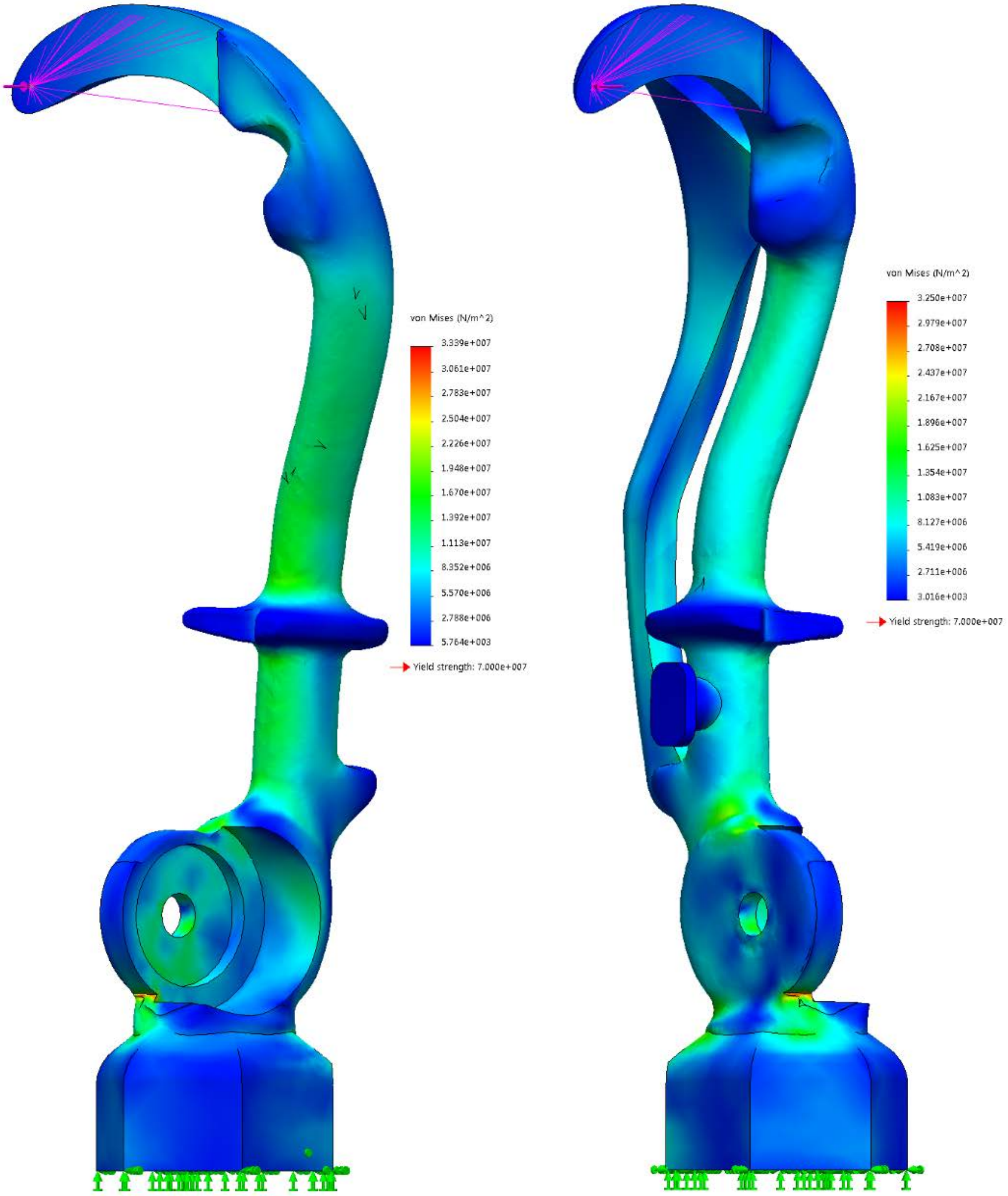


Figure 37: Stress values of the screw-housing side of the prosthetic with no truss (left) and with truss (right) using PLA properties.

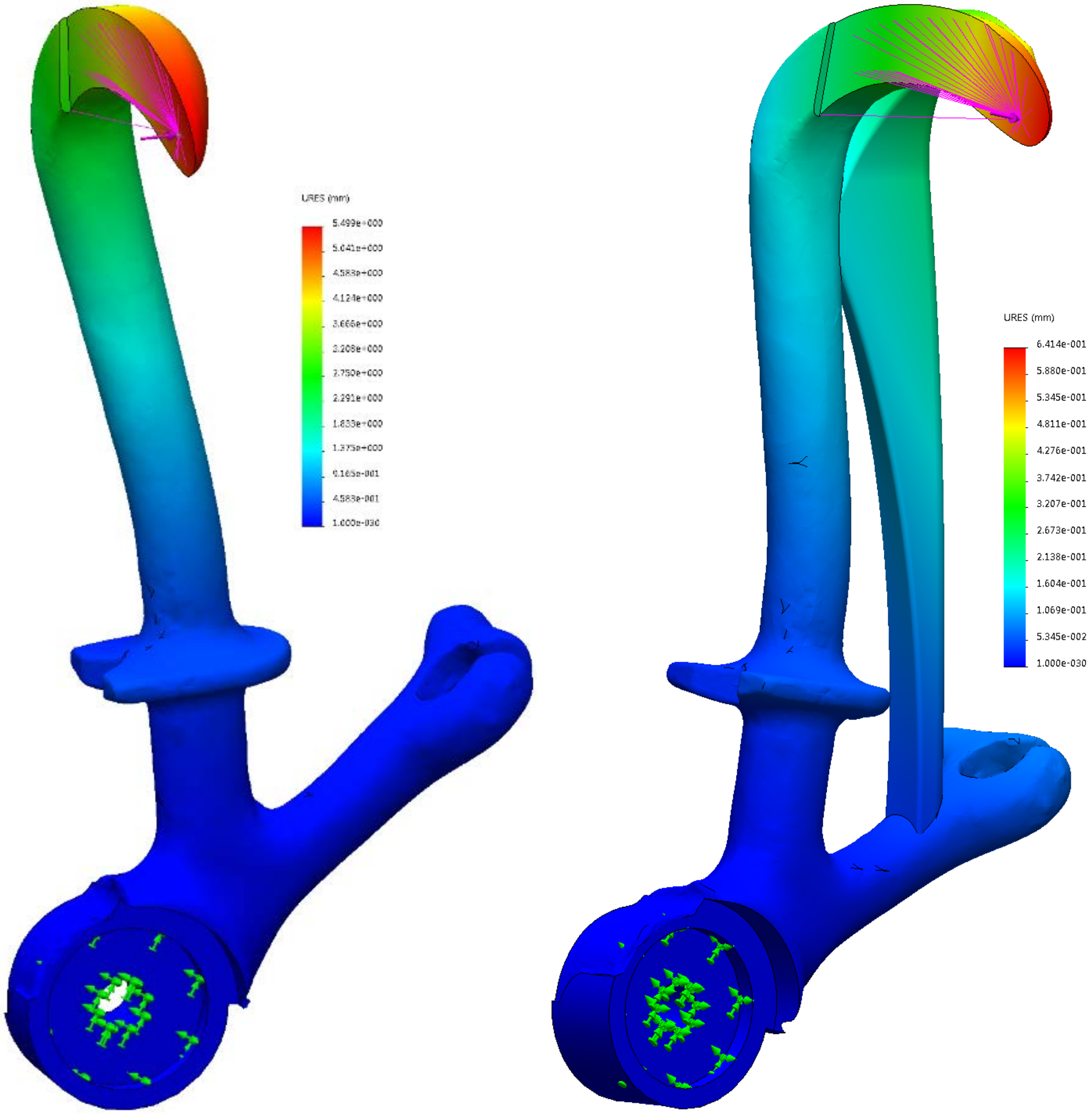


Figure 38: Displacement values of the thumb side of the prosthetic with no truss (left) and with truss (right) using PLA properties.

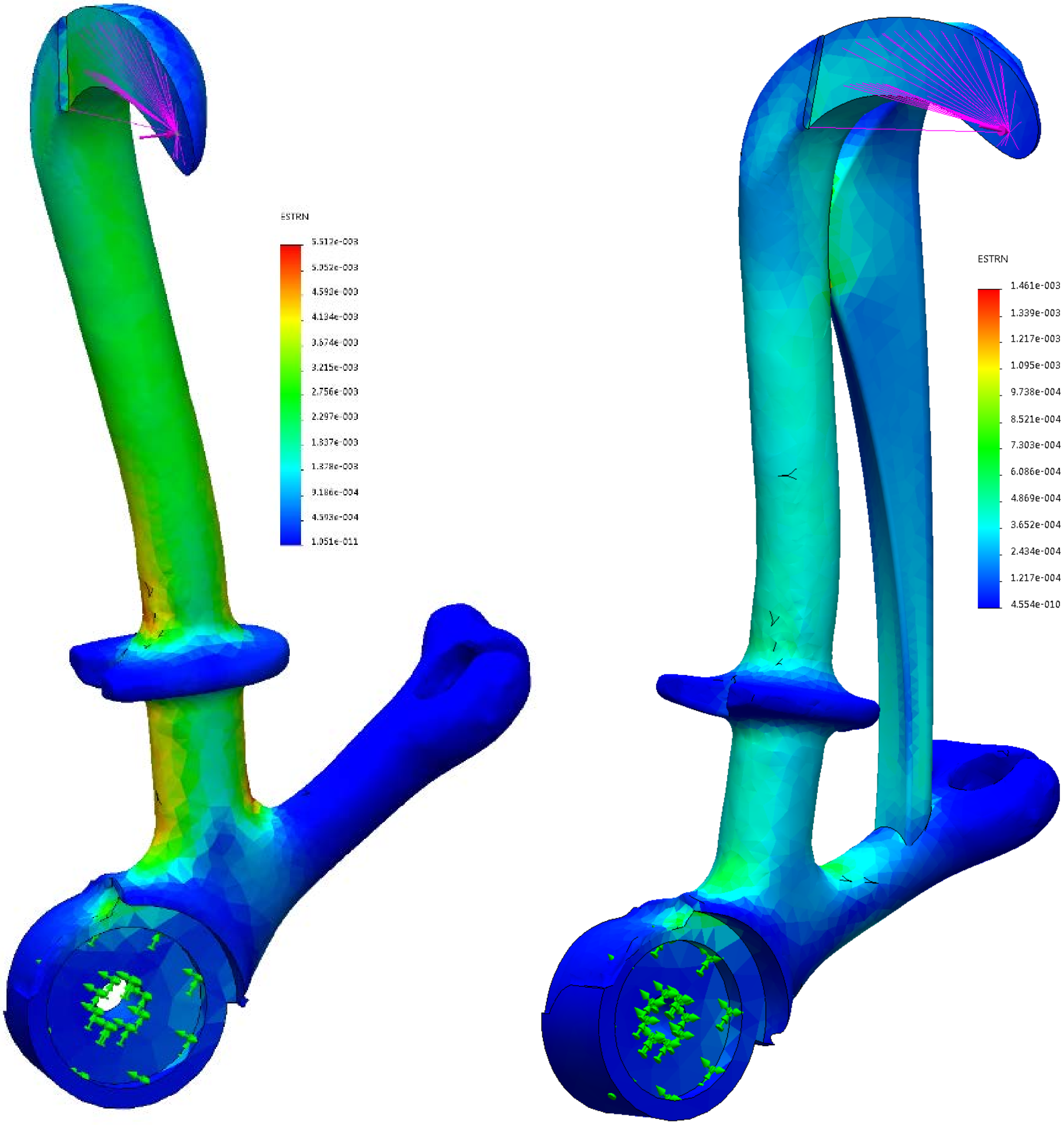


Figure 39: Strain values of the thumb side of the prosthetic with no truss (left) and with truss (right) using PLA properties.

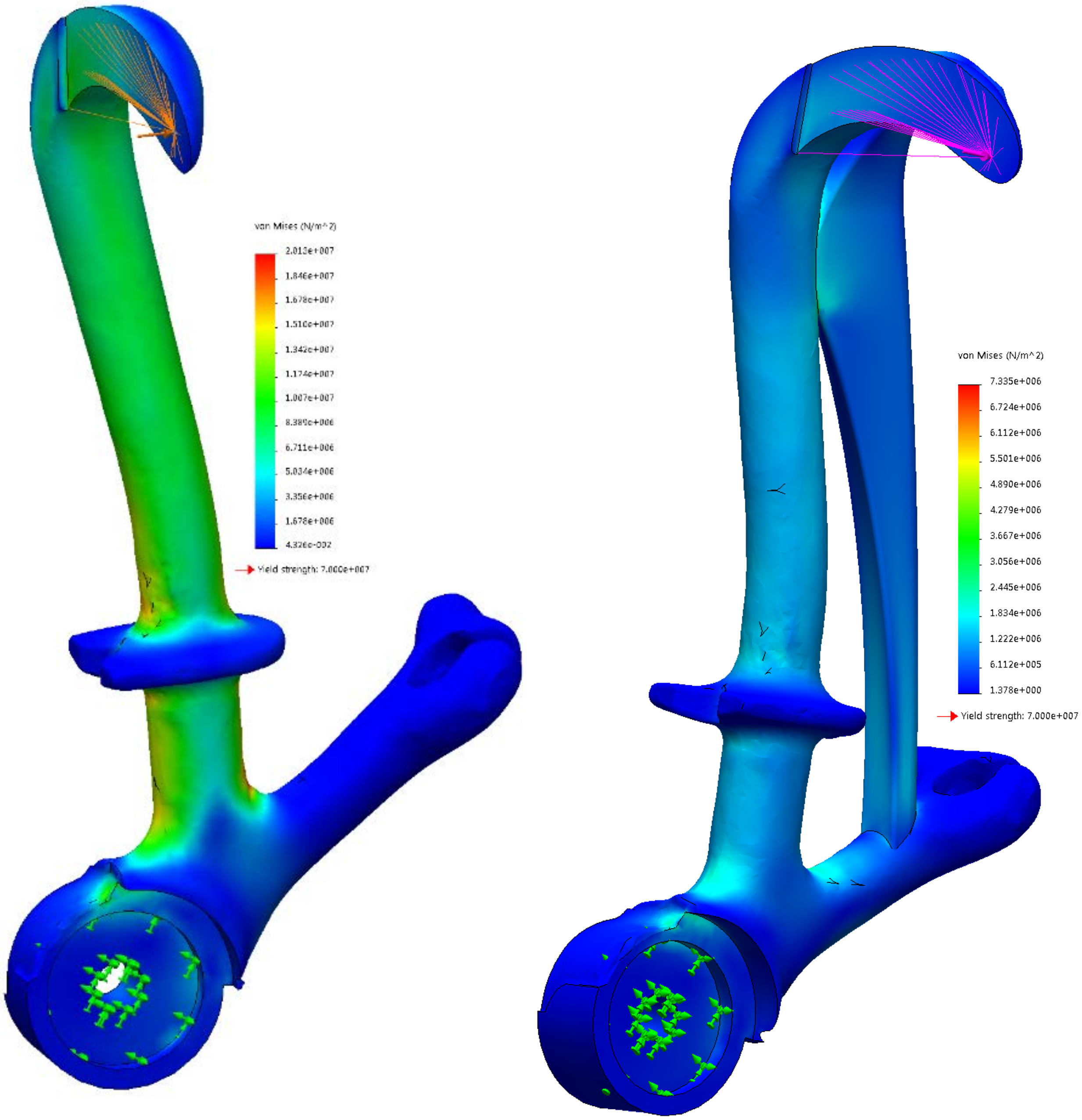


Figure 40: Stress values of the thumb side of the prosthetic with no truss (left) and with truss (right) using PLA properties.

Figure 41: Post stress test of screw-housing half of the 3D printed prosthetic with no truss.

Figure 42: Post stress test of screw-housing half of the 3D printed prosthetic with truss.

Figure 43: Post stress test of thumb half of the 3D printed prosthetic with no truss.

Figure 44: Post stress test of thumb half of the 3D printed prosthetic with truss.

Figure 45: Entire configuration for the above-arm simulator.

Figure 46: Above-arm simulator.

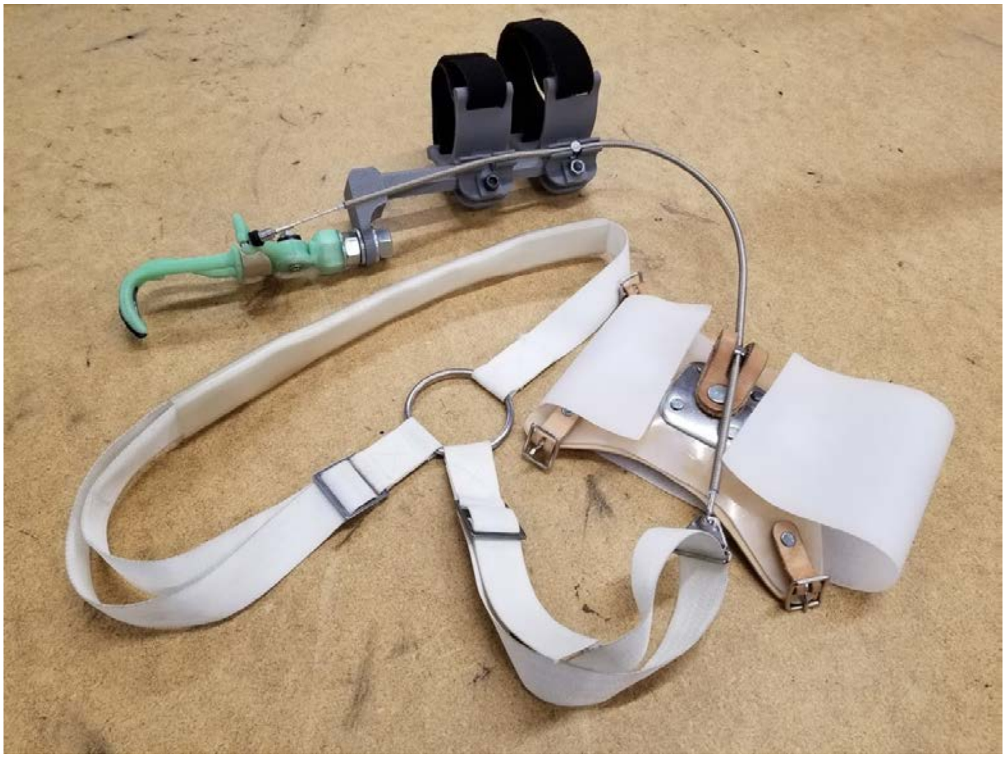


Figure 47: Entire configuration for the below-arm simulator.

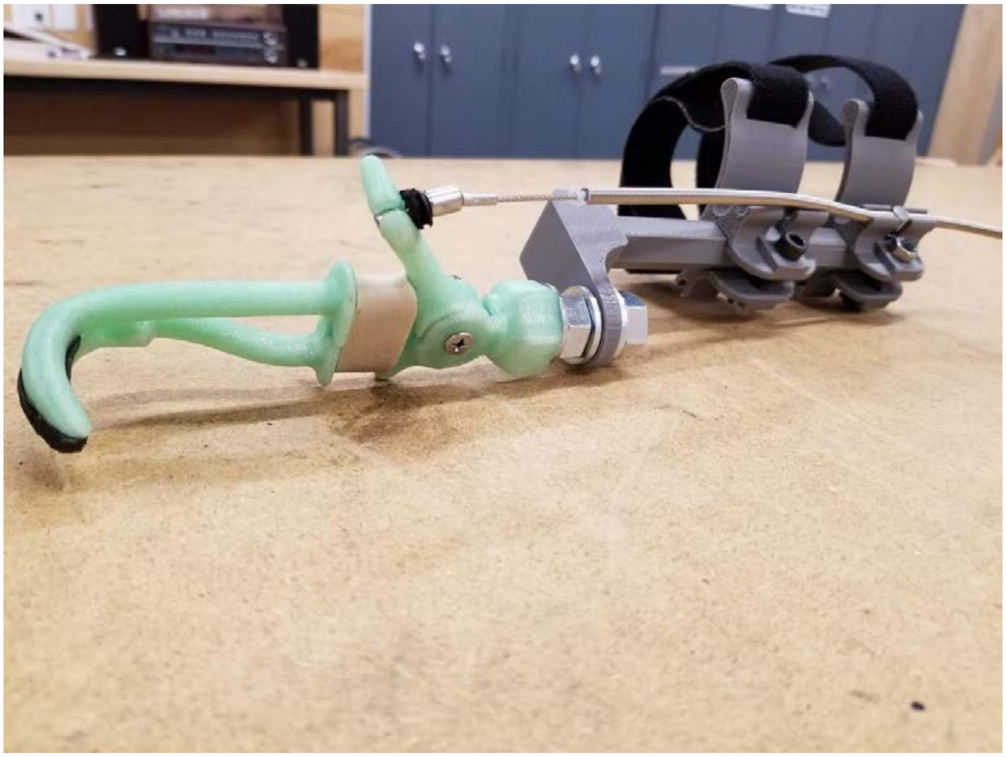


Figure 48: Below-arm simulator.

Figure 49: Simulator prototype number two with a sideways grabbing handle and round bar for the ribs to clasp on to.

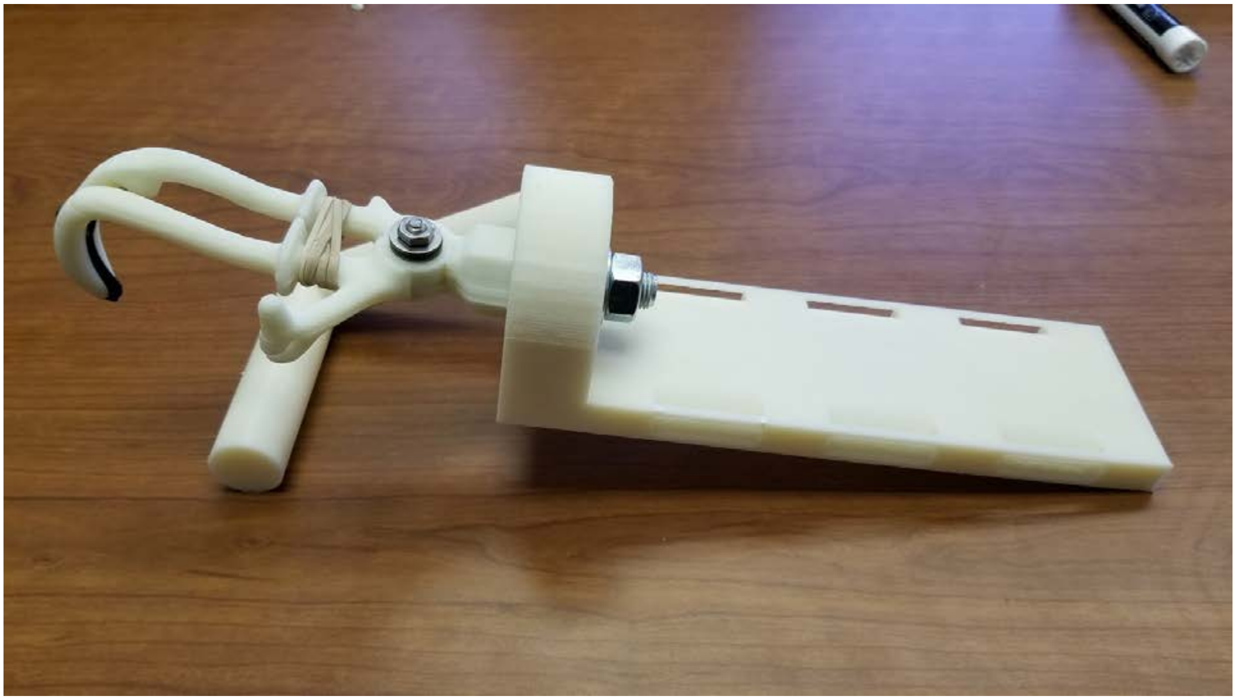


Figure 50: First prototype of the simulator.