Optimization & Validation of 3D Printed Prosthetics

UC San Diego
JACOBS SCHOOL OF ENGINEERING

Wong, K., Henning, B., Bagheri, P., Navarro, E., Cabrera, I., Lin, A., & McKittrick, J.

Department of Mechanical and Aerospace Engineering, University of California, San Diego

Introduction

- There are 40 million amputees worldwide, 95% who don't use prosthetics
- On average, prosthetic feet can cost upward of $5,000 to $8,000, and typical transtibial sockets can cost upward of $70,000.
- Limited accessibility to prosthetists in developing regions makes it difficult to obtain proper medical care and devices that could enhance quality of life
- Our solution is to develop low cost, 3D printed prosthetic feet, modeled based on human foot characteristics of gait
- Additive manufacturing of prosthetic feet could reduce the cost of the medical device to less than $100.

Objective

- To improve upon already existing prosthetic feet, we modeled our design around characteristics of human gait while maintaining low weight to reduce material costs.

[1] [2] [3]

[1] Heel Only Stance
[2] Flat Foot Stance
[3] Toe Off Stance

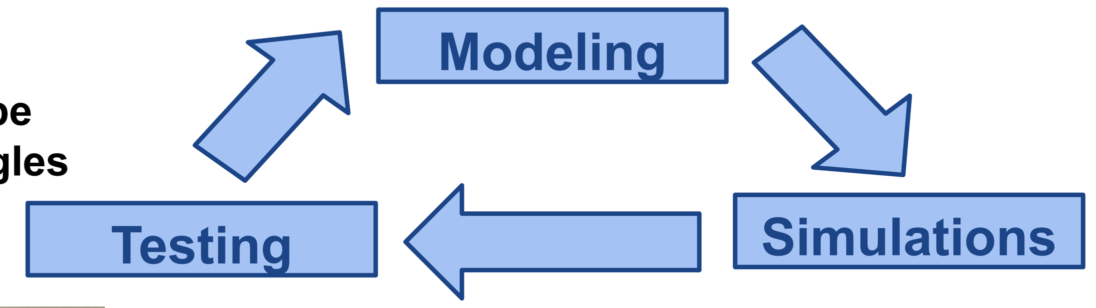
[a] [b]

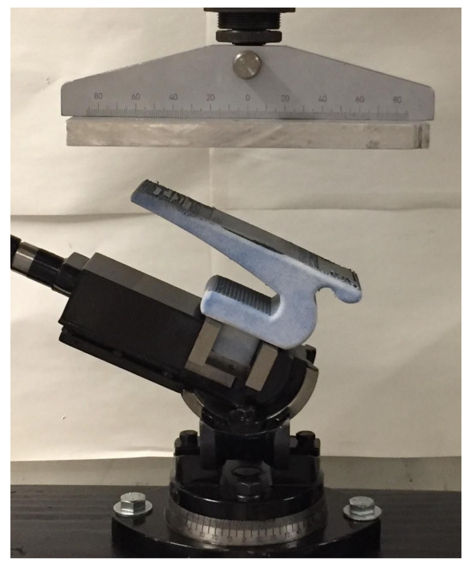
[a] Dorsiflexion & Plantar flexion
[b] Inversion & Eversion

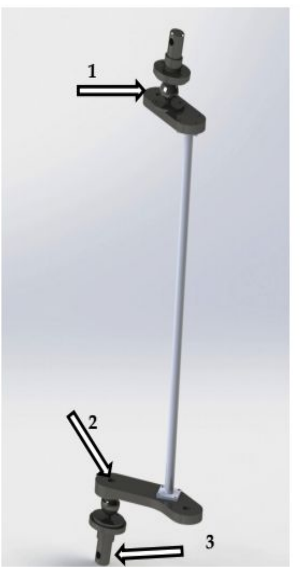
- The mechanical engineering team aimed to mechanically test the foot and transtibial socket to obtain results that corroborate with results from finite element simulations.

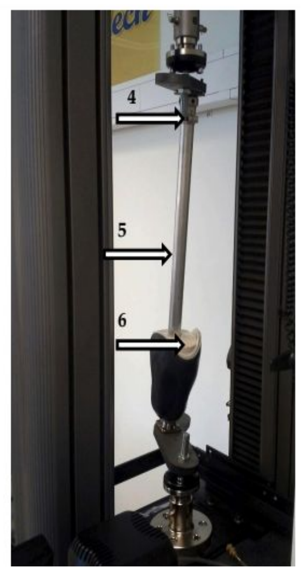
Methods

- To perform compression testing for proof and ultimate strength on the prosthetic feet and socket, the team designed and replicated testing rigs custom fit to the Instron machine that is used in the McKittrick laboratory.
- The rigs allow compressive force to be applied at different angles to imitate human gait.

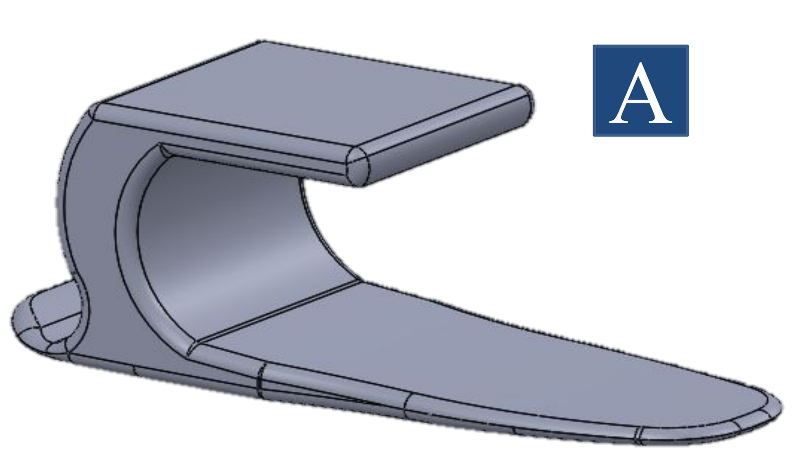


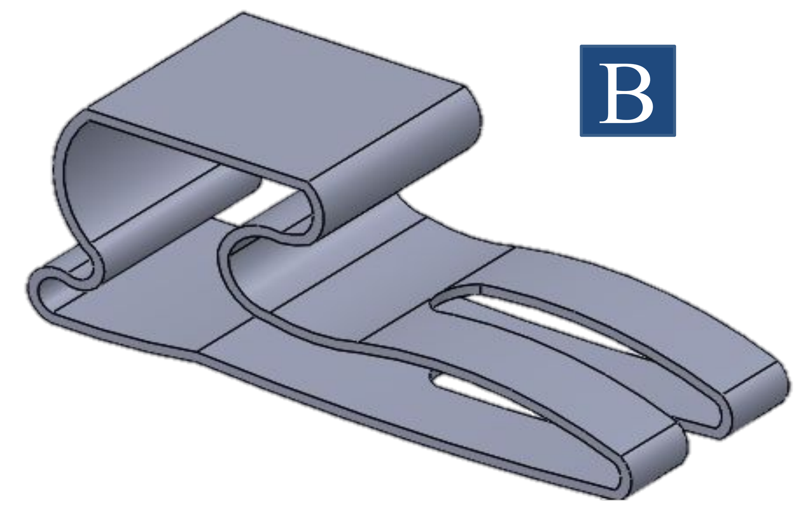




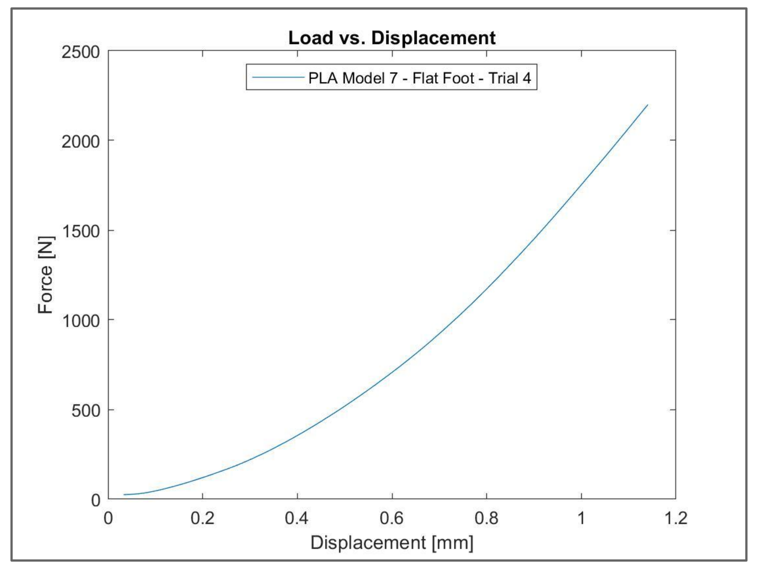


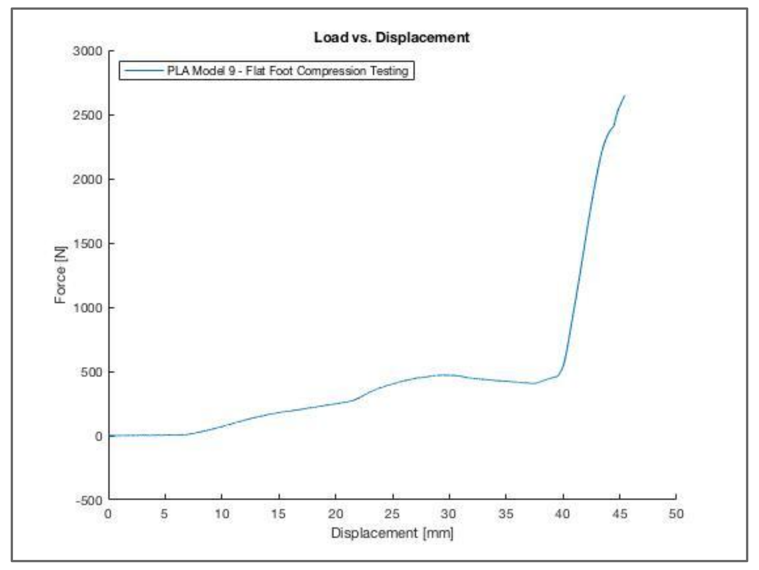
Design Process





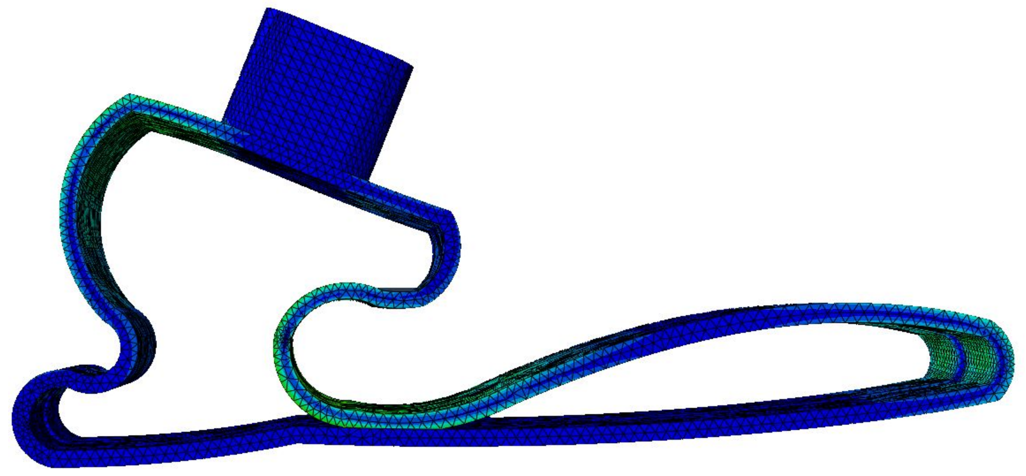
- The cantilever design of the first model increases energy return and imitates dorsi and plantar flexion in actual human feet.
- The split toe design in the second model imitates inversion and eversion without having an articulating ankle joint.





- Both of the models were printed and mechanically tested at half scale.
- The figure on the left shows the elastic deformation of the solid cantilever design under flat foot loading, while the figure on the right shows plastic deformation of the hollow foot design under flat foot loading
- To avoid catastrophic failure, we decided to move forward in optimizing and strengthening the hollow body cantilever foot.

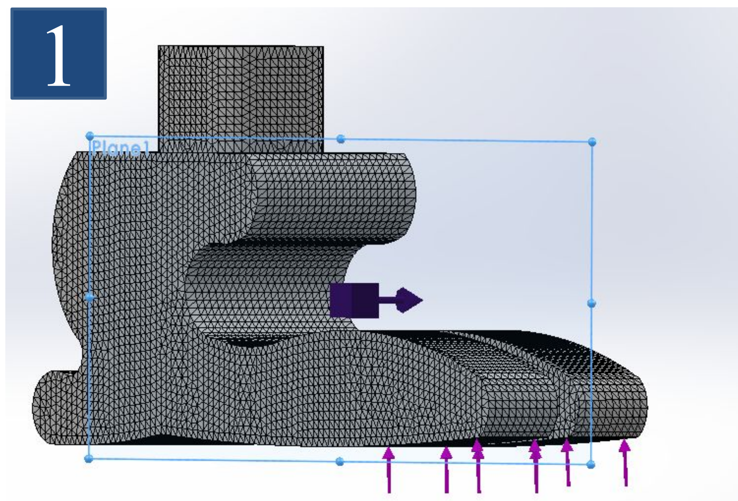
Simulations & Analyses

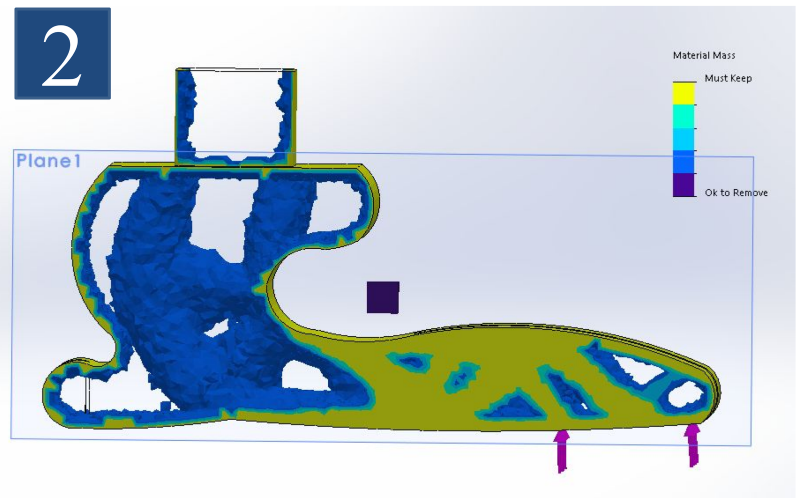


- Finite Element Analysis (FEA) was conducted on the hollow foot design at half scale, applying a 100 N load in the toe loading condition
- Specifically under 100 N, the model bent out of proportion, but the max stress experienced in the simulation was less than the fracture stress of the material
- The strain was distributed over a large area, instead of a localized strain under compressive forces, which reduces risk of catastrophic failure

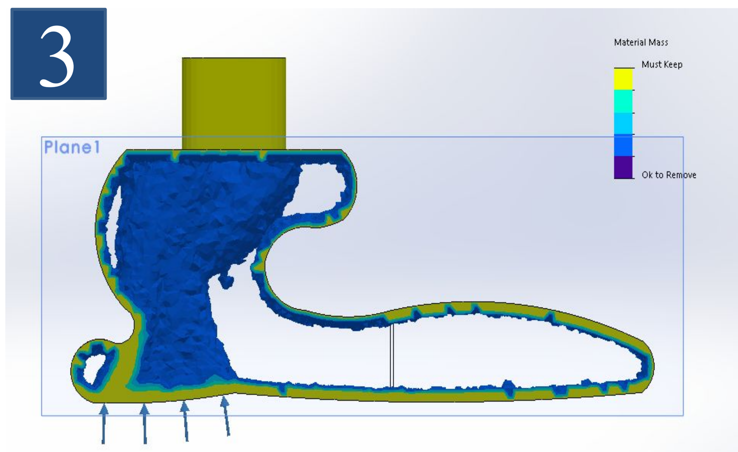
Results

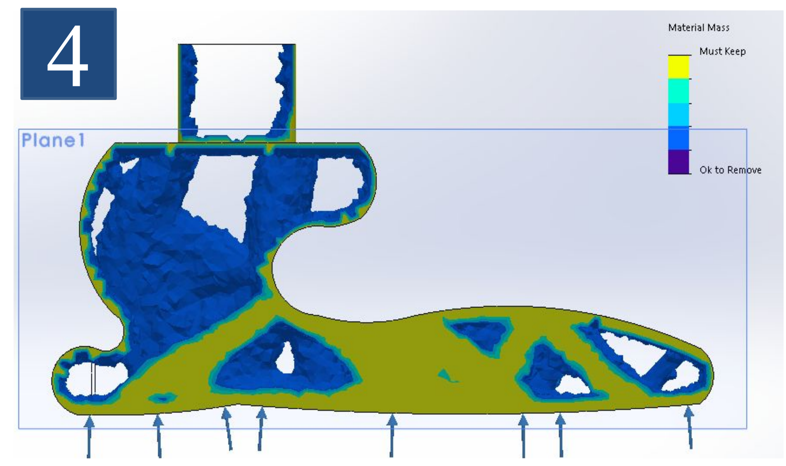
- The results from the FEA simulation of 100N toe loading on the hollow cantilever design shows that the design needs to be strengthened, and the compliance of the model reduced
- Topology optimization was used to obtain the best stiffness to weight ratio, and a maximum desired weight was set as the constraint.



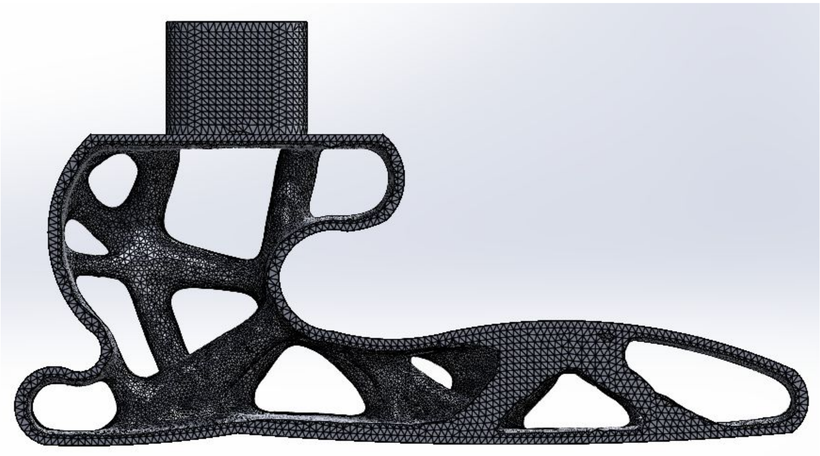


- Solidworks software only utilizes the subtractive method of topology optimization, so a solid model of the original hollow cantilever split toe foot was created for topology optimization simulations.





- Figures 2 through 4 depict the results from simulations of the solid cantilever foot undergoing 500N loading in the toe only, heel only, and flat foot conditions respectively.
- Residual blue material represents the material that is necessary to strength in the foot under the respective loading conditions.



- This final model was obtained by combining all the loading conditions.
- 500N was applied to the midsole &1000N was applied to the toes and heels
- A minimum member thickness was defined to preserve the exterior walls of the foot

Conclusions & Future Work

- We plan to conduct similar mechanical testing, finite element simulations, and analyses on the 3D printed socket. We will use 3D digital image correlation in conjunction with strain gauge arrays to measure the pressures exerted internally on the socket by the residual limb.
- The foot and socket will be printed at full scale, which will be used to create a full transtibial prosthesis, to be tested and worn by Albert Lin.

Acknowledgements

Dupont: Developing a Better Prosthetic Foot for Amputees.http://www.dupont.com/corporate-functions/our-approach/global-challenges/protection/articles/safe-footing.html; ISO 10328: 2006, Prosthetics - Structural testing of lower-limb prostheses - Requirements and Test Method; McPoil, T.G., & Knecht, H.G. (1985). Biomechanics of the foot in walking: A function approach. Journal of Orthopaedic and Sports Physical Therapy, 7 (2), 69-72.; Quinlan Julia, Tran Lilly, et al. "The Effect of Prosthetic Socket Texturing on Suspension." *Northwestern University Prosthetics-Orthotics Center and Prosthetic Design Inc.* April 2018.; Sigmund O. "A 99 line topology optimization code written in Matlab." *Technical University of Denmark-Department of Solid Mechanics.* October 1999.; Skoglund Per. "Prosthetic socket in Titanium - An outer shell prosthetic socket for a lower-leg amputee manufactured in Ti6Al4V by Electron Beam Melting." *Mid Sweden University.* Jan 2015.; Wong Kaela. "Low Cost 3D Printed Prosthetics for Developing Nations-Strauss Foundation Proposal." *University of California, San Diego.* January 2019.; Wong Kaela. "Mechanical Testing of 3D Printed Prosthetic Feet." *University of California, San Diego.* August 2018.; World Health Organization. World report on disability 2011, vol 9. 2011.
This work is supported by the UCSD Jacobs School of Engineering, Mechanical and Aerospace Engineering Department. We would like to thank the McKittrick lab, MAE Department, the Qualcomm Institute, Center for Human Frontiers, and Engineers Without Borders for providing the resources and support to make this research effort possible.