In this research paper an analysis has been completed to inform a discussion on the material selection process in the design of a prosthetic foot. Through the use of additive manufacturing, a study has been performed to determine the structural properties of the materials in question. This structure was initially designed to hold the weight of an average human standing still with a safety factor of three. As the design became better understood, it was enhanced to include dynamic movement with more attention paid to customization options. Designs, models, fabrication, and testing are presented.

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Introduction/Background

Need and Problem Statement

Prosthetics have been used across the globe for centuries and have allowed those who use them to try and regain some mobility back in their life. Currently one out of every 190 Americans suffer from the loss of one or more limbs (Ziegler). The design to be created during this semester is a mechanical load bearing prosthetic foot structure. This project will address the lack in the current prosthetic market for an affordably priced prosthetic foot structure. The scope of this project for this semester is to design, prototype and (test) perform a compression test on a structural frame from which all future designs (in the following semesters) will be based on to create a full working prosthetic foot.

Introduction

Next, the group found an abundance of studies that compared the walking gait of both amputees and non-amputees. For example, some of the research papers compared a person who did not have a prosthetic foot versus someone who had a prosthetic foot. Other studies compared different types of prosthetic feet (such as different brands or different models from the same company). The conclusion of the research proved that someone with a prosthetic foot had a changed (and usually unnatural) gait versus some who did not have a prosthetic foot (Hordacre).

After doing extensive research on the current available prosthetic foot structures, it became clear that there was no current design that included separated toes that served a purpose other than aesthetics. In other words there is currently no prosthetic foot structure on the market that uses independently moveable toes to perform a useful function that assists the user. This discovery has helped shift the scope of the design for the structure to include toes.

Also throughout the group’s research the discovery that options for materials that are used to build the structure of the prosthetic foot are very limited. The major choices are carbon fiber, titanium, steel and aluminum. Each of these materials has their downfalls. For example, carbon fiber and titanium are both very expensive, but are the strongest options currently available. Steel is relatively cheap and very strong but too heavy when too much of it is used. Aluminum is cheap and lightweight, but not strong enough to support a human when it becomes too thin (Uellendahl).

The group has also done a large amount of research into 3D printing and has decided to prototype the final design using a 3D printer. The major reason for this is
that it allows the group to create a finished deliverable product to be able to present to an audience. The group will run a feasibility study as well as a materials study to determine whether 3D printing could be a future option for the manufacturing aspect of the project.

All of this research conducted about the current types of prosthetic feet available today solidified the group's belief that there must be a better solution. The group has decided to start with just the frame of the foot for this semester. The features that are to be included in the design are the ball of the foot, structural bars, heel and central ball joint.

Along with building a prosthetic foot structure this semester, the group will also conduct a 3D printable material strength test. With the use of 3D printers, the group will print six different types of materials, test them using both compression and tension and then compare the results to one another.

**Data/Formulation/Methodology**

**Primary Constraints:**

The primary constraints for this project are that the static foot structure must hold the weight of an average human which was researched to be 178 pounds (Walpole). Another constraint is that the completed foot should not weigh more than 1.4% of the average weight of a human (or 2.49 pounds). This was determined through research that stated that the average weight of a foot on a person is 1.4% of their weight (Clauser). This group has also chosen a safety factor of 3, which falls within a range of safety factors seen in prosthetics (from 1.7 to 3.7) (Sup, F).

**Primary Objectives:**

The objectives of this project include cost, sizing, overall shape, and functional goals. It is hoped that by focusing on affordability and overall shape and size, users will be more likely to use our product, and by focusing on reproducing the function of a natural foot, users will be more likely to continue using our product. To that end, these are our objectives identified and explained:

The structure should cost less than $1000. The driving force behind the cost chosen is the relative lack of affordable powered lower-leg prosthetics. It is the group’s goal to produce a product which will provide a lower-leg replacement solution that will be widely affordable as well as functional.

The foot should fit within the same dimensions of the foot it will be replacing or be the same size as the opposite foot. Because not everyone wears the same shoe size, the group has agreed on a scalable approach, allowing a foot to be produced in virtually any size. The group has started the design process with the weight of an average human for the purpose of early static structure design.

The foot should maintain a form factor similar to that of a natural human foot. Re-addressing the statement above, one of the motivating factors behind the design is the concept that most people wear either shoes on both feet, or wear no shoes at all. This means that if the user chooses to wear shoes that the product will be more likely to be used if it fits inside a shoe properly.

The ankle joint, which will be a ball joint on the structure, should have at least two degrees of freedom to help replicate what a natural human foot has. Again, because the product is designed for people with lower limb loss, the prosthetic will be replacing not only the appearance of the foot, but also the function of the affected limb. Because the human ankle has a natural two rotational degrees of freedom, the prosthetic has been designed to replace at least those movements. Future analysis will determine if it is practical to replace the rotational degree of freedom inherent to the lower leg.

Solidworks assembly drawings of the foot are shown below in Figure 1 (a, b, c, d).
In order to hold up the weight of the user, the group intends to use fused deposition modeling (FDM, also called 3D printing) with plastics to form the bulk of the structure. Early in the brainstorming and design processes, the group considered the materials they had available to them and looked ahead to what they wanted to build the foot out of. On the material side, the group considered carbon fiber, aluminum, and FDM plastics. The carbon fiber was eliminated due to difficulties in shaping, as well as a poor understanding of composites within the group. Future designs may involve carbon fiber, but there was not enough time to fully undertake a carbon fiber structure without a composites background. Aluminum was considered but later eliminated due to its higher cost and greater difficulty in shaping for both basic shapes and complex shapes. Also factored into the assessment was the ease of production. With the group’s current capabilities, FDM plastics (or 3D printing) became the group’s best option. Compared to the alternatives mentioned above, FDM is less expensive, easier to shape, and can be shaped into much more complex shapes if need be.

The group spent a large majority of the first two weeks of the semester brainstorming. Usually for hours at a time, the group would sit together and talk about potential solutions. After the end of each session the group would collect all the different ideas and converge onto one idea they felt was the best. The group has spoken about different areas of the mechanical design including how the relative motion of the pieces of the foot look and feel as a load is applied. This is done using mechanical joints that transfer load from one section of the foot to another. Some examples of joints may include spheroidal joints, pin joints, welded joints, and rotary joints. Please refer to Appendix (A) for three different ideas created by the group that were considered during the brainstorming process.

To provide the desired two degrees of freedom, the group intends to use a ball joint at the ankle. For the joint, the group considered a Hooke’s universal joint and a ball joint. The Hooke’s joint was eliminated due to its vulnerability to shearing, its relative complexity (three structural parts plus up to six interfacing parts), and the complexity of adding another degree of freedom during potential future expansion. Instead the ball joint was chosen because it provides three rotational degrees of freedom, the two that were desired by the constraints and one additional for future expansion. It also has relatively few failure modes.

All of the solutions for both the material and the joint have been organized in a “best-of-class” chart that can be found at the end of this paper in Appendix (B).

The objectives and constraints of the best-of-class chart have been defined as to why they are used in the Primary Objectives and Primary Constraints section of this paper. If you have any questions as to why one was
used as an objective or constraint, please refer to the above mentioned section. In the best-of-class chart, the numerical values given for each of the three materials discussed are on a scale of 0 to 10, with 0 being the least ideal, and 10 being the most ideal. Constraints have been numerically represented by either a 1 or 0, where 1 is meeting the constraint, and 0 is failing to meet the constraint. Constraints have been indicated with a (C) in the name column, and Objectives have been indicated with an (O).

**Analysis**

**Accomplishments & Obstacles**

The group successfully completed its creative brainstorming session coming up with a number of ideas including the ones mentioned above. After the brainstorming was complete the group moved on to the conceptual development phase. This allowed the group to refine their ideas and form possible solutions to create the structure for the prosthetic foot. During the conceptual development the group defined their constants and principle functions as listed and explained above. With this information the group created a common outline that each group member then interpreted as they saw fit and created their own individual design.

The individual design process for the group was more of an undertaking than first predicted. The group did manage to complete their individual designs using Solidworks in the allotted three weeks with some adjustments to the design criteria. After a group discussion about the complexity of the structural model, the group decided that toes were not actually needed at this time. The actions that toes do in the foot to support a human and provide dexterity are far less important to the overall structural design than first predicted. This is because the toes themselves are not truly load bearing. After going back and reviewing the previous research, the group found that the ball of the foot will incur the majority of the load when the center of gravity of the user is shifted forward past the center of the foot. For example during normal operating conditions (such as walking or climbing stairs) the toes do not play a major role in caring the weight of the user. On top of this, the structural design of the toes depends heavily on the hydraulics used to control them. At this time the research and development behind the hydraulic system of the foot is outside the scope of this class. Therefore the toes cannot be properly constructed until further research is completed.

With all the individual designs completed, the group held a meeting to allow each member to present and explain their design. Each member received feedback, both positive and negative, and the best ideas were collected to be used in the collaborative design. An entirely new file was created and each member was tasked with designing a portion of the foot (for example the ball of the foot, heel, structural bars and ball joint). Each component was completed and then added to an assembly where static testing will be conducted. One major change from the individual designs to the collaborative designs is that of a connected heel. Previously the group was only going to connect the foot’s heel to the ball joint (via a structural bar) and nothing else. Instead the group has opted for a triangular shape where the heel is connected to the ball joint as well as the ball of the foot. This will provide a stronger structure and allow for the foot to carry more electronics and sensors in the future if necessary. The only major complication with the collaborative design was the ball joint. This ball joint needed to allow for two degrees of freedom as determined by one of the constraints of the project. Determining a method on how connect the three structural bars and the ball joint to move freely took some creativity to design in Solidworks, but the group eventually worked through the problem.

With the end of the semester having arrived, the group has officially completed all of the line items on its gantt chart. An updated version of the gantt chart can be found at the end of this paper in Appendix (B).

On previously submitted gantt charts the group allotted time during the design process to be used for individual simulation. After discussing the time commitment to simulate four different sub-par designs the group decided to eliminate individual simulation in exchange for a more rigorous collaborative design and collaborative static simulation. The deciding factor for the change was the amount of time it would take for each group member to simulate their model only for the model to be to be discarded (along with the simulation data) when it was redesigned collaboratively. The data from the individual designs may have been useful but with an entirely new model few valid comparisons of improvement could have been drawn between the individual and collaborative designs. With the time saved, the group was able to go back and refine their collaborative design after it was simulated when at first the model did not yield a high enough ultimate strength.

Once the model had reached the ultimate strength goals (178 lbs with a safety factor of 3) the group could then 3D print it. The group decided to print the model at half scale to allow for a faster printing time (a savings of roughly 3 hours). The model was printed with a MakerBot Replicator 2x using ABS plastic.
3D printing is a relatively new and still highly under developed method of producing printed parts. The printers tend to breakdown and require lots of repair and upkeep. The current 3D printer used this semester has had a broken thermocouple and build plate temperature inconsistencies in the past few months. These problems were addressed throughout the semester as necessary and did not affect the progress of the project. Also the material used to 3D print also has inconsistencies. These inconsistencies lead to peeling and deformed parts. The group purchased the necessary items (painters tape and acetone) to allow the printer to reduce its inconsistencies as much as possible.

While all the individual and collaborative designing was going on the group was working on the material study that would accompany the completed structure. The group has researched previous experiments using 3D printed material to gain the necessary background knowledge to accurately perform the materials strength test. One of the research papers in particular the group used to create parameters for the material study was one published by a group of students at the University of California, Berkeley and Gyeongsang National University, Chinju, Korea titled: ‘Material Characterization of Fused Deposition Modeling (FDM) ABS by Designed Experiments’. The report focuses on how the layers of plastic are formed while 3D printing and corresponds that to the differences in stress and strain on 3D printed parts based on the direction the parts were pulled (compression or tension). The paper also summarized the results and created a set of rules that should be adhered to when 3D printing listed below.

- Parts should be built so that the tensile forces are subjected along the length of the fibers.
- If a radius is required in the design, a contour should be built into the radius in order to ensure structural integrity.
- Parts should be built so that the layers of the material are overlapping.
- The shear strength is greater between layers of material rather than the in the axial direction.
- The bead width and temperature do not affect the strength of the part.

One of the biggest problems with FDM cited in the paper is the fact that there are stress concentrations that occur at the seams of the layers. One of the ways this is resolved is by “moving” the layers closer and closer together. Another way to alleviate this problem is by laying the layers in a different pattern (Montero). These advanced techniques were outside the capabilities of the current 3D and will be looked into in the future if 3D printing becomes a feasible option.

Along with the increased interest in 3D printing, there has been a rise in the number of different types of plastics that can be used. Currently the group has ordered six different types of material. The first three materials, ABS (acrylonitrile butadiene styrene), PLA (polylactic acid), and carbon fiber PLA were included in the materials study. The other materials ordered, were backordered and were not included because of the lead time. The material study used the University of Southern Maine’s Instron 5882 tensile machine located in the John Mitchel Center’s Mechanical Engineering Lab. Having seen the machine be used for similar tests with metal, the group felt it would be perfect for testing different types of plastic. After thoroughly researching the process of how this specific model works, the group has created two Solidworks models, one for compression and one for tension, of a standard test sample used in the machine. This data came directly from the ASTM D638 and ASTM D695 and served as a guideline for the models. Using these models the group then 3D printed four test samples of each material to be analyzed. Two test samples of each material are for compression while the other two are for tension. Each of the two samples (for their respective test) has a different infill percentage.

When a 3D printer prints, it uses a method of hexagonal slicing to create the internal geometry. This slicing process creates a partially hollow center known as infill. Using an infill allows the part to be sturdy, lightweight and print relatively quickly. With the slicing process in mind the group chose to print test samples at both 50% and 75% infill. Once the test sample was printed, the group meticulously measured them and recorded its physical measurements and compared them to the standard used to create the Solidworks model. The group chose not to test the various materials at a 100% infill because there are multiple studies that exist that have done this before. As stated in the design constraints, the group is trying to minimize the weight as much as possible and finding enough strength to satisfy the design at a lower infill percentage would be ideal.

An ABS foot was printed using the Solidworks drawings. The dense fill ABS worked well, considering the length limitations for the damper spring enclosure.
After printing the test samples the group used the Instron testing machine to gather data about the tensile properties of the machine. Drawing the sample at 2.5mm/min provided valuable data about the materials being used in this comparison. Shown in Appendix (D), the tensile data gathered shows the stress over strain curves for the six samples tested. The group concluded that the PLA sample tested at 75% infill provided the most strength, but proved to be very brittle. With the tension data gathered the group continued to research the compression characteristics of the materials. Due to not having the proper fixtures needed to test compression on the Instron machine the group was forced to use the Tinius Olsen hydraulic compression machine located in the University’s Materials Testing Lab. This machine utilizes hydraulic pressure and manual controls to modulate the testing surface. The data gathered from testing on this machine provided the group with only the maximum compression values of the samples tested shown in Appendix (D). The compression data again proved that the PLA material printed at 75% infill was the strongest. Due to PLA’s poor printing performance (extended time to print as well as drastic inconsistencies in material) the group chose to accomplish its goal for the full size model using ABS plastic. Using ABS allowed the group to print multiple models in a very short period of time, which was the most ideal choice when choosing a material. After printing the individual components of the full scale model, the group assembled it using press fits and then prepared the model for testing. To test the full size model under compression loads the group repeated the process it had used for the compression testing. Using a baseline force of 178 pounds with a safety factor of 3 to consider the test a success a force of 534 foot pounds needed to be applied to the sample. The group placed the model in the machine and slowly loaded the machine until the indicator displayed 535 foot pounds of force shown in Appendix (E). Having tested the model without failure to the desired load the group proved that ABS plastic is a viable material for the structural design of the prosthetic foot.

When the group had completed its final testing it calculated the cost of the overall cost of the foot. Located in Appendix (F) is a chart that shows the money spent on the material, labor and miscellaneous expenses of the project. The foot weighed a total of 189.7 grams (or .418 pounds). This put the foot structure well below the 2.49 lbs that was set forth as a constraint for the project. With 3D printing plastic being $28 a kilogram and machine time costing $20 per hour, the total cost of the foot was $315.31, well below the $1000 objective set forth by the group. If the product were sold at $1000, it would result in a 68% profit margin.

Simulation: Finite Element Analyses

The model was tested with three different materials for:
- Stress,
- Strain, and
- Deformation

According to the formulation shown in Figure 3.

\[ \sum F_x = 0 = F_{x1} + F_{x2} \ldots \]

\[ \sigma = \frac{F}{A} \]

\[ \sum M_o = 0 = (d_1 \times F_1) + (d_2 \times F_2) \ldots \]

\[ \sigma_{\text{max}} = \frac{M_c}{I} \]

\[ c = \frac{\sigma_{\text{max}} l}{M} \]

\[ l = \frac{bh^3}{12} \]

Figure 3. Simulation format for the prosthetic foot.
The simulation results are shown in Figure 4 below. The setup for simulation testing was as follows:
Fixed Bottom of Foot;
Applied 7000N Loading Force through Ball Joint Location; and
Replaced Spring & Damper with equivalent Spring Force.
Actual tests were performed with the following observations and results:
Limitations
-Known limits of SolidWorks simulations
-Linkage bar weaknesses
The analytical vs. Solidworks Simulation showed less than 5% difference.

With all of these results, the group is proud to say they have meet each and every constraint and objective set forth at the beginning of the semester.

**Conclusions**

With conducting an in depth study on other practical solutions to lower limb replacement the group researched the problems and challenges to building a prosthetic. By analyzing the natural gait of a human the group set out to construct a model that meets the needs of today’s market. The current model that the team has designed is the structural frame from which the rest of the foot design process can build upon. Using materials that would be widely available the group built several iterations of their design until they reached to the final model. The usage of FDM thermoplastics was critical to the timeline of this project and served as a way to make quick revisions while taking very little time. Through conducting the materials study the group learned about the material characteristics of FDM thermoplastics including carbon fiber impregnated PLA, ABS, and PLA as a standalone material.

When it came to the actual structure, the model was vigorously tested in Solidworks simulation where it passed with a safety factor close to 5. The final structure using the data collected from the materials study was tested to 534 pounds on the Tinius Olsen hydraulic compression tester (located in the material testing lab). This number comes from the constraint that the average person weighs 178 pounds and with a safety factor of 3. In the final testing the foot was subjected to only compressive loading because of the constraints set forth in the project. The structure was able to withstand the 534 lb compression with only minor deformation on the structure. The foot also came in under budget and meets each and every constraint and objective set forth at the beginning of the semester.
Authors

Matthew Adam Gordon is a Mechanical Engineering student with a minor in Electrical Engineering from the University of Southern Maine slated to graduate in May of 2016. His main contributions to the research at hand have been in obtaining the necessary standards and performing the finite element analysis of the prosthetic foot structure. His professional interests include complex robotic mechanisms as well as the product development of consumer and medical products.

Kevin Andrew Hutchens is a senior Mechanical Engineering student from the University of Southern Maine graduation in May 2016. His main contributions to the research have been in materials research and processing, and structural design. Outside the project, Kevin’s abilities include process engineering, additive manufacturing as well as product development and manufacturing.

David James Manzenberge is a senior Mechanical Engineering student with a minor in Physics at the University of Southern Maine on track to graduate in May of 2016. His contributions to the research have been in the areas of computational simulation, structural design, and testing and implementation. His interests outside the project include microsatellite design, manufacturing engineering, and extraplanetary exploration. David’s hobbies are coding, playing sandbox games, and reading science fiction.

Zachary Jon Stewart is an Electrical Engineering student from the University of Southern Maine expected to graduate in May of 2016. His main contributions to research have been in developing a repeatable printing process and the creation of samples. With a passion for design and tinkering he knew this research project would offer him a chance to explore a new biomedical field. His expertise includes additive manufacturing and concept development.

James V. Masi is a Professor Emeritus from Western New England University and a Professor in Engineering at the University of Southern Maine. He has a B.S. and M.S. in Physics and a Ph.D. in Applied Science (Material Science) from the University of Delaware. He is widely published and has numerous patents in many fields. He has mentored many students/researchers

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