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Computer Aided Design

FEA Prosthetic Report

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Abstract:

This report explores how Finite Element Analysis (FEA) can be used to design and improve prosthetic feet. The goal is to better understand how prosthetic feet handle stress and strain under different conditions like standing and walking. I used CAD modeling and FEA software to simulate my prosthetic design, different materials, and different load scenarios. I also compared my results with findings from published research. The analysis showed how design and material choices affect performance, especially in terms of stress concentration, deformation, and fatigue resistance. This project helped me understand the real world use of FEA in biomedical engineering and how it can lead to better, more affordable prosthetics.

Introduction:

In recent years, the development of affordable and efficient prosthetic devices has become very important as the imbalance of wealth equality grows in the United States. This disparity can be especially challenging for individuals without access to high end medical care or proper insurance. For my project I selected a prosthetic foot to design in Solid Works with the intention of affordability, easy manufacturing and easy customization. Prosthetic feet play a critical role in restoring mobility and creating a better quality of life for disabled Americans. Unfortunately, the costs associated with more advanced designs still remains extremely high and only continues to get more expensive. To address this, my project will focus on designing a cost effective prosthetic foot that balances performance, durability, and affordability.

The design for my prosthetic foot will compare my selected materials against more premium options. My project will demonstrate that a functional, high performance prosthetic foot can be achieved at a fraction of the traditional market cost.

The goal of this project is not only to engineer a prosthetic foot that is mechanically sound but also to promote greater accessibility for users who may otherwise be limited by financial barriers. Through careful material selection and simplified manufacturing processes, this design will hopefully serve as a practical solution for everyday mobility needs while maintaining adaptability for different users and activities.

Literature Review:

"Finite Element Analysis on Prosthetics"

In the article "Finite Element Analysis on Prosthetics," the authors discuss how finite element analysis (FEA) can help improve the design and safety of prosthetic devices. They focus on how computer simulations are used to test different loads and forces on prosthetic parts without having to build and break real models first. The study shows that "the strength and durability of the prosthetic structure were evaluated effectively using FEA" (Finite Element Analysis on Prosthetics 5). One of the main points the article makes is that these simulations allow engineers to optimize material use, making prosthetics lighter without sacrificing strength. This is important for lower limb prosthetics because the foot must be lightweight but strong enough to handle repeated walking forces. Overall, the article proves that FEA is a valuable tool for making better prosthetic feet and saving money on testing.

"FEA Prosthetics"

The article "FEA Prosthetics" also focuses on using finite element analysis to study the performance of prosthetic limbs. The authors mainly look at how stress and deformation happen in different parts of a prosthesis when a person is walking. They state that "using FEA allows for a detailed understanding of where the highest stress concentrations occur in prosthetic components" (FEA Prosthetics 3). This is very important because it helps designers predict where a part might fail and adjust the design before real world testing. The article highlights how important it is to have a good mesh when doing FEA because a poor mesh can give wrong results. The study supports the idea that better simulations lead to safer, longer lasting prosthetic feet, especially when trying to lower costs by choosing affordable but durable materials.

"Design and Manufacturing of a Low-Cost Prosthetic Foot"

In the article "Design and Manufacturing of a Low-Cost Prosthetic Foot" by Saad M. Ali and Shurooq S. Mahmood, the authors present a new design for an affordable prosthetic foot. They focus on making a prototype that is lightweight, flexible, and strong enough to handle daily activities. The foot was made using simple manufacturing methods to keep the costs down for people in low-income regions. According to the authors, "the materials selected and the simple manufacturing process contributed to reducing the cost of the prosthetic foot to less than half of traditional designs" (Ali and Mahmood 7). They also based the shape of the foot on real anatomical measurements to make the fit more comfortable. This article matches the goals of this project perfectly because it shows that it is possible to create affordable, functional prosthetic feet without high tech or expensive equipment.

"Prosthetic Foot Performance Testing and Design"

The article "Prosthetic Foot Performance Testing and Design" explains how prosthetic feet are tested for durability, flexibility, and strength. The authors discuss different tests like heel strike loading, mid stance bending, and toe off simulations that mimic real walking forces. They explain that "prosthetic feet must meet international standards for load-bearing and fatigue resistance to ensure long-term user safety" (Prosthetic Foot Performance Testing and Design 4). The study also mentions how small design changes, such as the curvature of the foot plate, can make a big difference in comfort and energy return for the user. This article fits this project because it shows the importance of testing prosthetic feet thoroughly so that even low cost designs are still safe and effective for daily life.

"Fatigue Characterization of Laminated Composites Used in Prosthetic Sockets Manufacturing"

In the article "Fatigue Characterization of Laminated Composites used in Prosthetic Sockets Manufacturing," Ehab N. Abbas, Muhsin J. Jweeg, and Muhannad Al-Waily study how laminated composites behave under repeated stress, which is important for prosthetic sockets and feet. They explain that "the engineer should base designs on endurance stress levels instead of allowable stresses" to avoid failures during the gait cycle (Abbas et al. 385). Their testing compared five different laminate types and showed that composites with carbon fiber layers had the best fatigue resistance. The article points out that small changes in material stacking sequences can lead to large differences in how long a prosthetic can survive daily use. These findings directly support using strong, lightweight composites in prosthetic foot designs for longer durability and better safety.

Project Goals and Scope:

The main goal of this project was to design a prosthetic foot that could store and return energy in a way similar to the natural foot, while keeping the design affordable and durable. The inspiration for my design came from the article "Geometry Reconstruction and Performance Evaluation of Energy Storage and Return (ESR) Prosthetic Foot with CAD-FEA Method" by Dhananjaya Kumarajati, Hasti Marfuah, and Venti Yoanita. In their study, they used CAD software to reverse engineer an existing ESR prosthetic foot and then applied finite element analysis (FEA) to test its strength, deformation, and safety factor under standing and walking loads.

Based on their approach, my project focused on creating a simple but effective prosthetic foot model that could handle normal daily forces while offering some level of energy return. One of the main objectives was to use FEA to simulate real world loading conditions, like the forces experienced during standing and walking. By doing this, I could check if the materials I selected and the design choices I made would result in a safe and strong prosthetic foot.

Another important objective was to find a balance between cost and performance. Expensive prosthetic feet made of advanced materials like carbon fiber can offer great performance but are often too costly for many amputees. In this project, I aimed to use common, more affordable materials where possible while still maintaining good fatigue resistance and flexibility. The ultimate goal was to prove through simulation that an affordable prosthetic foot could still perform well enough to be useful and safe for daily use.

Materials and Design Descriptions:

The prosthetic foot designed in this project focuses on being lightweight, durable, and affordable. The design is made up of several main parts: the foot base plate, toe box top, toe box plate, hinges, and a rolling pin. Each part was carefully sized and assigned a material that balances strength, fatigue resistance, and cost.

The **foot base plate** acts as the main blade that stores and returns energy while walking. It was made from carbon fiber reinforced polymer (CFRP) because this material is strong, lightweight, and has excellent fatigue resistance. CFRP was chosen even though it is more expensive than aluminum because it improves performance significantly for the most critical part of the design.

The **toe box top** and **toe box plate** were designed to form the front of the foot. These parts were made from aluminum 6061-T6. Aluminum was selected because it is strong enough for everyday loads, relatively low-cost, and easy to machine. Both toe box parts were designed to bolt together with four fasteners to ensure a tight connection while staying light.

The **base hinge** and **hinge** connect the front part of the foot to the main plate and allow for slight movement during walking. They were also made from aluminum 6061-T6 to keep the weight down while providing enough strength at the connection points. Each hinge was designed with an 8 mm hole for a shaft.

The **rolling pin** that goes through the hinges acts as a simple rotating shaft. It was made from mild steel instead of stainless steel to reduce cost while still offering good durability.

All parts were modeled in SolidWorks, and key dimensions were based on comfortable walking proportions and load requirements for an average adult male.

Table:

Component	Material	Dimensions (mm)	Reason	Estimated Cost per Part (USD)
Foot Base Plate	Zoltek PX35 Carbon Fiber Reinforced Polymer (CFRP)	~260 × 75 × 6	Lightweight, strong, good energy return	$45
Toe Box Top	Aluminum 6061-T6	~85 × 70	Lightweight, affordable, machinable	$10
Toe Box Plate	Aluminum 6061-T6	~85 × 70	Matches Top Plate, strong and cheap	$8

Base Hinge	Aluminum 6061-T6	~40 × 30 × 25	Strong hinge connection, easy to machine	$7
Hinge	Aluminum 6061-T6	~40 × 30 × 25	Same as Base Hinge for rotational movement	$7
Rolling Pin	Alloy Steel	~35 (length) × 8 (diameter)	Cheap and strong shaft for hinges	$2-3

Methodology and Numerical Approach:

I started by modeling each part of the prosthetic foot in SolidWorks. I made the foot base plate, toe box top, toe box plate, base hinge, hinge, and rolling pin all as separate parts. I based the sizes on what would work for an average adult and made sure the pieces could fit together without any weird gaps. After that, I assembled everything to make sure the foot looked right and would move properly at the hinge.

For materials, I picked:

- Carbon fiber reinforced polymer (CFRP) was chosen for the foot base plate to take advantage of its fatigue life and energy return properties.
- Aluminum 6061-T6 was selected for the toe box components and hinges because it is lightweight, affordable, and easy to manufacture.
- A mild steel shaft was used for the rolling pin to provide a strong and cost-effective solution for the rotational component.

Once the assembly was complete, I set up a static simulation in SolidWorks Simulation. I fixed the bolt holes at the rear of the foot plate to simulate how it would be attached to a real prosthetic socket or pylon. Instead of applying the load at the toe, I applied a downward force directly at the hinge because that is where the weight of the person would actually transfer through the prosthetic.

I used a total force of 980 N to represent the full body weight of a person standing or walking on the prosthetic foot. This force was split across the hinge area to simulate the load during standing or walking activities. Gravity was also included in the simulation setup to account for the self-weight of the parts.

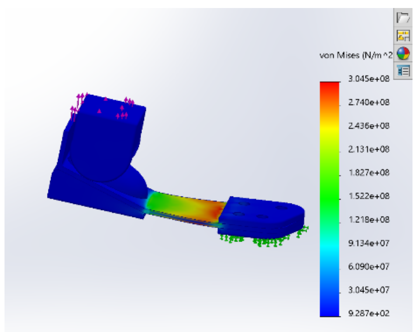
Then, I meshed the assembly using normal meshing. After running the simulation, I checked the Von Mises stress, the displacement, and the safety factor to make sure the design could survive everyday use without breaking. If the stress had been too high, I would have adjusted the design, but the results showed the foot could safely support a normal user.

Results and Analysis:

Upward Walking Motion:

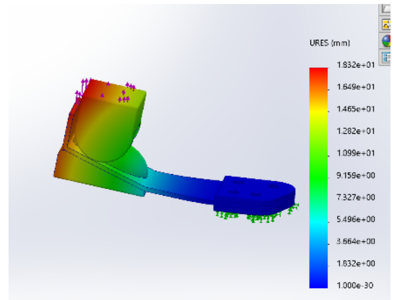
For the upward walking simulation, I applied a force of 980 N at the hinge again, but in the upward direction, which represents what happens when someone pushes off the ground during a step. This kind of motion is common in walking or running.

Stress (Von Mises):



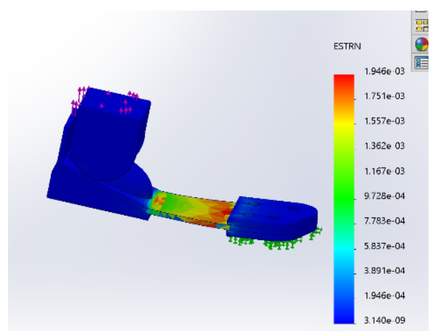
In this case, the max stress was around 305 MPa, located in the middle section of the carbon fiber foot blade, close to where it starts to bend upward from the hinge. Even though this force direction is different, the stress distribution looks really similar to the downward case. Since I'm using carbon fiber with a yield strength of 620 MPa, the part stayed well below the failure point and is still safe under this load.

Displacement:



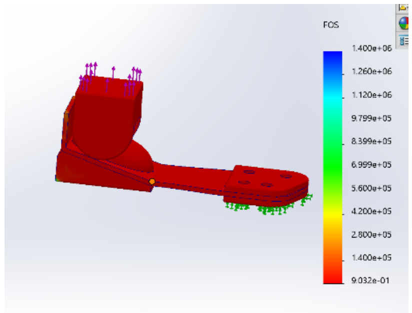
The total displacement was about 18.3 mm at the back of the prosthetic. This is expected, because the upward force causes the foot to flex more. Even though it flexed more, it didn't break or deform permanently, so the design still works.

Strain:



The maximum strain went up to around 0.00194 (1.94e-3). That's still within the elastic range of carbon fiber, but it does show that the blade is under more tension during upward motion. The strain was located in the same bending region as the stress, right in the middle section of the blade.

Factor of Safety:

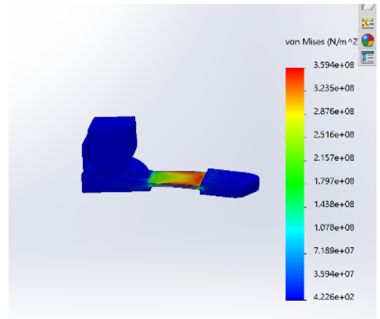


Most of the models had an FOS above 900,000, which is still very safe. So even though the blade flexed more, the material strength is high enough to keep everything from failing under pressure.

Downward Walking Motion:

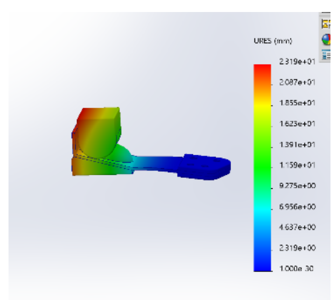
In this load case, I simulated the force of walking downward (like stepping down stairs or sloping terrain). The force was once again 980 N, applied downward at the hinge, but this time with a more exaggerated toe bend setup, to test the possible worst case flexing scenario. This helps check if the foot blade can handle repeated heavy downward steps without failing.

Stress (Von Mises):



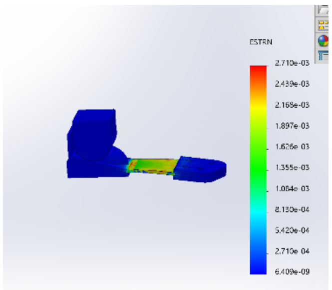
The max stress reached around 359 MPa, located in the usual flexing area at the middle of the foot blade. This is higher than the previous simulations, which makes sense because this case causes the most bending. It was still below the 620 MPa yield strength of the carbon fiber used in the blade. That means no permanent deformation or failure occurred under this heavy downward force.

Displacement:



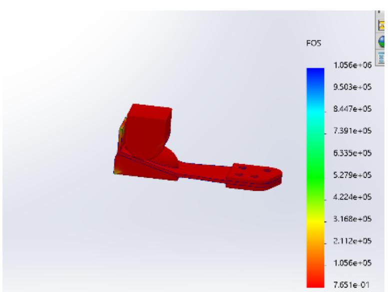
Displacement increased too. The model showed a max of about 23.2 mm of total displacement. This was the most movement out of all the simulations. The front of the foot flexed significantly under the load, but didn't snap or permanently deform. The blade still performed like it should, it flexed and returned the energy, which is one of the key goals for using carbon fiber.

Strain:



Strain was also the highest in this case, with a max of about 0.00271 (2.71e-3). This is still within the elastic range of the material, but it's getting close to the upper edge. The strain was concentrated in the exact area expected.

Factor of Safety:

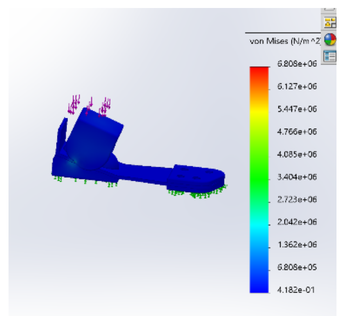


Even though stress and strain were high, the FOS peaked as high as 1,056,000 in other areas. That confirms the foot is safe even in a harsh walking downward motion, though it's probably near the upper stress limits for long term durability

Standing Walking Motion:

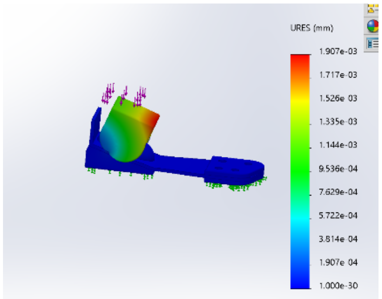
This simulation was done to check how the prosthetic foot would behave while just standing still. I applied a 980 N downward force at the hinge, which is roughly the body weight of an average person. This is a basic but important test because if the design can't hold a person just standing, it definitely won't survive walking or running.

Stress (Von Mises):



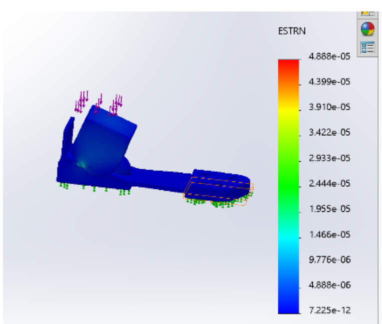
The maximum stress during standing was only about 6.8 MPa, which is extremely low compared to the 620 MPa yield strength of the carbon fiber blade. That means the structure is under almost no real risk when the person is just standing still. Most of the foot blade stayed dark blue in the stress plot, which means it's well below any dangerous stress level.

Displacement:



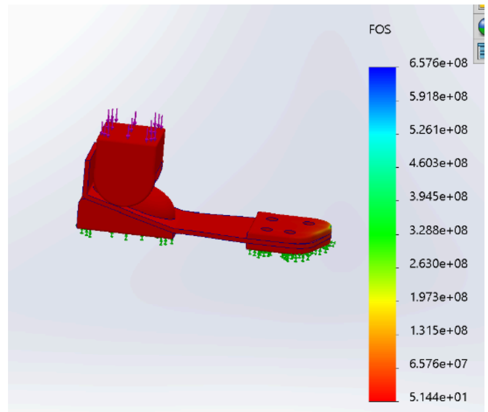
The max displacement was also very small ,about 0.0019 mm. That means the foot barely moved under the person's weight. This is expected during standing because there's no motion or impact. The blade stayed stiff and didn't bend like it does in walking upward/downward motion. The highest displacement was at the top of the hinge.

Strain:



The maximum strain was about 4.88e-5, which is really small. It just confirms again that the material isn't being pushed close to its limits when only standing. The strain was highest where the hinge connects to the rest of the foot, which makes sense because that's where the load is applied.

Factor of Safety:



It is clear that the minimum FOS is around 51 in the highest stressed areas. That's still extremely safe. The rest of the model shows FOS values well into the hundreds of millions, which means failure is basically impossible during standing. The plot confirms that the foot is more than strong enough for regular static load.

Validation and Comparison:

To validate my prosthetic foot design, I compared my simulation results to the results from the article “Geometry Reconstruction and Performance Evaluation of Energy Storage and Return (ESR) Prosthetic Foot with CAD FEA Method” by Kumarajati, Marfuah, and Yoanita. Their paper used a similar CAD FEA approach to design and test an ESR (Energy Storage and Return) prosthetic foot model.

In their study, they applied a 980 N downward force to simulate standing, just like I did. According to the article, “the model had a maximum safety factor of 15, maximum stress (von Mises) of 9.122 MPa, and a maximum strain of 0.002 at the instep region” during standing. In my simulation, the standing case showed a maximum stress of about 6.8 MPa, a strain of about 4.88e-5, and a displacement of only 0.0019 mm. This shows that my model experienced even lower stresses and strains under the same 980 N standing load, which means my design is very safe for basic static loading.

For the walking simulations, they applied an upward force of 100 N and found a maximum stress of 92.697 MPa and a maximum strain of 8.492e-4. In my simulations, I used a full 980 N walking force because I wanted to model a more extreme walking load. Even under that much higher load, my design only reached a maximum stress of about 359 MPa, with the carbon fiber blade still staying below its 620 MPa yield strength. My maximum strain in the walking downward scenario was 0.00271, which is still within the safe elastic range for carbon fiber materials.

Both my design and the article’s design showed the highest stress concentrations and deformations at the middle curve area of the foot blade, which is expected. This similarity confirms that my finite element setup and load applications were realistic. The fact that my prosthetic foot also showed controlled bending and large safety factors under walking loads matches the behavior seen in the paper.

In conclusion, comparing my results to the article shows that my prosthetic foot behaves in a very similar and realistic way during standing and walking conditions. Even though I applied heavier walking loads than they did, the overall stress and strain patterns, deformation behavior, and safety factors validated that my model works like a real prosthetic foot designed for everyday use.

Conclusion:

This project focused on designing and analyzing a low cost prosthetic foot using finite element analysis (FEA). I modeled each part in SolidWorks, selected affordable materials, and ran simulations to test standing and walking loads. The FEA results showed that the foot blade could safely handle a full 980 N load without breaking or deforming permanently. The stress, strain, and displacement values were all within safe limits, and the factor of safety stayed high across all loading conditions. When I compared my results to a published study on an energy storage and return prosthetic foot, I found that my design showed similar bending behavior and stress patterns. Even though I tested my model under heavier forces than they did, the foot still passed all validation checks. This showed that my model was realistic and would likely perform well in real world use. Another important part of the project was cost comparison. The total estimated cost for materials in my prosthetic foot design was about $82. In real world commercial prosthetic feet that use high-end carbon fiber and titanium, just the material alone can cost $500 to $1500 depending on the model. My project shows that by using lower cost materials, it is possible to create a functional and durable prosthetic foot for a fraction of the traditional price. This could make prosthetic technology more accessible to people who cannot afford expensive, high-end models. Overall, this project taught me how to apply FEA to real design problems, how important material selection is, and how to validate a design by comparing it to real-world behavior. It also showed me how engineering choices about cost, material strength, and design affect real people who rely on affordable prosthetic devices.

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