3D Printed Prosthetics: Materials Selection and Testing

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Executive Summary

Each year there are around 50,000 new amputations in the United States, according to the National Center for Health Statistics. Far too often, it is extremely difficult for amputees of all ages to get the prosthetic they need due to their high prices and the lack of support from insurance companies. This inability to obtain a prosthetic arm is especially true for children and young adults, as their bodies grow as they get older. A potential solution to this problem is open sourced 3D printed prosthetics. These online communities allow amputees to download and print their own prosthetic CAD files. Although these communities offer immense promise, the filaments that these open source designs call for are not well-suited to serve as a durable prosthetic limb. Our project is focused on determining a new filament that can better serve as the forearm and hand of a 3D printed prosthetic arm.

Goals

The goals for this project involve building a 3D printed open source arm, and determining the optimal material to serve as the forearm and hand for a 3D printed prosthetic. Our first goal is to build the open source arm, with all of the necessary electronics included. Through this, we will be able to gain a better understand of how prosthetics work in general. Things like attachments of the joints, look and feel of the device, and how the electronics function are some of the key takeaways from the construction of the arm.

The most important goal for our group is to determine a better filament that is used to print the forearm and hand of the prosthetic. Key features of this filament include: low density, high toughness, and low cost. These features will be discussed in detail throughout the paper. It is critical for an amputee to have a prosthetic limb that can withstand all of the loads and forces it might experience in day-to-day-use. Finally, the long term goal of this design project is to utilize Additive Manufacturing to decrease the cost of prosthetic limbs, providing amputees young and old an alternative option to more expansive traditional prosthetics.

Methods

With ample support and insight from the Arizona Additive Manufacturing Committee (AAMC), we were able to determine the proper steps to take in order to fully optimize the filament used in 3D printed prosthetics. Thorough materials selection analysis was done to narrow the possible filaments that could serve as the arm. Based on our materials selection analysis, four different filaments were selected for testing: Onyx, Onyx with continuous Carbon Fiber, Nylon, and Nylon with continuous Kevlar®.

After an in depth literature search, our team determined three loading situations that a prosthetic arm might experience in its day-to-day use. These loading situations are a tensile load, a bending load, and an impact load. From this research we determined that the data from a tensile test, 3-point bending test, and impact test would give us the properties to confidently determine a better filament for the arm compared to traditional filaments such as: Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid (PLA). In addition, measurements of apparent density and total cost of the filament (including labor required to print) were factored into the decision of the optimal filament. Smaller, less important tests such as aging and Differential Scanning Calorimetry (DSC) were completed to ensure proper function of the arm.

Results

Through our materials selection and testing phases, we were able to come to the conclusion that overall, Nylon with continuous Kevlar® met the design requirements we had determined. It offered the highest tensile modulus with relatively high tensile strength, good flexural modulus, low density, and low cost. Overall we saw a 40% increase in tensile yield strength and a 38% decrease in component weight using Nylon with Kevlar® compared to ABS. Nylon with Kevlar® had a suitable flexural modulus that fit the design criteria, but the Charpy impact data yielded inconclusive results due to the resolution of the machine. Glass Transition Temperature (T_g) data resulting from DSC confirmed proper behavior of the polymers in a wide range of temperatures. From the experience of building the open source limb, we were able to do a slight redesign of the arm with critical improvements to aesthetics, motor placement, and size.

Summary

During our senior design project, we were able to build and test an open source 3D printed prosthetic arm, run mechanical and thermal tests of new 3D printing filaments, and determine that Nylon with Kevlar® was the best choice to serve as the forearm and hand of a prosthetic arm. With the new filament, we calculated that the entire arm, including electronics and labor, would cost around $500. This is a 98% decrease in price compared to traditional myoelectric prosthetics, which typically cost around $30,000 or more. The impact of such a cheap, yet durable prosthetic is massive. Children will no longer have to live without a prosthetic arm due to the high prices of traditional prosthetics, and no longer will families need to bear these high costs at the expense of their standard of living. There is much more work to be done, including improving the control system of the arms, developing a novel attachment method to the user, and designing passive elbow joints for transhumeral amputees. However, through our materials selection and testing, we have made significant progress in the long term goal of introducing 3D printed prosthetics as a more viable alternative for amputees.

Motivation

There are around 50,000 new amputations every year in the United States based on information from the National Center for Health Statistics. Among these, 60% of persons with arm amputations are between the ages of 21 to 64 years old and 10% are under the age of 21. While some of these amputations or limb losses are caused by birth defects, most amputations are caused by some sort of trauma. A prosthetic arm can be life changing for any amputee, but an even larger impact can be made by providing children access to prosthetics as they grow up. However, there are many challenges associated that must be overcome to equip children with prosthetic limbs.

One of the main issues with providing children and young adults with prosthetic limbs is that they will continue to grow. Children under the age of 16 typically grow about 2 inches per year until 15. Traditional prosthetic arms that are fitted to children traditionally are much larger than their opposite, so the child will grow into the arm as they get older. . Due to this constant growth and the high price of traditional prosthetics today, most insurance companies will not cover the cost of a prosthetic limb until the amputee reaches an age of 16 or older. Even with the help of insurance companies, the constant replacement and adjustments needed of prosthetic limbs becomes very costly, and thus many young children do not have prosthetic arms until much later in life.

Through our materials selection and testing steps, we will be able to determine a suitable material that will reduce the cost of manufacturing prosthetic arms for amputees of all ages. . It is our hope that by utilizing Additive Manufacturing, we will be able to dramatically decrease the cost of the prosthetic and allow for easier replacement of the limbs during the amputees lifetime. With this type of continuous replacement, the prosthetic arm can ultimately “grow” with a child, and replacement arms will not have a significant financial burden on the child’s family. Due to the lower cost of a 3D printed prosthetic arm compared to traditional prosthetic arms, there will be more access for thousands of new amputees, both young and old, to get the prosthetic they have always wanted.

Literature Review

Traditional Prostheses

Traditional prosthetics have a wide range of prices depending on the complexity and functionality of the arm. These limbs can range from $5,000 for a purely cosmetic arm, $10,000 for a functional prosthetic arm that ends in a split hook, and up to $20,000-$100,000 for an advanced myoelectric arm which is controlled by muscle movements with a functioning artificial hand[5]. A cosmetic arm is simply aesthetic, and due to the high cost of myoelectric prosthetics many amputees resort to these type of prosthetics. . A more affordable option for a functioning prosthetic arm is the split hook model, which allows the patient fine control and manipulation of everyday items, but lacks the aesthetics of a human hand. The most expensive models are advanced myoelectric arms. Controlled by muscle movements, these arms have a functioning artificial hand that can perform a variety of different hand gestures and sometimes wrist movements.

The complexity of manufacturing prosthetic limbs significantly contributes to their high costs. After the residual limb of the amputee is healed and no swelling remains, a prosthetist takes a plaster mold or fiberglass cut of the amputee's remaining residual limb. This mold will serve as a guide for building the prosthetic arm. . The prosthetist then takes the mold and transforms it into a positive model of the patient's limb using plaster. A clear plastic replica is then created using the modified mold which will be used to test and fit the prosthetic during the initial phases of fabrication. Once the casts are made, a sheet of clear thermoplastic is heated in a large oven and vacuum-formed around the positive mold. After the test socket is adjusted to the patient, the permanent socket is then vacuum-formed using polypropylene. A wide variety of materials are used to create the limb including acrylic resin, carbon fiber, thermoplastics, silicone, aluminum, and titanium. After the limb has been created, fitted, and delivered, small adjustments over time are necessary to ensure the proper fit of the prosthetic is maintained.

There are many ways to manufacture the parts of the prosthetic limb after the socket has been formed. Plastic pieces are typically made in the usual plastic forming methods which include vacuum forming, injection molding, and extruding. Pylons which are made from aluminum and titanium are usually die-caste. The various components are then put together using bolts, adhesives and lamination. According to the National Limb Loss Information Center, an average device has a lifespan of around three years. This estimation of the arm lifespan comes from how much the amputee uses the arm. If the user wears the arm every day then the arm lifespan is going to be shorter than an amputee who only wears their prosthetic on special occasion.

Open Source 3D Printed Prostheses

Open source is defined as a product or idea where the original source is made freely available to be redistributed and modified. There are multiple 3D printed prosthetic open source communities such as e-NABLE, Limbitless, and Open Bionics, who have allowed designers to print or make improvements to their arm and hand designs on the internet. While there are many open source prosthetic designs, most of them are mechanically functional with only a few gestures, including open and closing of the hand using the amputee's wrist. In addition, almost all of these open source designs are for amputees who still have their elbow and or wrist. An even greater problem with these open source arms are the filaments that the open source communities recommended for printing. generally used to print the arm. Polylactic Acid (PLA) and Acrylonitrile Butadiene Styrene (ABS) are two of the typical filaments used to print open source prosthetic arms. While these materials are great for one time use objects and models, they are not suited to serve as the outer shell of a prosthetic arm due to their high density and brittleness.

Bulk Material	**Tensile Modulus (MPa)**	**Tensile Strength (MPa)**	**Flexural Modulus**	**Density (g/cm^3)**
Polypropylene	1345	33	1241	0.905
Polycarbonate	2206	65	2585	1.2
ABS	2344	45	2206	1.04
PLA	3500	58	4000	1.3

Table 1: Mechanical properties of materials used in traditional prosthetics (Polypropylene and Polycarbonate) and current 3D printed prosthetics (ABS and PLA).[1-4]

Goal

The goal for this project is to determine the best possible material for a filament that can effectively be used in a 3D printed prosthetic arm, as well as fabricating an open source 3D printed prosthetic. Through extensive materials selection research, testing, and materials performance analytics, the combination of a specific design geometry and material will be able to withstand the forces human arms experience while lasting at least one to two years in service. This research will allow for the development of strong and lightweight 3D printed prosthetics that will become easily accessible to amputees. The long term goal is to create a 3D printed prosthetic arm that emulates the most commonly used movements of a natural arm, is visually appealing, comfortable, easily replaceable, and cost a total of $5000 or less to the buyer. Not only will 3D printing allow for a cheaper prosthetic limb, but it will also allow for children to have access to prosthetics that can growth with them as they get older. Deliverables will include material properties data for each combination of build pattern and material, analysis of said data, and final conclusion of the best possible combination.

Design Criteria

Mechanical

Compiling exact loading specifications for a prosthetic itself can be a process that takes months and requires designing tests based on the customer's specific proportions, daily habits, and a variety of other factors. In an attempt to keep the scope of the project manageable, mechanical specifications were broken down into basic mechanical loading problems for both the whole arm, hand, and the general mechanics. Effective calculations were made to obtain minimum and maximum values for the materials selection process. In first considering the whole arm loads, three specific situations were considered.

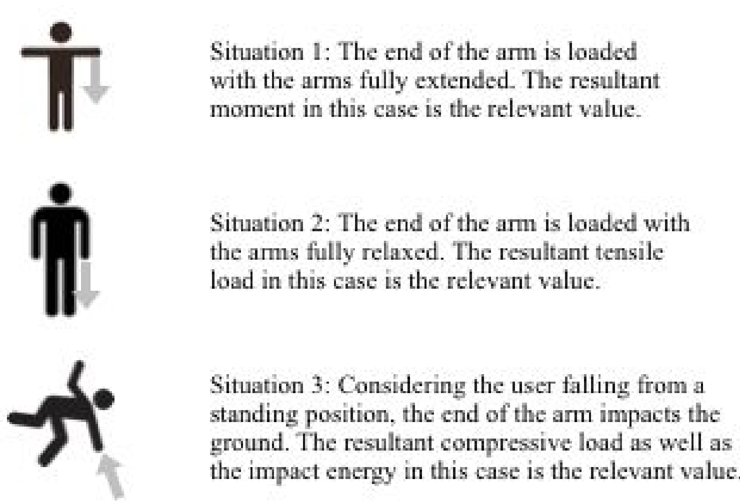

Figure 1: Three common loading situations the prosthetic limb will experience.

All three situations can be broken down into a simple beam design problem and the relevant parameters can be specified from there. The results from these models are summarized below.

In situation one, a working load is applied to the end of a fully extended arm. A cantilever beam with an end load was used to model the loading condition. The parameters of constraint for this condition is the deflection (δ) under a specified load, this is given by the following equation:

$$\delta = \frac{Pl^3}{3El}$$

In situation two, tensile strength and tensile modulus will be the relevant property constraints which will be in accordance with a load of 20 lbs in the relaxed arm position. This situation will likely be the most common loading the prosthetic experiences, therefore this constraint will have a heavy influence on the final decision of the optimal filament.

In situation 3 the arm is subject to an impact energy similar to what would be applied if the user were to use the prosthetic to try and break a fall. The material property that would bear this constraint is the impact energy to fracture. This loading situation is the least common and thus carries less importance than the previously discussed loading conditions.

Cost

Traditional prosthetic arms today cost anywhere from $25,000 to $100,000 or above[5]. The goal is to print a fully mechanically myoelectrical functional arm for less than $5,000. The cost constraint is where an important distinction regarding the goal of the prosthetic. The aim is not to compete with commercial prosthetics, it is to provide an option for those whose health insurance does not cover and or cannot afford the cost of a prosthetic. With this distinction in mind the relevant cost is the total cost to customer of the arm, thus we compare retail cost of a commercial prosthetic with the cost to produce our open sourced 3D prosthetic. This does not mean that this is a fair comparison if one were considering the actual values of the prosthetics, as a retail cost especially with a medical product includes much more than raw cost to produce, however, as stated above the aim here is to make the relevant comparison (that being cost to customer), not the fair one. The cost of the printed arm is broken into the following categories: cost of printing(including materials, labor ,and shipment), electronics cost, other hardware cost, and construction labor costs. Estimates of these costs are listed below, while an accurate cost analysis of the final prosthetic can be seen in the results section.

Category	Estimated Cost
Printing	$300
Electronics	$200
Other hardware	$50
Construction Labor	$75 per hour
Total Cost	$925 (5 hours of labor)

Table 2: Table depicting the cost to create a 3D prosthetic arm

Weight

The weight of the arm should be minimized in order to make attachment easier, reduce user fatigue, and increase comfort. Realistically, the current state of Additive Manufacturing for prostheses is not at the point where weight could be minimized without compromise. However, the team has borrowed ideas from several real-world applications in an attempt to mitigate the overall weight of the arm.

The volume of an adult forearm is approximately 750 cm^3. The density of nylon-6,6 is approximately 1.14 g/cm^3. Based on this, a cylindrical forearm of the width and length of an average adult forearm would weigh around 0.855 kg.

One weight reduction method that the team has learned about in MSE 211 (Mechanics of Materials) was through geometry. A hollow tube is almost as strong as a rod of the same diameter because upon bending, one side of the object is under tension and the opposite side is under compression. Near the center, the two opposing forces cancel each other and the net force experienced at the center sums up to zero. This means that, ideally, if the arm is cylindrical in shape, it would be the best choice to hollow it out. Removing 35% of the material through hollowing yields a forearm that weighs 0.556 kg. Assuming that any surface flaws have been taken into account and fixed, hollowing the geometry would have a dual benefit.

Another method for decreasing the overall weight of the arm goes in conjunction with hollowing is through the use of infill. An infill pattern of 75% reduces the volume used by an additional 25%. In addition to the 35% hollowing, infill would yield an overall material volume of 48.75%, or 51.25% less than a solid rod. In terms of weight, this would translate to a weight of 0.417 kg for the forearm. Although infill patterns and percentages are viable options for certain parts of the prosthetic (ideally the hand), we were unable to test various infilled samples due to time constraints.

Though a combination of hollowing and infill, this solution would significantly reduce the weight of the arm but the weight of the electronics will still need to be taken into account. Prosthetic hand weights cannot be found online, so they will be assumed to weigh approximately 500 g. A servo motor typically weighs approximately 20 g. A 3000 mAh battery can weigh between 50 and 75 g. This brings the total weight of the prosthetic arm to approximately 1.012 kg.

Biological

Due to the amount of interaction the amputee will have with the prosthetic arm, ensuring the prosthetic is safe is a huge priority. During a detailed conversation with Dr. Justin Ryan at Phoenix Children's Hospital, we learned that the FDA requirements for prosthetic limbs do not need to be explicitly followed when we design our 3D printed arm. Phoenix Children's Hospital has all the clearance we need to build our prosthetic arm with the only requirement being that it needs to be built "in house". Although this gives us a little more creative freedom during our design process, we still need the arm to be as safe as possible: biocompatibility of the materials in the arm, ensuring the arm will not react negatively to commonly used chemicals (sweat, dish soap, hand sanitizer, other cleaning agents), ensuring the arm will not leak any toxic or carcinogenic chemicals into the amputee, making the arm food safe, and making the arm easy to clean. Unfortunately, due to the fact that we cannot test on live subjects, we cannot use any

ASTM methods to test cytotoxicity. We also cannot test the roughness of all the parts in contact with the skin because it requires using either guinea pigs or human test subjects to check chemical irritation.

Methodology

Collaboration and Communication

To be able to succeed in any project of this size and scope requires attention to the aspects and structure of collaboration and communication. Meetings among team members, industry, patients, and advisors were frequent and made productive using a structured format that allowed tasks to be assigned and completed efficiently. It was only through this awareness of effective communication techniques that the project goals were able to be met.

During the planning stage members met on a weekly basis with each other in order to discuss leads and advances in finding a topic for the project. Members also met biweekly with advisors to discuss progress. The first semester of meetings was rather unorganized, however this improved as time went on, leading to extremely well structured and productive meetings.

The first breakthrough came in connecting with our Mentor Karl Schultz who introduced us to the Arizona Additive Manufacturing Committee. The first meeting with the committee acted as a springboard to all further progress and partnerships. Shortly after establishing the basic premise of building a 3D printed open source prosthetic design, we met with a smaller group of the committee interested in the project. We met at Titan to start discussing our direction for the project which was initially to simply build an arm for children and prototyping the design on Diana Gazzano, a recent transhumeral amputee in need of a prosthetic arm. While the ultimate goal was still unclear progress was able to be made on the investigation and selection of a suitable pre-existing open source design to start with.

The clarification and development of our final goal came after a meeting with prosthetist Dr. William Yule. He expressed concern over the current durability of 3D printed prosthetics, showing us one produced for a finger that broke upon arrival. He also noted that the weight of our printed prototype was way too high and needed to be significantly lowered to produce a comfortable and viable prosthetic. From this we were able to refine one of our goals to selecting a suitable material that would be light and durable enough to be considered feasible.

Further meetings among group members at this point were structured with an agenda, review of previously assigned tasks, and assignment of new tasks which lead to extremely productive meetings which occurred every Sunday. The online app Trello was used to keep up to date on current end upcoming tasks, this reduced confusion, made direction more clear, and kept team members accountable for tasks. Communications with industry collaborators were delegated giving each industry partner a single contact for major communications to avoid confusion and keep member roles clear and defined.

Using these skills and techniques allowed for the productivity and impact of the project beyond just achieving the goals and was critical in being able to access the resources that we did.

Durability

The designed arm shall last for a minimum of two years under normal use. Normal use is considered to be all usage within the design requirements pertaining to mechanical, chemical, and electrical properties of the materials. Although normal maintenance is expected such as adjustments of the prosthetic to the residual arm, and tweaking of parts, this two year durability requirement focuses on the breaking of a major component of the arm. The durability also depends on how much the arm gets used within a day and the two year lifespan. If the user only uses the arm once a week then the prosthetic may last longer than the expected lifespan. The actual product lifespan will be expected to be much less than the durability requirements if the end user is a child due of the growth rate.

3D Printing:

A critical part of the methodology is the 3D printing process itself. In order to optimize a material one must consider structure, properties, and processing. In this project the processing method has critical implications of the properties of the part. To explain the relationships mentioned we will discuss the type of printing, infill parameters, and the technology used to take the part file and convert it into a series of operations for the printer to produce a physical part. We will also discuss the specific brands and models of the filament and printers we utilized.

3D printers come in a variety of types operating of different principal mechanism. Of all types, fused deposition modeling(FDM) is the most inexpensive and commonly available, because an important aspect of the goal is to increase availability and decrease cost, this was a fairly obvious choice of printer type. Picking FDM however comes with drawbacks as well, the first being that it tends to offer less resolution than other options like Selective Laser Sintering(SLS) printers. Additionally FDM printing requires the use of dissolvable support materials for some design features. However the main drawback that needs to be addressed is introduction of anisotropy and reduction in properties like modulus and yield strength from those of the bulk material. A diagram of a FDM print head is shown in figure 14, the layering process produces an interface between that layers that is significantly weaker than than the strength of the bulk material. This ultimately leads to a lower strength if loaded normal to the layers then if loaded parallel to the layers. While using proper print settings and good practices can reduce the extent of anisotropy and weak layer interfacing there is no way to totally eliminate it, as such it is important to consider orientation of the print when testing.

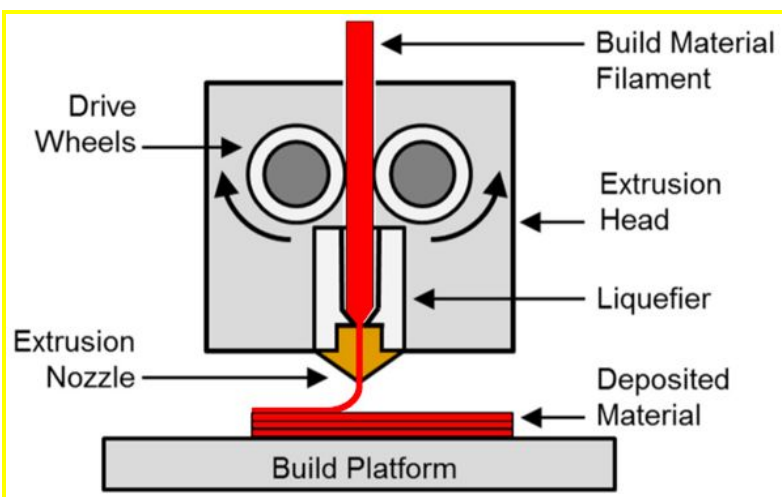

Figure 2: Fused Deposition Modeling (FDM) printing schematic. All samples were printed using an FDM printer. Notice the layering that occurs as the material is deposited. This layering effect of the processing creates a weaker interface between consecutive layers of the component. For this reason, a decrease in value of many mechanical properties such as tensile strength and modulus is seen in 3D printed samples.[10]

Another aspect of the process critical the overall properties of the part is the infill of a part. Because of the nature of additive manufacturing, internal volumes of a part are able to be modified in ways typical machining methods are not capable of doing. Infill of a part is one such modification, where instead of a solid or shelled part, there exists an internal 3D structure within a closed body that allows for variability in the strength and weight of the part. The infill percentage indicates that volume of solid material used to fill a closed body as a percentage of the total internal volume of the body. Figure 15 shows various infill percentages of a tensile sample, as one would expect the larger percentage of infill of a part, the stronger the part will be with a maximum strength at 100% infill(A fully solid body), however the larger infill also increases the weight, material used(increasing cost), and time to print of a material. These aspects must be weighed when considering what infill to use for a particular part.

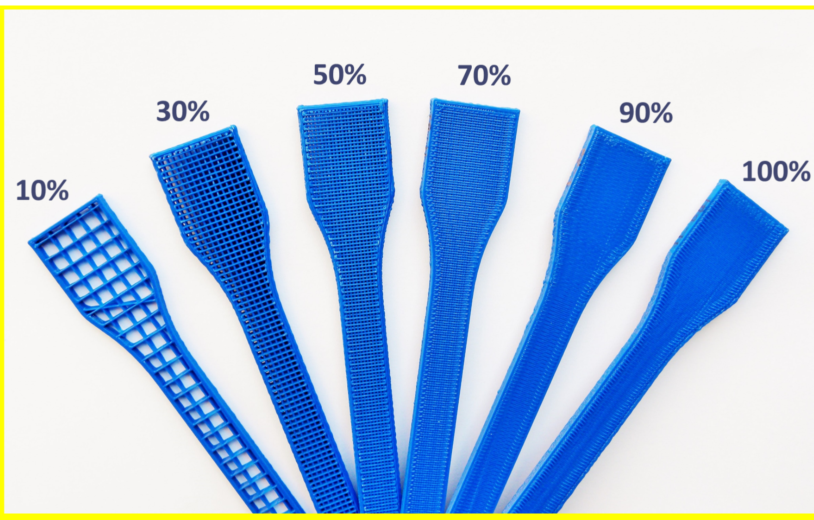

Figure 3: Infill percentage examples of a tensile sample. Parameters including strength, weight, cost, and print time can all be affected by the infill percentage of a part, as such is must be considered carefully when choosing the infill. All samples tested in this report were infilled 50%.[11]

For the samples tested in this paper all were printed on a Markforged two with 50% infill in a simple square pattern and at a 45 degree angle from the XY plane. For the nylon with kevlar and the onyx with carbon fiber the fiber, one layer of the fiber was placed on the third layer from the top and bottom. Pictures of the samples can be seen in the index.

Materials Selection

Process Narrowing Stage

The process narrowing section eliminates the most material options of any of the processes. The purpose of this stage is not to apply stringent criteria but just the criteria needed to make the subset of materials to be analyzed manageable. The primary criterion on which a material is selected in this stage is whether the material can be 3D printed with existing commercial FDM or SLS printers. One goal of the project is to establish 3D printing as a viable way to produce prosthetics, this means that the process must be scalable. This also eliminates newer experimental 3D printing methods as they do not lend to the overall goal. Through these criteria the subset of materials is narrowed to metals, polymers, and engineered composites.

Requirements Stage

The requirements narrowing stage is essentially an extension of the process narrowing stage with the exception that the selection criteria are based upon quantifiable properties rather than process ability. The first criteria used here is tensile yield strength a large portion of the overall loading in the arm will come in the form of a tensile load, thus it is important to eliminate any materials with inadequate strengths. As seen in table.

The second and equally if not more crucial selection criteria for this stage was density. The importance of weight in the design of prosthetics is very often underestimated by engineers unfamiliar with the industry, simply being the weight of a regular human arm or slightly less is an oversight on the comfort of the user. . The minimum flexural strength threshold value was set to 1/2 that of bone(approximately 160 MPa), while this choice may seem rather unusual it is important to mention that in addition to this only being a minimum rather than optimal value, it is desirable to have a material that would fracture before any part of the body would, while it would be expected that the attachment method would fail under extreme loading before any sort of residual limb fracture would occur, having a double failsafe is always advisable.

Performance Optimization Stage

The most labor intensive stage in this process is the optimization stage, this stage requires the most design oversight and is the heart of the selection process, while the first to stages are made to eliminate materials which will not make good candidates, the performance optimization stage takes potentially good candidates and chooses the best using a mixture of priority matrices, material indices, and as processed testing. The selection matrix brings all these together into a quantifiable system. The first step in building this matrix is to construct a property priority matrix, as shown in Table 3.

Property	Priority Number
Light Strong Tie Index	4
Light Stiff Tie Index	5
Light Stiff Beam Index	4
Cost Per Unit Volume	3

Table 3: Performance optimization criteria and corresponding priority numbers.

This matrix is transformed into the final materials selection matrix in Table 10 by including relative rankings for each test. Take for example the light strong tie index, with a priority value (from the previous matrix) of 4. After all materials are tested, their specific values for this test are tabulated, and then ranked by lowest to highest for this index (all except cost per unit volume are given the largest number rank for the largest value, for cost this is reversed as a minimum cost is desired). Each of these values is put into columns in the selection matrix. The material selection number is obtained by taking summing the value of each property rank multiplied by the corresponding property priority.

The performance optimization stage involves assigning performance index values for given situations (see appendix for example derivation) and finding the material with the largest value of the material index for that situation. Figure 5 shows an ashby chart exemplifying this process with the constant performance indices guidelines in the lower right corner. In this specific Ashby chart, the second performance index is the most relevant and thus was calculated for a light stiff beam (see appendix). The material with the best performance would be the one that falls on the line that is of the highest index (the line farthest to the upper left of the graph if the line were to be translated in that direction). This stage is also in progress.

Ashby Chart Analysis

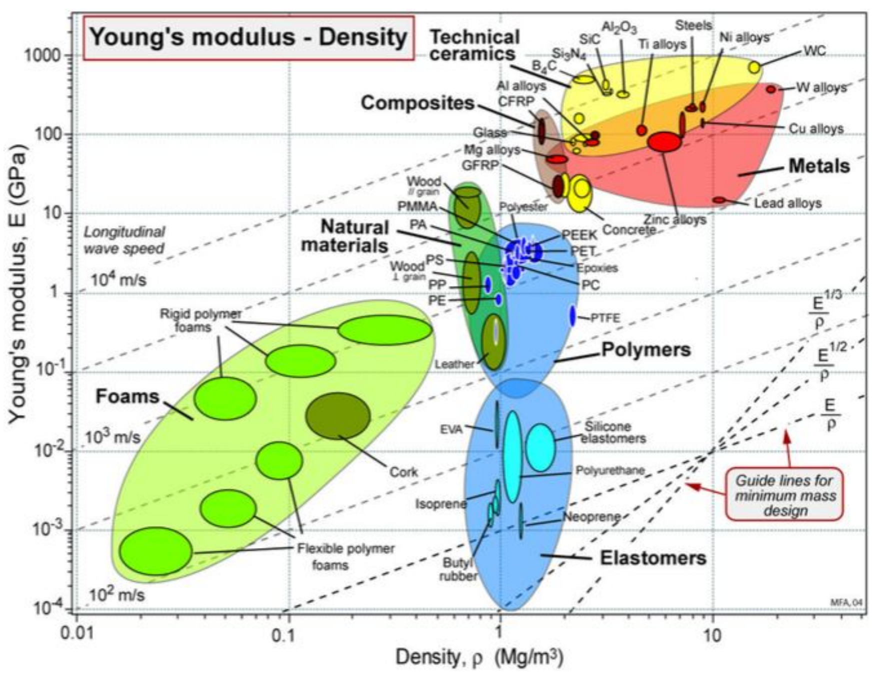

Figure 4: Ashby chart of young's modulus versus density.[11]

When analyzing this Ashby chart of Young's Modulus (E) vs. Density (ρ), it is important to notice the guidelines for minimum mass design in the bottom right of the chart. Using this guideline rather than the original E/ρ lines, we can determine the best materials in which we should test. By superimposing this guideline over the chart and keeping in mind materials that can be 3D printed (no foams or woods), we can see that the guideline intersects the large bunch of polymer materials in the center of the chart, as well as many of the metal alloys. With the Young's modulus and density of bone (~10 GPa, ~2 g/cm^3) in mind, we can begin to eliminate materials, considering cost, ease of production, Additive Manufacturing capabilities, and more. The goal of this analysis is to determine suitable materials that have high stiffness to density ratios, in order to minimize the weight of the prosthetic.

Metals

At first glance it seems most of the metals like titanium, magnesium, and zinc, would serve as the best material replacement due to their similar properties to bone. All metals have a Young's Modulus of at least 10 GPa paired with a similar density to bone. However, the human body is not made entirely out of bone, so an idea was brainstormed to use these metals to create a 3D printed prosthetic arm. The idea was to print a structure similar to the CORTEX cast created by Jake Evill, which has plenty of open space, but still maintains its structural properties. Since titanium has been used as a replacement in bone as osseointegrated screws for dental implants, we contacted Titan Industries with the idea to print this structure with Titanium. CTO Karl Schultz informed us that prints similar to this cast of titanium and most other metals would cost thousands of dollars, which would not allow us to achieve our goal of dramatically lowering the price of prosthetic arms. In addition, the technology required to 3D print metals is still relatively new and therefore still too expensive for this project. However, future advancements in Additive technologies may allow for cheaper printing of metal components, and may make a design similar to this a viable options for amputees.

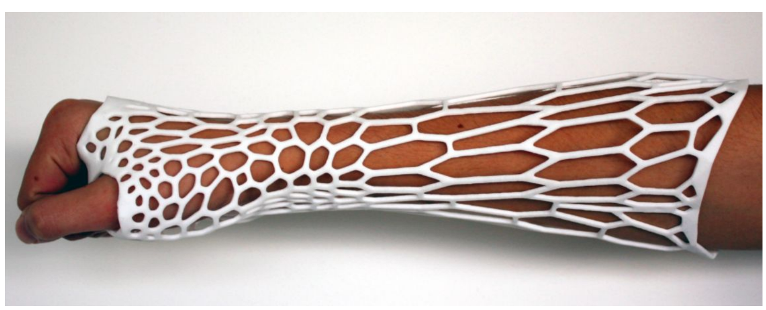

Figure 5: CORTEX cast by Jake Evill.[14]

Composites

The next option is based on Figure 6 or the Ashby chart of modulus vs. density. Composite materials according to the chart have just as high of a modulus as most of the metals, while at the same time having a lower density. Again it seems like this type of material would best suit our needs, but the material must be 3D printed for a variety of benefits listed earlier in this paper. Although there has been some progress in the 3D printing of short fiber composites, researchers have shown that due to the limitation of the size of fibers available to 3D print, the load transfer between these short fibers is simply not enough to have a significant effect on strength in comparison to conventional materials, such as metals.[14] Therefore the properties of 3D printed composites are less attractive to us compared to traditionally manufactured composites. In addition, the costs of printing composites is too high (see Figure 7) based on our design criteria. However, there may be some options for us with 3D printed composites.

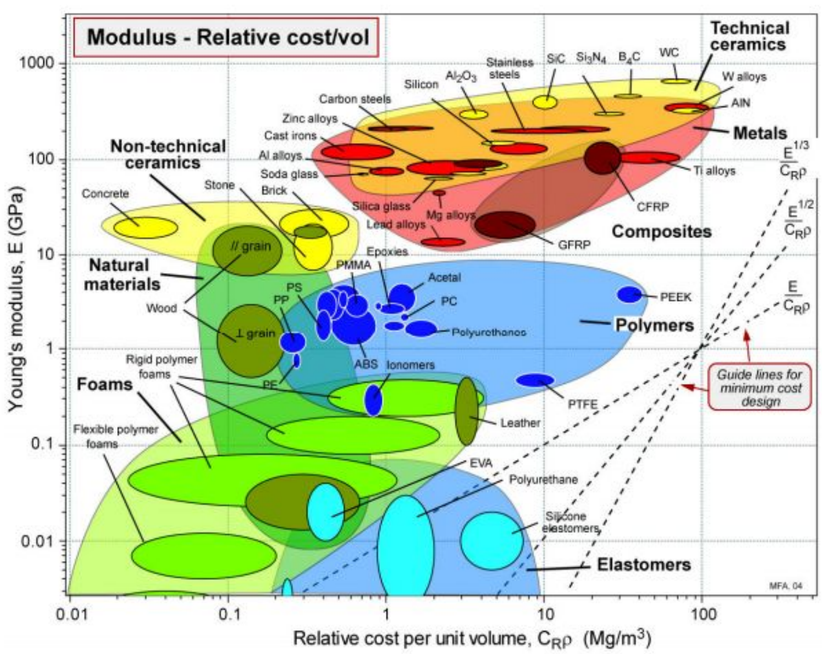

Figure 6: Ashby chart of Modulus vs. Relative cost/volume.[11]

STAX 3D, who has generously offered to print test samples for us, has the composite filaments that were used: onyx with carbon fiber and nylon with kevlar. Unfortunately mechanical properties for these materials have not been characterized in any available literature, including that from the manufacturer, it is because of this lack of available properties that testing was required.

Materials Testing

In order to ensure the best properties and reliability of the arm, it is important to choose the right materials. By choosing the best properties of the materials, we can ensure that our prototype is comfortable, safe, reliable, and durable. ASTM provides excellent guidelines for standardizing material property tests that we will utilize throughout the spring semester.

Testing

Tensile Test

In order to test tensile modulus, ultimate tensile strength, tensile yield strength, ductility, and toughness of the various 3D printed materials, we will be using an ASTM standard tensile machine. This test requires the test specimen to be in the shape of a bone with the dimensions similar to that seen below in Figure 7.

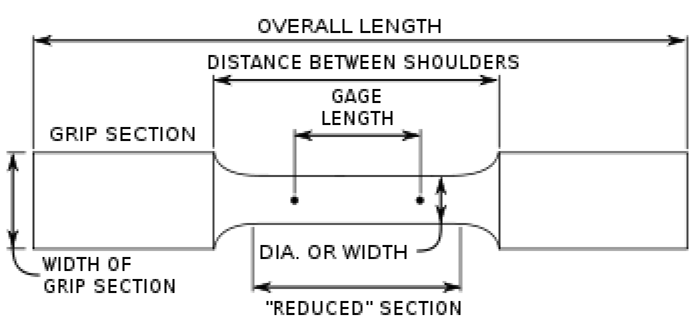

Figure 7: A bone-shaped sample is used in a tensile strength test (ASTM D638).[17]

Since we want the arm to hold 50 lbs, with less than 0.2% strain or deflection, we have to test several different properties. To test for tensile strength, we must divide the maximum load by the original cross sectional area. To test for tensile yield strength, we must find where the data deviates from a linear trend in the elastic region. To find the tensile modulus, we must find the slope of the elastic region of the stress vs. strain graph.

Charpy Impact Test

The Charpy Impact test is a standardized ASTM test that determines the amount of energy absorbed by a material during fracture. The absorbed energy can thus be found to measure the material's toughness. While the machine has a simple setup as seen in Figure 7a, one must create a notch in the middle of the test specimen in accordance to the ASTM dimensions as seen in Figure 8b. This test was chosen due to the fact that there is a Tinius and Olsen Charpy Impact test machine here at Arizona State University.

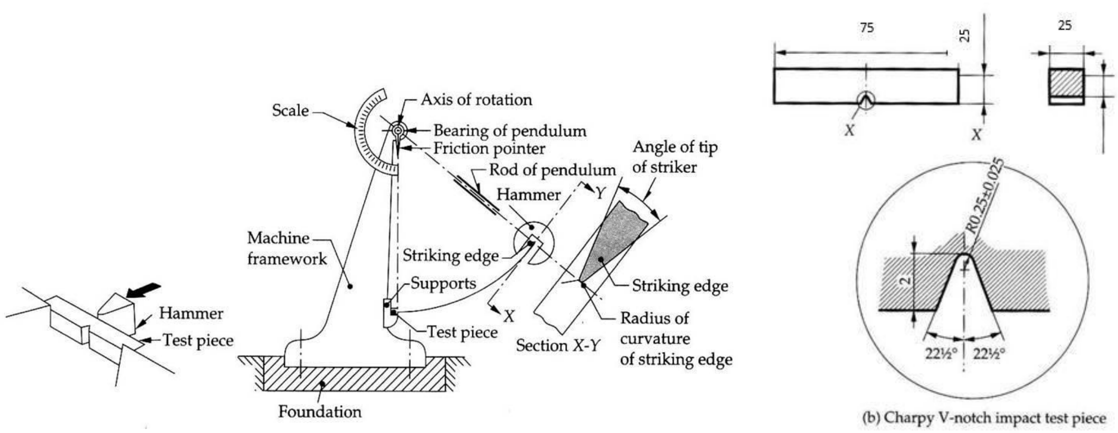

Figure 8a (left): Representation on the Charpy Impact Test Machine. The test specimen will be placed at the bottom on the machine with the notch facing the opposite side of the hammer. 8b (right): Test specimen.[20]

3-Point Bend Test

A three-point flexural test will be run in order to determine properties like modulus of elastic bending (E_f) and flexural stress (σ_f), flexural strain (ϵ_f), and stress intensity factor (K_I). Due to some of the unique loadings and forces that can act on a human arm, ensuring these properties are maximized in our material of choice is of utmost importance. Relevant equations include:

$$E_f = L^3m/4bd^3$$

$$\sigma_f = FL/\pi R^3 \text{ (for circular cross sections)}$$

$$\epsilon_f = 6Dd/L^2$$

$$K_I = (6P/BW)a^{1/2}Y$$

To test the flexural modulus and flexural strength, we must utilize ASTM D790. The flexural strength is the maximum stress experienced by the material as a constant bending stress is applied to it. It can be calculated using the following equation:

$$\sigma_f = \frac{3PL}{2bd^2}$$

Where P is the load at a given point on the load-deflection curve, L is the support span in mm, b is the width of the beam test in mm, d is the depth of the beam tested in mm, and σ_f is the stress in the outer fibers at midpoint, at MPa. To test the flexural modulus, we can use the equation:

$$E_b = \frac{L^3m}{4bd^3}$$

Where E_B is the elastic bending modulus, L is the support span in mm, m is slope of the tangent to the initial straight line of the load deflection curve, b is the width of the beam tested in mm, and d is the depth of the beam tested in mm.

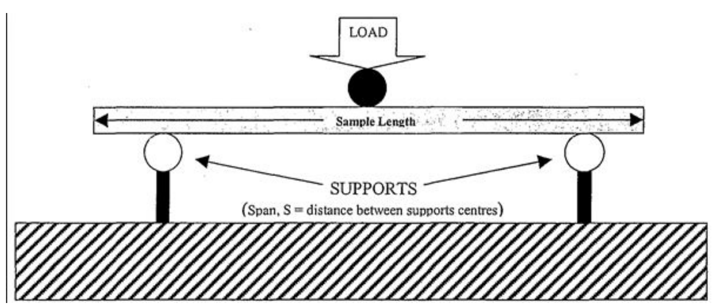

Figure 9: Visual representation of a three point flexural test. The specimen is loaded on the supports and loaded with a force to measure deflection.[21]

Thermal Properties

Differential Scanning Calorimetry

In addition to the mechanical testing, it was important for us to determine if the filaments would be able to stand up to the environment, specifically temperature. A 3D printed prosthetic must be functional in extreme cases of hot and cold. For this reason we decided to run Differential Scanning Calorimetry tests (DSC) to determine the glass transition temperatures of each filament.

DSC is a thermal test in which two samples are heated and cooled in a cyclic matter. One sample is the filament included the filament under examination, and the other is an empty reference plate. The DSC machine is capable of keeping the plates at the exact same temperature during the cyclic temperature range. The DSC takes measurements of the heat flow to the sample of interest as this heating and cooling occurs, and from that data we can extract information regarding the thermal properties of the sample filaments.

The important property of the filaments we are examining is the glass transition temperature. The glass transition temperature (T_g) is a temperature at which the chains of the polymers begin to move around more relative to one another, leading to a more rubbery and viscous material. In the DSC graphs of heat flow vs. temperature, the glass transition temperature can be seen as a change in slope due to the higher heat capacity of the polymer above T_g. Below the glass transition temperature, the polymer is hard and brittle. Above the glass transition temperature, the polymer is rubbery and softer. It is critical for the outer shell and hand of the prosthetic to remain below the glass transition temperature to ensure that the device will not bend easily. It is also critical for the Ninjaflex joints to remain above the glass transition temperature so it is tough and flexible.

We used a Perkin Elmer DSC 7 Differential Scanning Calorimeter with Argon as the inert gas. All the filaments except nylon were subjected to the following temperature cycle: hold for 1 minute at 25℃, heat to 150℃ at a rate of 5℃/min, held at 150℃ for one minute, then cooled back down to 25℃ at a rate of 20℃/min. The Ninjaflex filament was started at -20℃ for one minute, heated to 45℃ at a rate of 5℃/min, held at 45℃ for one minute, and then cooled to 25℃ at a rate of 20℃/min. The samples were plated in an aluminum DSC plate, and the reference plate was an empty aluminum plate.

Results

Mechanical Properties

	Nylon		Nylon with Kevlar		Onyx		Onyx with Carbon Fiber	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Density(g/cm^3)	0.62	0.00	0.72	0.00	0.64	0.00	0.78	0.00
Tensile Modulus(Mpa)	71.60	7.51	262.34	105.16	24.49**	15.16**	161.32	10.97
Flexural Modulus(Mpa)*	236.65	4.55	803.36	378.08	634.21	155.34	2901.20	225.57
Tensile Strength(Mpa)	15.83	0.29	44.78	2.36	32.53	1.42	71.19	10.51

Table 4: Tabulated mechanical properties with standard deviations.

Tensile Properties

The most common loading situation a prosthetic arm will experience on an everyday basis is holding an object with the user's arms at their side. In this particular situation, maximum loads will be applied. In order to test this loading situation, a tensile load was applied to the various filaments. From the data we concluded that Onyx with continuous carbon fiber resulted the highest tensile strength with a value of 71 MPa while Nylon with Kevlar ® yielded the highest tensile modulus with a value of 262 MPa as seen in Figure 11. In this test, we are looking for the perfect balance between tensile strength and modulus. We do not want the prosthetic arm to be too brittle that it breaks upon impact, but we don't want the arm to elongate over a time. Since this loading situation is the most common situation a prosthetic arm encounter, this is also the most important and most highly weighted criteria.

Another important note is the ductility, while we want the strongest yield strength, ductile failure is always preferred over brittle, as it gives more warning and prevents a more catastrophic release of energy. With that said, since the determined safety factor in the finite element analysis was above 4 it is reasonable to say that the increase in strength at the cost of ductility is justified given that the user would have to load to over 4 times the recommended minimum load in order to have yield.

One thing to notice in the data represented in Figure 11 is the dramatic difference in ductility between the Nylon and Onyx samples. During tensile testing, the Nylon samples elongated ¼ of its height. The Nylon with Kevlar ® samples elongated in the same fashion except the Kevlar ® fibers broke first and then the sample elongated. For the Onyx with carbon fiber samples, once the fibers broke, the onyx broke soon after which is similar to the pure onyx sample.

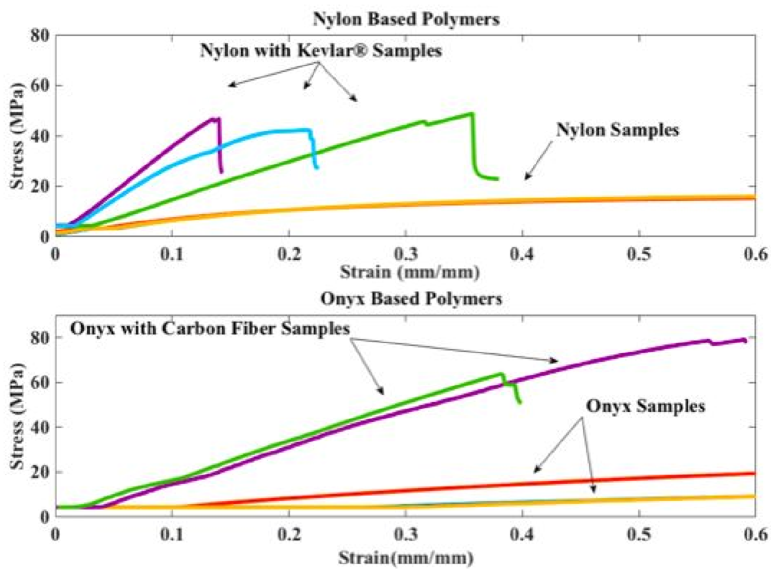

Figure 10: Tensile testing data.

Flexural Properties

The second most common loading situation a prosthetic arm experiences is holding a lighter weight object with their arms extended. To test this situation, flexural modulus was measured using a 3 point bend test. In this test, Onyc with carbon fiber had the highest flexural modulus and Nylon with Kevlar ® coming in a close second. Because this was not as common as a loading situation compared to the first situation, it was weighted lighter and didn't have as much as an impact on the final decision as the tensile test.

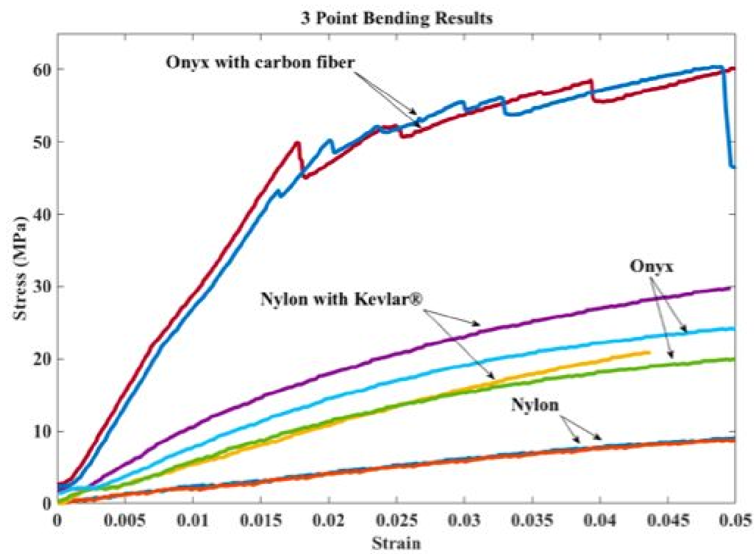

Figure 11: 3-point bend testing data.

Impact Properties

The least likely loading situation a prosthetic arm may experience would be an impact, such as the user tripping and falling. To test this loading situation we used Charpy Impact testing. Because the Charpy Test machine was designed for metal specimens, it resulted in some complications. The resolution was too low for the purposes of the project, and because of its size, it split the samples down the center and pulled them through the notch instead of fracturing them, resulting in inaccurate and inconclusive data. The large error bars are also the result of the low resolution of the machine. However, despite the wide range of error, the values are still relatively low and prove that impact strengths for current technology require significant improvement. The data gives values that were acquired from the tests and is significantly lower than the values of the monolithic material, which most likely caused by poor bonding between the layers, as well as the anisotropy that is characteristic of 3D printed components.

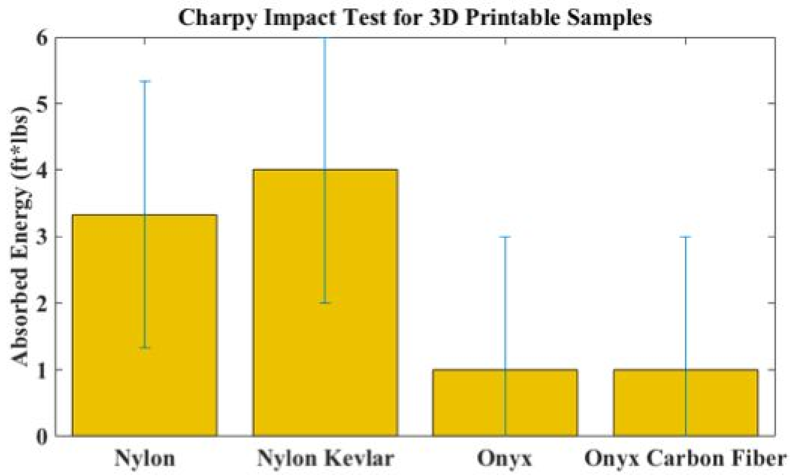

*Figure 12: Charpy Impact Testing Data. Nylon resulted in an average value of 3.33 ft*lbs, nylon with Kevlar® resulted in a value of 4 ft*lbs, and both Onyx and Onyx with carbon fiber resulted in a value of 1 ft*lbs*

Density

Filament	**Apparent Density (g/cm^3)**
Onyx	0.65
Onyx with Carbon Fiber	0.78
Nylon	0.62
Nylon with Kevlar®	0.72

Table 5: Apparent density of tested samples. Apparent density was obtained by simply dividing the weight of the samples with the total volume. This is different from bulk density in that it is not the density of the solid material but is more indicative of the density of the printed arm as it will have the same infill of 50%

Thermal Properties

Bulk Material	**Glass Transition Temperature (℃)**
Nylon-6	47

Kevlar	315
Carbon Fiber	200
Polypropylene	0
ABS	80-120
PLA	57

Table 6: Glass Transition Temperatures of bulk materials commonly used in prosthetics.[25-28]

Filament	**Glass Transition Temperature (℃)**
Nylon	60
Nylon with Kevlar®	52
Onyx	61
Onyx with Carbon Fiber	62
Ninjaflex	-10

Table 7: Table showing the Glass Transition Temperatures of the various tested filaments found using DSC. All filaments except for Ninjaflex will easily remain in the glassy state in any realistic environment. Only when temperatures dip below -10℃ will the Ninjaflex transition to a glassy state. This may be an issue in extremely cold climates, and could lead to the Ninjaflex losing its ductility and toughness as the joints of the prosthetic.

Filament	**Cost ($/cm^3)**
Onyx	$0.15
Onyx with Carbon Fiber	$0.25
Nylon	$0.12
Nylon with Kevlar	$0.18

Table 8: Cost per cm^3 for each of the tested filaments. According to STAX 3D, this cost data includes the cost of the filament as well as the labor and other associated costs required to print the test samples.

Material	Light Stiff Beam Index $\frac{E_f^{1/2}}{\rho}(\frac{MPa^{\frac{1}{2}}}{g \cdot cm^3})$	Light Stiff Tie Index $\frac{E}{\rho}(\frac{Mpa}{g \cdot cm^3})$	Light Strong Tie Index $\frac{\sigma_y}{\rho}(\frac{Mpa}{g \cdot cm^3})$
Nylon	24.8	113.8	25.5
Nylon w/ Kevlar®	39.4	364.4	62.2
Onyx	39.3	38.3	50.8
Onyx w/ Carbon Fiber	69.1	206.8	91.3
ABS	46.1	2211.5	42.3
PLA	48.7	2692.3	44.5

Table 9: Material Properties compared to traditional 3D printed prosthetic filaments (ABS and PLA). The values for the tested filaments were normalized to the apparent density as specified in the index equation, while the ABS and PLA were normalized to the bulk density because the corresponding modulus or yield strength in the equation was that of a bulk material.

Redesign

In addition to material improvements, the arm design itself was updated to address issues with the current open source design including weight, aesthetics, loading capacity, and fit of the internal components. There were two initial goals of the redesign of the arm, the first was to improve the boxy and unrealistic design of the current design by limbitless, and second to have better fit and placement for the components of the arm, like the servo motor and fishing line.

First the palm STL file was imported from the flexy-hand design on thingiverse. As discussed earlier the printed prototype hand from this file was much too big for Dianna, let alone a child, as such the file was scaled down to 80% its original size and this is what was used for reference when constructing the front of the arm including the holes for the fishing line coming from the hand. The shape was a simple and made to resemble an actual arm, even though this core would be encased in a silicone sleeve. An extruded shelf inside the arm provided a clear place for the servo motor to be glued, a small amount of ribbing was added to provide further structural stability, and a guide for the fishing line leading all the way from the front of the arm to the servo horn was modeled. Additionally a custom servo horn was modeled with holes for the line holders to insert, a cut portion to reduce unneeded weight and space, and a pulley like groove for the line to wrap around. Renderings of all these improvements can be seen in figure 13. After initial modeling of the arm finite element analysis was done to analyze the stress concentrations and the deformations under the required loads.

Analysis was done using experimentally obtained values for 3D printed nylon with kevlar that can be seen under the mechanical property results. The analysis was limited to the main bottom body of the arm in order to simplify the analysis and also address the worst case scenario of the lid being off. The result of the first analysis for stress can been seen in figure 15 on the left. As seen in the figure stress concentrations were significant on the corner of the lid cutaway, edges of the ribbing where it met the wall, and where any extra extrusions in the body ended. To address these concentrations fillets were added to edges where there was high stress, and an especially large fillet was added to the top cutaway corner, the results of this modification are shown in figure15 on the right. The full report of the analysis done on the final design can be seen in the appendix.

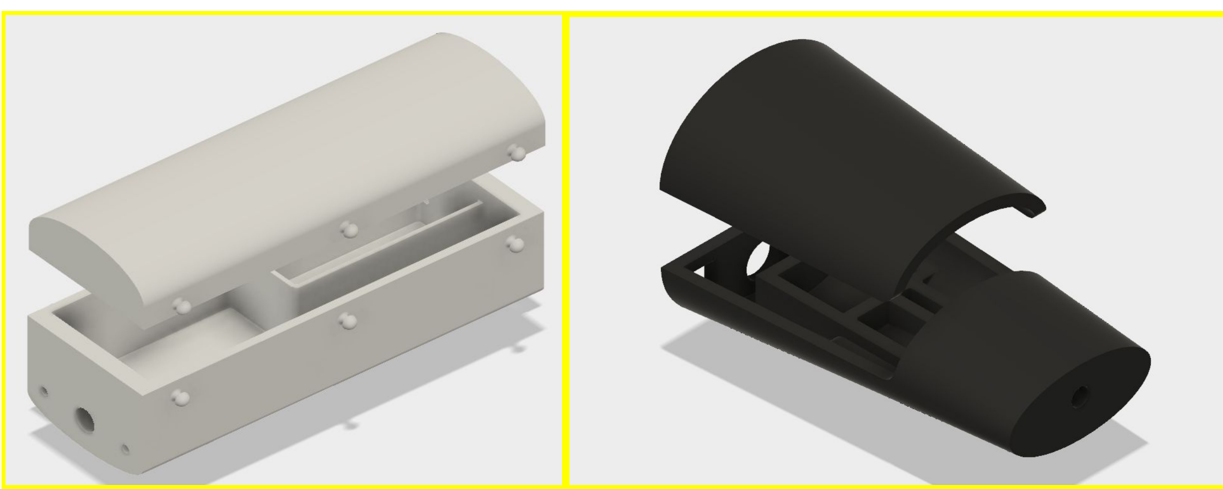

Figure 13: Computer models of the current Limbitless design(Left) compared with newly developed design(Right). Major improvements can be seen in the form factor of the arm as well as improved structural rigidity and organization for internal components.(Not pictured: Line guide and line

guide support also developed with new design)

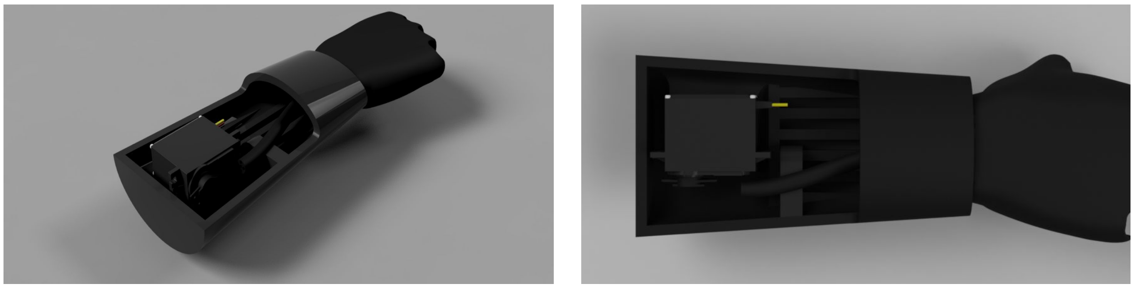

Figure 14: The re-designed arm

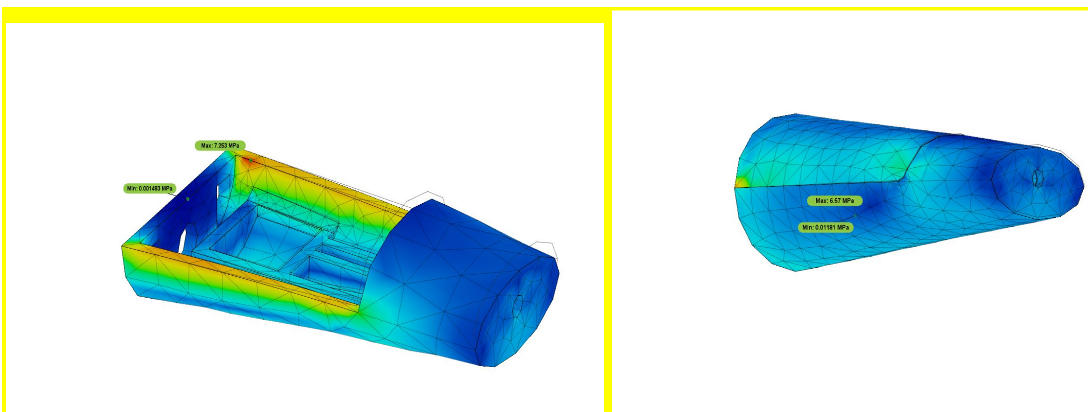

Figure 15: Finite Element Stress Results Mapping on first iteration(left) and second iteration(right). Although some view is obscured on the right by the cover, the max stress is reduced.

3D Scan

In addition to the print of the prosthetic, a laser scan of the amputee's opposite arm can be used to help cast a silicone sleeve that will fit over the prosthetic and have similar dimensions to the amputee's opposite arm. Laser scanning the patient's arms will cost around $175. Once the scan of the patient's arms has been completed, the printing of the prosthetic arm can begin.

The laser scan not only helps the prosthetists determine who to dimension the prosthetic arm to the amputee's remaining arm, but the scan also helps produce a socket for the prosthetic to fit onto the amputee's residual limb. Currently there are no easier techniques available to produce a prosthetic socket but having a laser scan can make the process easier and faster.

Figure 16: Laser scan of Diana's left arm. Done with the help of Dr. Justin Ryan at Phoenix Children's Hospital.

Discussion

The mechanical and thermal properties test that were conducted during this project were all conducted on ASTM standards. For the tensile test and 3 point bend test, all dimensions of the test specimens were up to date with the ASTM standards. This was done so the various filaments that were untested previously could be compared to traditional filaments used in prosthetics such as ABS and PLA. Because the Charpy Impact machine that was used in this research was made to test metal samples, the impact specimens were made as large as possible to get the best results. Once the testing began, it was found that the Charpy Impact specimens were made too long to fit into the machine. Due to this, the specimens were sawed down to a smaller size. While data was found from this test, it was inconclusive due to the low resolution of the machine. One way this could have been avoided was to make a smaller Charpy Impact machine. Due to time constraints, this was not possible. In addition, we were not able to test all the filaments we wanted. If there was more time available, PETG, polypropylene, NylonX and other filaments would have been tested and compared to the Nylon, Nylon with Kevlar ®, Onyx and Onyx with carbon fiber samples.

		ONYX	ONYX w/CF	Nylon	Nylon W/ Kevlar®
Light Strong Tie Index	Rank	2	4	1	3
$\frac{\sigma_{yT}}{\rho}$	PN[1]	4	4	4	4
Light Stiff Tie Index	Rank	1	3	2	4
$\frac{E}{\rho}$	PN	5	5	5	5
Light Stiff Beam Index	Rank	2	4	1	3
$\frac{E_f^{1/2}}{\rho}$	PN	4	4	4	4
Cost Per Unit Volume	Rank	2	3	1	4
$\frac{f}{\rho}$	PN	3	3	3	3
MSN[2]		27	53	21	56

[1] Priority Number(from priority matrix);
[2] Material Selection Number

Table 10: Materials selection matrix: Each property priority and each materials relative rank in that property are multiplied and then added down each column to obtain the materials selection number. Using this system Nylon with Kevlar was selected as the best material out of the tested materials.

The old filaments used in open source 3D printed prosthetics are too brittle and not capable of handling the everyday loads and forces that are applied to it. With the new arm design and the new filament chosen, 3D printed prosthetics can have more of an impact to amputees lives. Through thorough research and experimentation, all filaments tested were chosen to be optimal material to serve as a prosthetic arm. All four filaments met the requirements that we set such as low density, low cost, and good mechanical properties.

No matter what material is chosen, all filaments are more suitable to serve as a prosthetic arm than the ones currently being used. With this new material, amputees of all ages and all over the world have a better chance to getting a prosthetic arm than they have had before. Not only will amputees have more of chance to get a prosthetic arm due to additive manufacturing, but due to our research, their arm will last them around two years which gives the amputees a time to grow as well as visit a prosthetist to get a traditional prosthetic. During this time, amputees will save around 98% due to the lost cost of the print, electronics, and labor involved in 3D printing prosthetic arms.

Currently prosthetic arms take close to ten weeks to produce. This includes the casting of the residual arm, making a positive mold of the residual limb, and the vacuum forming of the polypropylene. This does not include the adjustments that have to be made in order to insure proper fit of the prosthetic to the residual limb. By using additive manufacturing, an amputee can get a laser scan of their arm, print and build a fully myoelectric prosthetic arm within a two weeks. This will allow amputees of all ages from all over the world to have access to prosthetic limbs that are designed for them at a much faster and cheaper option. While this 3D printed arm is designed to help amputees of all ages, it is only another option for amputees and not a replacement for traditional prosthetic arms. This is because traditional prosthetic arms have much greater mechanical properties and capabilities than a 3D printed prosthetic arm will have. Our project was to help make 3D printed prosthetic arms a more reliable option than the arms currently being printed.

The redesigned arm will be uploaded to thingiverse as a modification of the original to allow free and open access to print and modify the design. The new design is still missing some features that will likely be added in the future including: holes for thread inserts and screws, grooves for O-rings, full waterproof encasement of the motor and electronics and features to allow a removeable attachment method of the hand. Additionally the design needs to be made parametric in order to allow for sizing to a particular individual, this is currently being implemented.

Conclusions and Recommendations

This year, as we started attending the Arizona Additive Manufacturing Committee meetings, we were able to network with industry professionals and meet lots of great people. A few of these professionals took interest in our Capstone project, and decided that they wanted to help us reach our goal of introducing open source 3D printed materials as a viable choice for amputees who could not afford traditional prosthetics. Along the way, information about our capstone team began circulating and eventually, a woman named Pamela Waterman heard about us. She reached out to us about writing about our Capstone project in her blog at a website called “Digital Engineering.” We agreed to have her write about us, and now, our Capstone group is mentioned in one of her entries titled “3D Printing Prosthetic Part 1: Ways to Get Involved.” Later in the semester, another person approached us interested in also writing about us, and he interviewed Bryan over the phone and ended up writing an article about us in a magazine called

TechConnect. The article is titled “Fitting Solutions,” and also features Dr. Justin Ryan, who worked closely with us throughout the year.

This semester, our team worked on gathering data on previously untested 3D print filaments. These include Onyx, Onyx with continuous carbon fiber, Nylon, and Nylon with continuous Kevlar®. We also documented their mechanical properties so that future teams could have the information readily available, should they need it. Besides testing filaments that were previously untested, we also tested materials whose properties *are* known, but are only documented in monolithic form.

We concluded that the best material to use for the application of 3D printed prosthetic arms is Nylon with Kevlar®, because it satisfies the most criteria that we prioritized in the materials selection matrix, which includes cost, density, as well as the properties determined by tests discussed previously.

Compared to 3D printed ABS, which is the filament that is typically used to print open source prosthetic arms, we were able to increase the yield strength by 40% from 32 MPa to 44 MPa. This is important because the arm is most likely going to experience high tensile loads when the user carries something to their side, such as a gallon of milk or a bags of groceries.

Also, compared to the original Arm for Alex design that we printed using nylon filament, through a combination of our newly designed arm, printed with Nylon with continuous Kevlar® fiber, we would be able to decrease the weight of the arm by over 38%. Weight is an especially important aspect of prosthetic limbs because additional weight causes faster fatigue for its users, and can lead to physical complications, such as shifting the user to one side.

The most important aspect of the project was reducing the cost of a prosthetic limb as much as possible in order to make open source designs a viable option for amputees who cannot afford a traditional limb. This is especially true for children, who are the demographic most likely to get rejected by insurance companies because of the rate they outgrow their limbs. Through the use of additive manufacturing, we were decrease the price of a prosthetic limb by 98%, from approximately $30,000 for a traditional limb, to $500 or less for an open source design. This price takes into account the 3D scanning of the arm, which was done by Dr. Justin Ryan from Phoenix Children’s Hospital for free. However, there is currently no institution that offers the services because of an almost non-existent demand, so the cost of 3D scanning for patients is currently unknown. The only currently known price is the cost of the 3D scanner, which costs $27,600 for the Artec Space Spider 3D Scanner that Dr. Ryan used. The harness alone costs $500 for a patient whose forearm was only partially amputated, so creating a cheaper alternative is also important.

Our team recommends that amputees print the arms using Nylon with continuous Kevlar® if it is available. However, if that specific filament is not available, a good replacement would be any chopped fiber blend, due to the load-transferring effect of the chopped fibers, which increases the overall toughness of the material, and ease of printing over a continuous fiber filament. Due to the inconclusive data obtained from the Charpy test, the exact increase of toughness is not known, however, in general, the toughness is increased when chopped fibers are added to monolithic samples.

Even though we were able to make progress towards our goal of introducing open source 3D printed arms as a viable option for amputees, there is still room for improvement. Future improvements include improving the control system, allowing for automatic calibration for each user. Currently, these designs have limited degrees of freedom, and there are only two modes for the fingers: the open position-- where all the fingers are simultaneously opened, and the closed position-- where all the fingers are simultaneously closed.

The development of a viable and easily-accessible harnessing system is also important. Currently, in order to get a harness, the user must go through a doctor, and it is costly and time-consuming to do so. Creating a harness that can be customized would also contribute to the reduced cost and increased availability to amputees.

Finally, current open-source designs currently do not take transhumeral amputees into account in their designs. This means that people who have their arms amputated above the elbow cannot use the arms. As a result, we want future teams to design a 3D printable passive elbow element so that a larger demographic of amputees has an equal opportunity to improve their lives.

EACH TEAM MEMBER'S ROLE

Tensile testing (4 hours) and literature review (6 hours) - Tayler

Charpy Impact Testing (2 hours) and literature review (6 hours) - Jason

3-Point Bend Testing (8 hours) and arm redesign (30 hours) - Nick

Differential Scanning Calorimetry (8 hours) and literature review (6 hours) - Brian

All members of the group contributed equally to all progress update papers, final reports, presentations, networking, and constructing the prototype arm (20+ hours).

Totals:
Tayler: 30+ hours
Jason: 28+ hours
Nick: 58+ hours
Brian: 34+ hours

ACKNOWLEDGEMENTS

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APPENDIX

Materials Index for a Light Stiff Beam

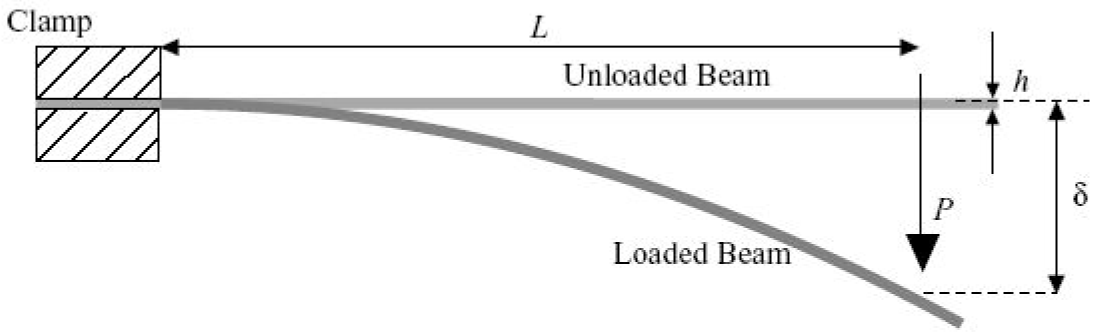


Figure A1: The beam model is that of a cantilever beam with end load. Cantilever beam of length l and end load P deflects a distance δ. Table A1 gives the function, objective, and constraints

Function	To carry bending moments
Objective	To minimize weight
Constraints	Stiffness

Table A1: Function, objective, and constraints for a stiff, light beam.

- Considering first the function, , the maximum deflection for this beam model is given by the equation:

$$\delta = \frac{Pl^3}{3EI} \qquad \text{Eq A1}$$

- Stiffness is defined by the force to displacement ratio and is obtained by rearranging Eq A1:

$$S = \frac{P}{\delta} = \frac{3EI}{l^3} \qquad \text{Eq A2}$$

- Because the final shape of the limb or support structure is still unknown, a elastic shape factor is incorporated in order to eliminate the second moment of inertia term (I). The definition of shape factor is given by:

$$\varphi_B^e = \frac{4\pi I}{A^2} \qquad \text{Eq A3}$$

- Solving for the second moment of inertia in Eq A3 and substituting it into Eq A2, one obtains the following function:

$$S = \frac{3EA^2\varphi_B^e}{4\pi l^3} \qquad \text{Eq A4}$$

- The objective function is:

$$m = \rho A l \qquad \text{Eq A5}$$

- Taking the constraint function (Eq A4) and solving for the area and plugging it into the objective function one obtains the performance equation:

$$m = (\tfrac{4}{3}\pi S)^{1/2}(l^{5/2})(\frac{\rho}{(E\varphi_B^e)^{1/2}}) \qquad \text{Eq A6}$$

- Here the performance equation is broken down into three parts, the first parenthesis is the functional requirements, the second is the geometrical constraints and the third is the materials properties(note that although the shape factor is a geometrical constraint it is convention to group it with the materials properties so it is included in the material index value. From the performance equation the Material index value is obtained. Convention is to have materials index values that are maximized in order to maximize performance, because maximizing performance in this instance involves minimizing weight, the material properties portion of the performance equation (Eq A6) is inverted in order to obtain the material index:

$$M = \frac{E^{1/2}}{\rho}(\varphi_B^e)^{1/2} \qquad \text{Eq A7}$$

δ	Deflection(m)
P	Load(N)
l	Length(m)
E	Modulus of Elasticity(Pascal)
I	Second moment of inertia(kg m^2)

S	Stiffness(N/m)
φ_B^e	Elastic shape factor
A	Area(m^2)
m	Mass(kg)
ρ	Density(kg/m^3)

Finite Element Analysis:

Initial Study:

Study Report

Analyzed File	New Arm v63
Version	Autodesk Fusion 360 (2.0.2995)
Creation Date	2017-05-04, 22:59:27
Author	Nicholas Lauer

Project Properties

Title	Studies
Author	Nwlauer

New Arm v63:1

Flexural Load

Study Properties

Study Type	Static Stress
Last Modification Date	2017-05-04, 22:52:09

Settings

General

Contact Tolerance	0.1 mm
Remove Rigid Body Modes	No

Mesh

Average Element Size (% of model size)	
Solids	10
Scale Mesh Size Per Part	No
Average Element Size (absolute value)	-
Element Order	Parabolic
Create Curved Mesh Elements	No
Max. Turn Angle on Curves (Deg.)	60
Max. Adjacent Mesh Size Ratio	1.5
Max. Aspect Ratio	10
Minimum Element Size (% of average size)	20

Adaptive Mesh Refinement

Number of Refinement Steps	0
Results Convergence Tolerance (%)	20
Portion of Elements to Refine (%)	10
Results for Baseline Accuracy	Von Mises Stress

Materials

Component	Material	Safety Factor
Bottom Assembly:1/Base:1	Nylon with Kevlar Flexural	Yield Strength

Nylon with Kevlar Flexural

Density	7.2E-07 kg / mm^3
Young's Modulus	803.4 MPa
Poisson's Ratio	0.35
Yield Strength	44.78 MPa
Ultimate Tensile Strength	44.78 MPa
Thermal Conductivity	2.81E-04 W / (mm C)
Thermal Expansion Coefficient	9.53E-05 / C
Specific Heat	1670 J / (kg C)

Mesh

Type	Nodes	Elements
Solids	3156	1500

Load Case1

Constraints

Fixed1

Type	Fixed
Ux	Yes
Uy	Yes
Uz	Yes

Selected Entities

Loads

Force1

Type	Force
X Value	0 lbforce
Y Value	-20 lbforce
Z Value	0 lbforce
Force Per Entity	No

Selected Entities

Results

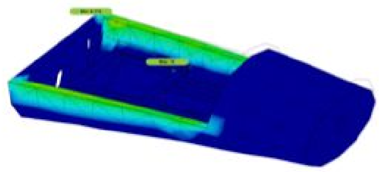
Result Summary

Name	Minimum	Maximum
Safety Factor		
Per Body	6.174	15
Stress		
Von Mises	0.001483 MPa	7.253 MPa
1st Principal	-1.522 MPa	7.446 MPa
3rd Principal	-4.583 MPa	2.034 MPa
Normal XX	-2.052 MPa	2.354 MPa
Normal YY	-1.612 MPa	2.493 MPa
Normal ZZ	-4.494 MPa	7.385 MPa
Shear XY	-0.4347 MPa	0.4771 MPa
Shear YZ	-1.633 MPa	0.8117 MPa
Shear ZX	-1.174 MPa	0.9531 MPa
Displacement		
Total	0 mm	5.21 mm
X	-0.1507 mm	0.1202 mm
Y	-4.951 mm	0.004217 mm
Z	-1.95 mm	0.1987 mm
Reaction Force		
Total	0 N	83.41 N
X	-20.89 N	23.09 N
Y	-12.4 N	27.45 N
Z	-78.23 N	73.32 N
Strain		
Equivalent	2.362E-06	0.0085
1st Principal	2.12E-06	0.009364
3rd Principal	-0.005114	-1.745E-06
Normal XX	-0.003187	0.001793
Normal YY	-0.003138	0.001978

Normal ZZ	-0.004729	0.008964
Shear XY	-0.001461	0.001604
Shear YZ	-0.00549	0.002728
Shear ZX	-0.003945	0.003203

Per Body

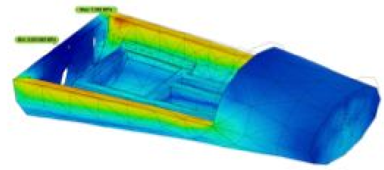
0 15



Stress

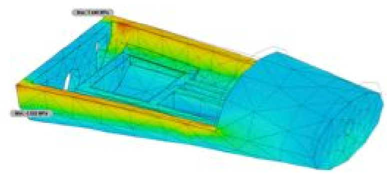
Von Mises

[MPa] 0.001 7.253



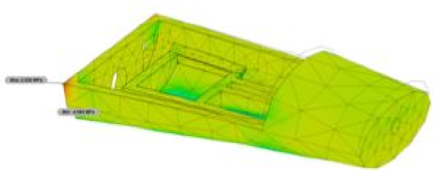
1st Principal

[MPa] -1.522 7.446



3rd Principal

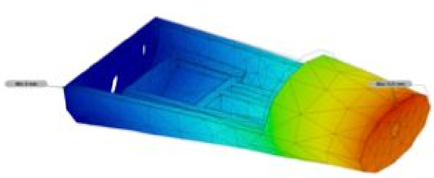
[MPa] -4.583 2.034



Displacement

Total

[mm] 0 5.21



Tensile Laod

Study Properties

Study Type	Static Stress

Last Modification Date	2017-05-06, 22:49:00

Settings

General

Contact Tolerance	0.1 mm
Remove Rigid Body Modes	No

Mesh

Average Element Size (% of model size)	
Solids	10
Scale Mesh Size Per Part	No
Average Element Size (absolute value)	-
Element Order	Parabolic
Create Curved Mesh Elements	No
Max. Turn Angle on Curves (Deg.)	60
Max. Adjacent Mesh Size Ratio	1.5
Max. Aspect Ratio	10
Minimum Element Size (% of average size)	20

Adaptive Mesh Refinement

Number of Refinement Steps	0
Results Convergence Tolerance (%)	20
Portion of Elements to Refine (%)	10
Results for Baseline Accuracy	Von Mises Stress

Materials

Component	Material	Safety Factor
Bottom Assembly:1/Base:1	Nylon with Kevlar	Yield Strength

Nylon with Kevlar

Density	7.2E-07 kg / mm^3
Young's Modulus	262.3 MPa
Poisson's Ratio	0.35
Yield Strength	44.78 MPa
Ultimate Tensile Strength	44.78 MPa
Thermal Conductivity	2.81E-04 W / (mm C)
Thermal Expansion Coefficient	9.53E-05 / C
Specific Heat	1670 J / (kg C)

Mesh

Type	Nodes	Elements
Solids	3156	1500

Load Case1

Constraints

Fixed1

Type	Fixed
Ux	Yes
Uy	Yes
Uz	Yes

Selected Entities

Loads

Force1

Type	Force
Magnitude	-50 lbforce
X Value	-9.394E-15 lbforce
Y Value	-2.067E-15 lbforce
Z Value	-50 lbforce
Force Per Entity	No

Selected Entities

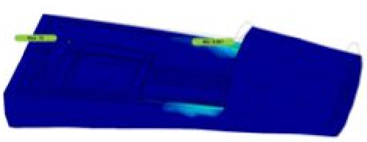
Results

Result Summary

Name	Minimum	Maximum
Safety Factor		
Per Body	8.961	15
Stress		
Von Mises	3.168E-04 MPa	4.997 MPa
1st Principal	-0.3449 MPa	5.449 MPa
3rd Principal	-1.703 MPa	0.8137 MPa
Normal XX	-1.197 MPa	1.827 MPa
Normal YY	-1.655 MPa	2.605 MPa
Normal ZZ	-1.093 MPa	5.391 MPa
Shear XY	-0.4329 MPa	0.4023 MPa
Shear YZ	-1.558 MPa	0.4359 MPa
Shear ZX	-0.6169 MPa	0.4139 MPa
Displacement		
Total	0 mm	6.596 mm
X	-0.318 mm	0.2687 mm
Y	-6.149 mm	0.009586 mm
Z	-2.981 mm	0.1332 mm
Reaction Force		
Total	0 N	32.61 N
X	-9.069 N	10.16 N
Y	-5.008 N	6.271 N
Z	-14.14 N	30.74 N
Strain		
Equivalent	1.767E-06	0.022
1st Principal	1.601E-06	0.02425
3rd Principal	-0.009726	-1.096E-06
Normal XX	-0.006722	0.005179
Normal YY	-0.007011	0.005386
Normal ZZ	-0.004345	0.01926
Shear XY	-0.004455	0.004141
Shear YZ	-0.01603	0.004486
Shear ZX	-0.006349	0.00426

Per Body

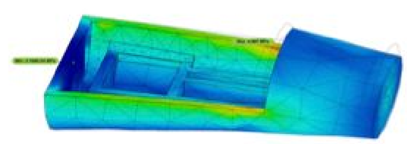
0 15



Stress

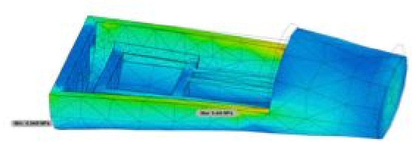
Von Mises

[MPa] 0 4.997



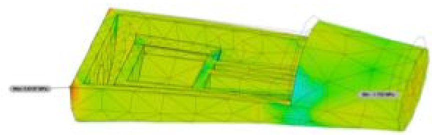
1st Principal

[MPa] -0.345 5.449



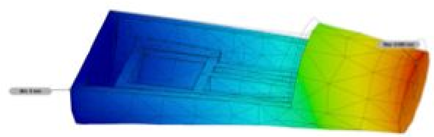
3rd Principal

[MPa] -1.703 0.814



Displacement

Total
[mm] 0 6.596



3D Printed Prosthetic Arm Redesign: Loading Analysis

Analyzed File	New Arm v60
Version	Autodesk Fusion 360 (2.0.2995)
Creation Date	2017-04-30, 16:36:21
Author	Nicholas Lauer
Summary	The following report is results from a simulation on the redisign of the Limbitless Arm for Alex design. The first situation is a flexuarl load and the second is a tensile load.

Project Properties

Title	Studies
Author	Nwlauer

New Arm v60:1

Flexural Load

Study Properties

Study Type	Static Stress
Last Modification Date	2017-04-30, 16:19:41

Settings

General

Contact Tolerance	0.1 mm
Remove Rigid Body Modes	No

Mesh

Average Element Size (% of model size)	
Solids	10
Scale Mesh Size Per Part	No
Average Element Size (absolute value)	-
Element Order	Parabolic
Create Curved Mesh Elements	No
Max. Turn Angle on Curves (Deg.)	60
Max. Adjacent Mesh Size Ratio	1.5
Max. Aspect Ratio	10
Minimum Element Size (% of average size)	20

Adaptive Mesh Refinement

Number of Refinement Steps	0
Results Convergence Tolerance (%)	20
Portion of Elements to Refine (%)	10
Results for Baseline Accuracy	Von Mises Stress

Materials

Component	Material	Safety Factor
Top Assembly:1	Nylon with Kevlar	Yield Strength
Bottom Assembly:1/Base:1	Nylon with Kevlar Flexural	Yield Strength

Nylon with Kevlar

Density	1.12E-06 kg / mm^3
Young's Modulus	2758 MPa
Poisson's Ratio	0.35
Yield Strength	70.4 MPa
Ultimate Tensile Strength	75.7 MPa
Thermal Conductivity	2.81E-04 W / (mm C)
Thermal Expansion Coefficient	9.53E-05 / C
Specific Heat	1670 J / (kg C)

Nylon with Kevlar Flexural

Density	7.2E-07 kg / mm^3
Young's Modulus	803.4 MPa
Poisson's Ratio	0.35
Yield Strength	44.78 MPa
Ultimate Tensile Strength	44.78 MPa
Thermal Conductivity	2.81E-04 W / (mm C)
Thermal Expansion Coefficient	9.53E-05 / C
Specific Heat	1670 J / (kg C)

Contacts

Bonded

Name
[S] Bonded1 [Top Assembly:1|Base:1]
[S] Bonded2 [Top Assembly:1|Base:1]
[S] Bonded3 [Top Assembly:1|Base:1]

Mesh

Type	Nodes	Elements
Solids	33,980	19,580

Load Case1

Constraints

Fixed1

Type	Fixed
Ux	Yes
Uy	Yes
Uz	Yes

Selected Entities

Loads

Force1

Type	Force
X Value	0 lbforce
Y Value	-20 lbforce
Z Value	0 lbforce
Force Per Entity	No

Selected Entities

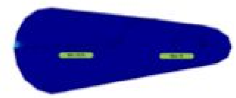
Results

Result Summary

Name	Minimum	Maximum
Safety Factor		
Per Body	10.72	15
Stress		
Von Mises	0.01181 MPa	6.57 MPa
1st Principal	-1.314 MPa	10.5 MPa
3rd Principal	-4.027 MPa	3.308 MPa
Normal XX	-1.828 MPa	4.799 MPa
Normal YY	-3.509 MPa	5.907 MPa
Normal ZZ	-2.388 MPa	7.921 MPa
Shear XY	-1.449 MPa	1.492 MPa
Shear YZ	-3.443 MPa	1.297 MPa
Shear ZX	-1.314 MPa	1.226 MPa
Displacement		
Total	0 mm	1.097 mm
X	-0.03276 mm	0.03574 mm
Y	-1.064 mm	0.009288 mm
Z	-0.3431 mm	0.08744 mm
Reaction Force		
Total	0 N	128.4 N
X	-21.72 N	22.32 N
Y	-50.67 N	18.89 N
Z	-42.38 N	118 N
Strain		
Equivalent	1.72E-05	0.005995
1st Principal	1.267E-05	0.006572
3rd Principal	-0.005217	-1.04E-05
Normal XX	-0.00174	0.001602
Normal YY	-0.002995	0.002912
Normal ZZ	-0.002183	0.004567
Shear XY	-0.002259	0.002853
Shear YZ	-0.00337	0.004359
Shear ZX	-0.003955	0.002379
Contact Pressure		
Total	0 MPa	4.964 MPa
X	-0.4999 MPa	0.6929 MPa
Y	-3.509 MPa	3.035 MPa
Z	-4.703 MPa	4.936 MPa

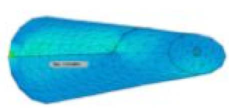
Per Body

0 15



3rd Principal

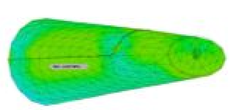
[MPa] -4.027 3.308



Displacement

Total

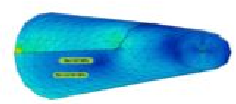
[mm] 0 1.097



Stress

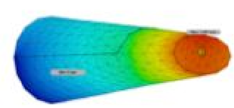
Von Mises

[MPa] 0.012 6.57



1st Principal

[MPa] -1.31 10.5



Tensile Laod

Study Properties

Study Type	Static Stress
Last Modification Date	2017-04-30, 16:10:47

Settings

General

Contact Tolerance	0.1 mm
Remove Rigid Body Modes	No

Mesh

Average Element Size (% of model size)	
Solids	10
Scale Mesh Size Per Part	No
Average Element Size (absolute value)	-
Element Order	Parabolic
Create Curved Mesh Elements	No
Max. Turn Angle on Curves (Deg.)	60
Max. Adjacent Mesh Size Ratio	1.5
Max. Aspect Ratio	10
Minimum Element Size (% of average size)	20

Adaptive Mesh Refinement

Number of Refinement Steps	0
Results Convergence Tolerance (%)	20
Portion of Elements to Refine (%)	10
Results for Baseline Accuracy	Von Mises Stress

Materials

Component	Material	Safety Factor
Bottom Assembly:1/Base:1	Nylon with Kevlar	Yield Strength

Nylon with Kevlar

Density	7.2E-07 kg / mm^3
Young's Modulus	262.3 MPa
Poisson's Ratio	0.35
Yield Strength	44.78 MPa
Ultimate Tensile Strength	44.78 MPa
Thermal Conductivity	2.81E-04 W / (mm C)
Thermal Expansion Coefficient	9.53E-05 / C
Specific Heat	1670 J / (kg C)

Mesh

Type	Nodes	Elements
Solids	32,137	18,612

Load Case1

Constraints

Fixed1

Type	Fixed
Ux	Yes
Uy	Yes
Uz	Yes

Selected Entities

Loads

Force1

Type	Force
Magnitude	-50 lbforce
X Value	-9.394E-15 lbforce
Y Value	-2.067E-15 lbforce
Z Value	-50 lbforce
Force Per Entity	No

Selected Entities

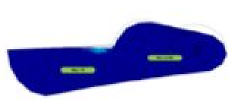
Results

Result Summary

Name	Minimum	Maximum
Safety Factor		
Per Body	5.449	15
Stress		
Von Mises	1.401E-04 MPa	8.218 MPa
1st Principal	-0.3336 MPa	8.892 MPa
3rd Principal	-1.751 MPa	0.927 MPa
Normal XX	-1.225 MPa	1.874 MPa
Normal YY	-1.741 MPa	3.273 MPa
Normal ZZ	-1.083 MPa	8.618 MPa
Shear XY	-0.7135 MPa	0.608 MPa
Shear YZ	-3.066 MPa	0.8975 MPa
Shear ZX	-0.6666 MPa	0.559 MPa
Displacement		
Total	0 mm	6.499 mm
X	-0.3624 mm	0.3266 mm
Y	-6.059 mm	0.009592 mm
Z	-2.927 mm	0.1318 mm
Reaction Force		
Total	0 N	32.41 N
X	-9.769 N	10.18 N
Y	-4.802 N	6.257 N
Z	-14.54 N	30.53 N
Strain		
Equivalent	7.03E-07	0.03945
1st Principal	5.287E-07	0.04235
3rd Principal	-0.0232	-4.637E-07
Normal XX	-0.01093	0.00591
Normal YY	-0.008739	0.009342
Normal ZZ	-0.004232	0.03068
Shear XY	-0.007343	0.006258
Shear YZ	-0.03155	0.009237
Shear ZX	-0.006861	0.005754

Per Body

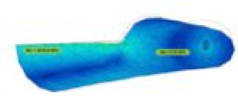
0 15



Stress

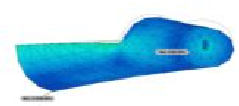
Von Mises

[MPa] 0 8.218



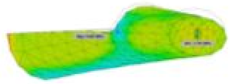
1st Principal

[MPa] -0.334 8.892



3rd Principal

[MPa] -1.751 0.927




Displacement
Total
[mm] 0
6.499