Analysis of Nonlinear Materials and Energy Absorption

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Introduction

Our capstone project and design stemmed from a product called UltraJump boots introduced to us by our capstone advisor. The goal for our capstone design project was to improve the effectiveness of the boots. The boots consist of a normal shaped shoe that sits on top of an elliptical-shaped elastic base, shown in Fig. 1. This base is used to absorb the impact energy of the boot into the elastic base. This stored energy could then be used to increase the rebound of the jump or step. These boots are worn all over the world for many different purposes including exercise and recreational fun. Our capstone group decided our project would consist of improving the current design of the UltraJump boots to achieve better absorption of the impact energy and improve the rebound energy from the elastic base.

Fig. 1 Original UltraJump boot

Literature Review

We began by investigating mechanisms to absorb impact energy. Clough et. al. [1] published a study on elastomeric microlattice impact attenuators. These materials are designed to absorb energy via the collapse of the microlattice pores, seen in Fig. 2. Their study found that the dynamic stress-strain response could be tailored to achieve vastly improved impact-attenuation performance and explores various optimization methods for the lattice structure. Our plan was to additively manufacture such a lattice and insert it into the original sole assembly.

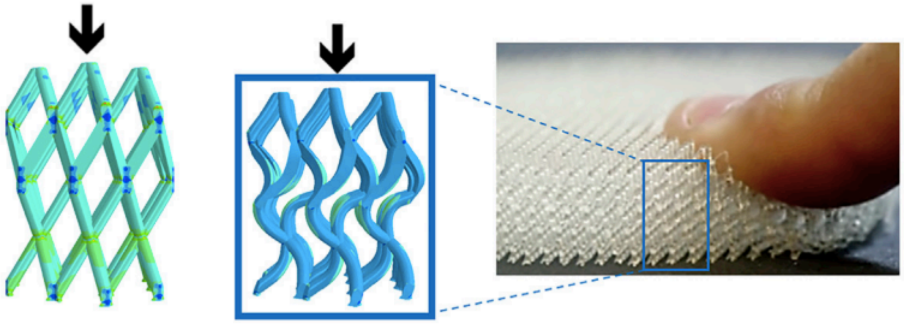

Fig. 2 Elastomeric microlattice impact attenuator pores being compressed

Project Schedule

To ensure that our team would complete this project in the time given, we created a schedule at the start of the project. This schedule was implemented into a Gantt chart that is shown in Fig. 3. This would create a visual representation for our team to see the progress we had made and the things that still needed to be completed.

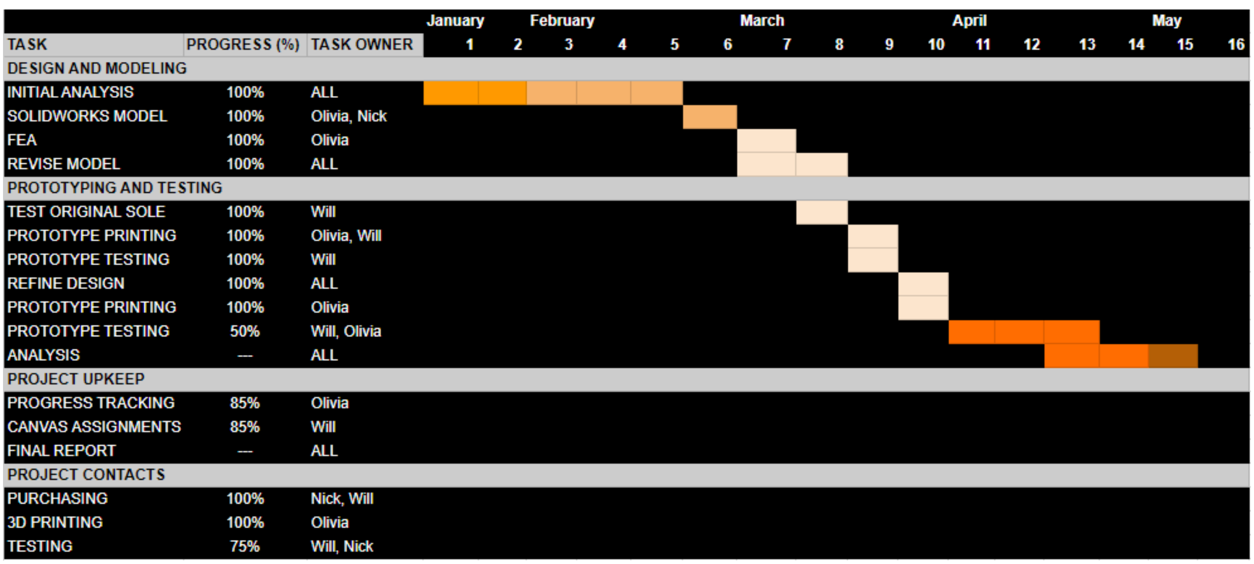

Fig. 3 Project schedule in the form of a Gantt chart

Throughout the entire Capstone course, our team did exceedingly well at keeping the project on schedule. While there were a couple of hiccups our team faced that shifted us slightly behind schedule, we were able to catch back up to the initial project timeline and even able to get far enough ahead to create two more prototypes than we had originally planned.

Design Methodology

Methods and Procedures

Our primary design space for this project was Solidworks. This CAD software was used to model each prototype effectively and was also beneficial for preliminary simulations. The original sole was measured and modeled to accurately size and fit our prototypes before printing, and the subsequent assemblies allowed us to better visualize our product.

Design Flow Chart

Our design process was collaborative and iterative and can be seen in Fig. 4. Our group would discuss our model goals and ideas, create a model, simulate the design, and test the assembly. Each of these steps will be explored later in this report.

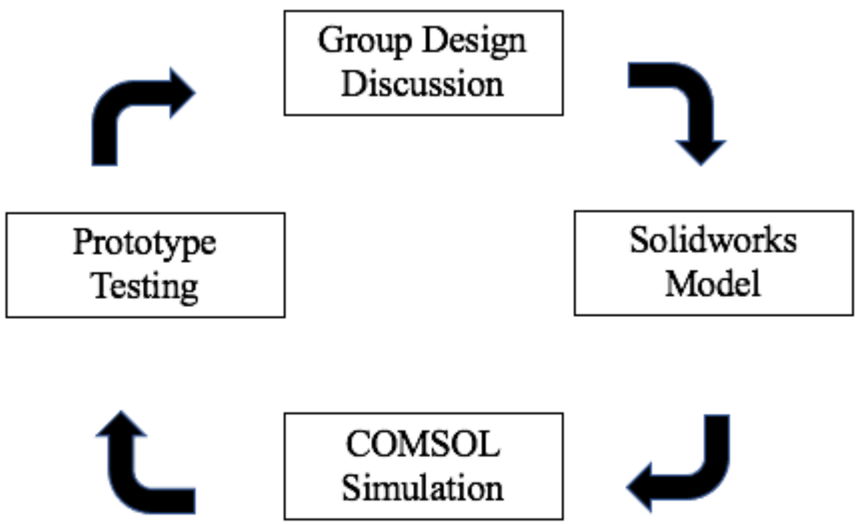

Fig. 4 Design flow chart

Design Constraints

As is the case when designing any product, several restrictions and requirements existed for us to be mindful of when designing. The proposed insert needed to fit in the original UltraJump soles, making proper dimensioning essential to the prototype's success. Additionally, the product should be lightweight, easy to manufacture, and cheap to achieve an optimal design. Fulfilling some of these requirements proved difficult when faced with the limitations of the facilities provided by us.

We needed a material with high yield strength and modulus of elasticity, but the availability of desired 3D printing materials was severely limited for our purposes. Figure 5 shows the range of materials that were desirable to us based on these properties. Thermoplastic polyurethane (TPU) was the best material option for our goal; however, our 3D print shop was unable to manufacture the lattice design with this material. Hard rubber was not available at all, so polyamide 12 (PA12 or nylon 12) was chosen for the project.

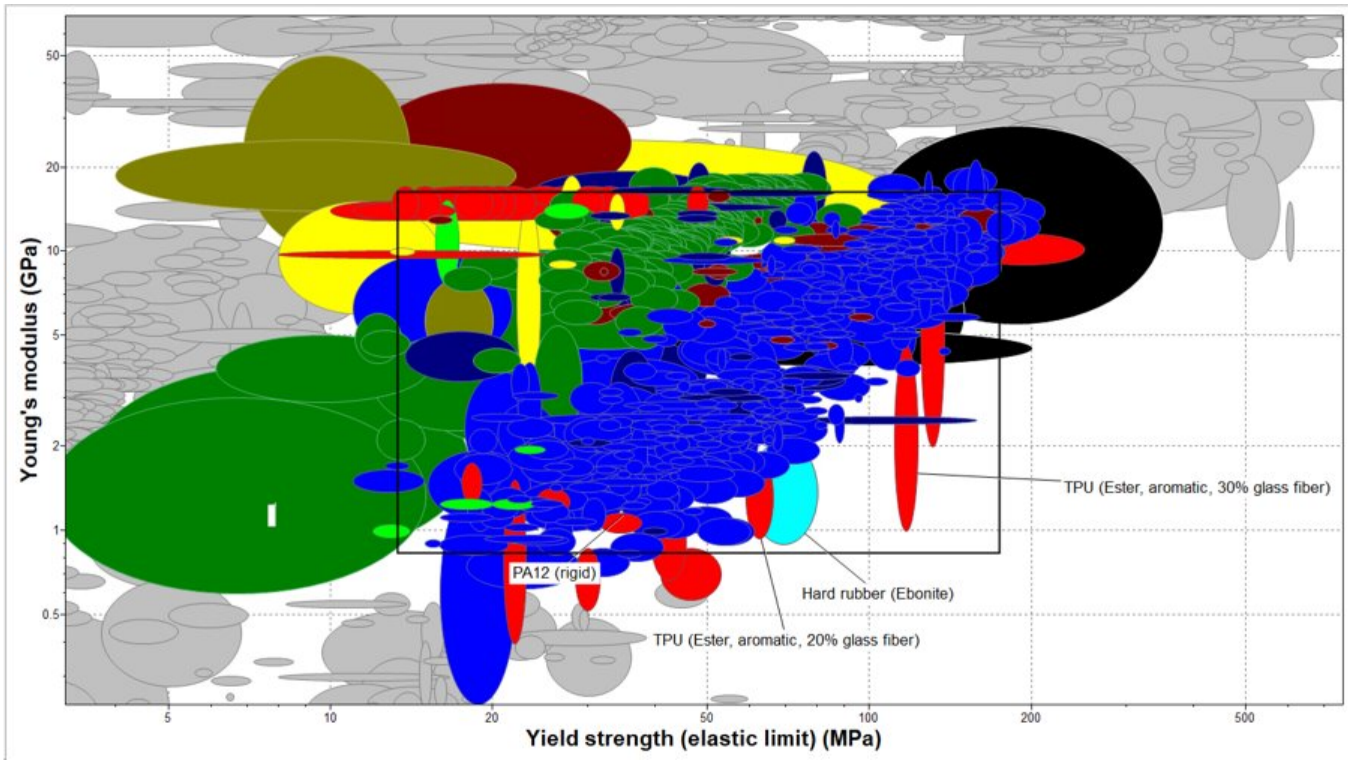

Fig. 5 Evaluation of materials based on yield strength and Young's modulus

The design was also constrained by its manufacturing method. Each iteration needed to be mindful of the range of 3D printing capabilities, especially when using nylon powder. Nylon 12 powder is an expensive material, so the prototype needed to be kept small, relatively thin, and oriented in a fashion that minimized volume usage in the 3D printing machine.

COMSOL software was used to simulate our prototype performance to optimize our design. When transferring our Solidworks model to the COMSOL software, we found that designing the part with a very fine mesh would be nearly impossible to simulate. If the part was designed too thin or the mesh was too fine, COMSOL was unable to successfully render a quality simulation. This caused us to design slightly thicker parts with larger lattices so we could properly analyze the parts performance.

Design Alternatives

Our team verbally discussed several unique designs that could be a viable alternative option to achieve the same goal as the inserts that we designed. We explored the possibility of constructing a completely new assembly that would attach to a new shoe. This discussion was short as we ultimately decided that this was impractical, and we were trying to improve upon an existing product, not reinvent the wheel.

Analysis Method

Our first form of analysis was the previously mentioned COMSOL simulations, and an example can be seen in Fig. 6. The parts were modeled and studied with nonlinear behavior. We set a prescribed displacement to the top of the prototype and measured the amount of force needed to achieve said displacement. This data was determined from a surface integration of the bottom half of the prototype and exported to MATLAB for comparison. Prototypes showing larger area under their force versus displacement curves in simulation were favored for 3D printing. Simulations were also run for the entire sole assembly, with and without the insert. However, due to lack of material property knowledge, we were unable to produce an accurate nonlinear model of the UltraJump sole.

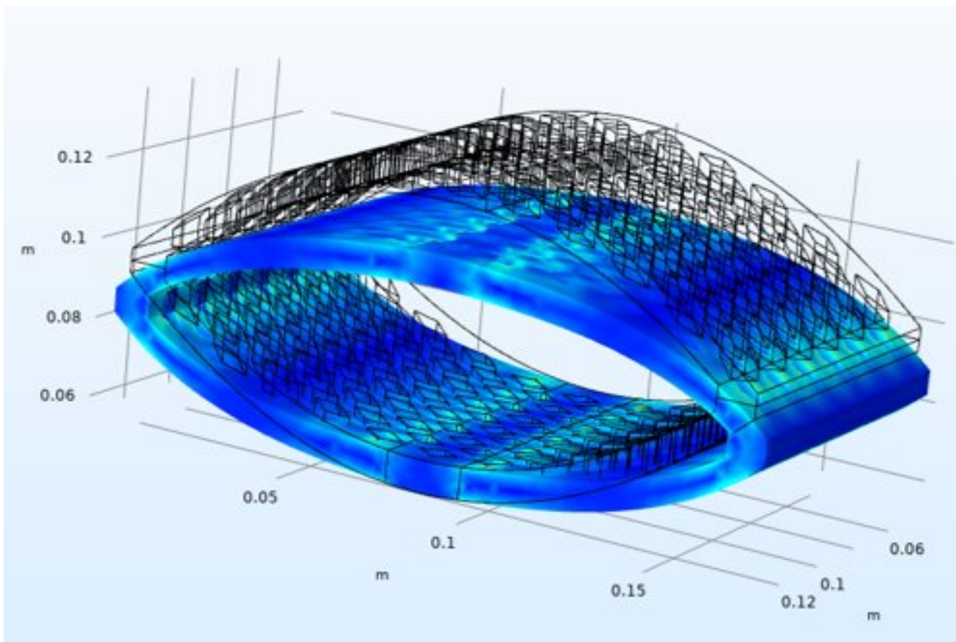

Fig. 6 Thick mesh design undergoing simulations

The next step in our analysis was prototype testing on the MTS machine provided in Lafferre. The original sole was tested first to act as a baseline for our prototype's performance, and this process can be seen in Fig. 7. The machine compresses the part a specified distance and measured the force required, similar to our simulations. These tests were completed for each prototype individually to check accuracy of the simulations as well as within the assembly to compare to the sole's baseline performance.

Fig. 7 Original UltraJump sole in the MTS testing apparatus

From these simulations and tests, we obtained force versus displacement plots. The prototypes exhibiting a larger area under this curve were deemed successful at increasing absorbed impact energy. Human tests were also attempted to analyze fatigue, but no performance metric was obtained.

Design Solution

CAD Drawings

Five prototypes were designed and 3D printed using a nylon 12 powder. The first design we came up with used a vertical microlattice structure, shown in Fig. 8. This structure was deemed implausible due to the stiffness of nylon, rendering the microlattice structure useless.

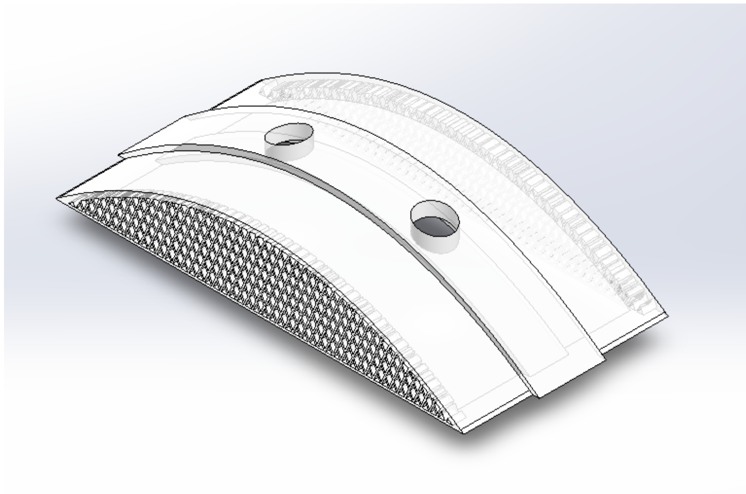

Fig. 8 Isometric view of vertical micro lattice insert

Once it was determined that the first prototype was not feasible, two different prototypes were made. The second prototype was a thin mesh, shown in Fig. 9. It was determined that this thin mesh structure was not stiff enough. This would reduce the amount of stored energy in the insert, reducing the possible released energy. The third design, shown in Fig. 10, was designed based on the original design of the jumper. The insert was similar to prototype two, except it had no mesh and included a center bar. These two new insert designs were sent through finite element analysis (FEA) in COMSOL. The thin mesh design was found to be slightly better than the center bar design, so we moved to improve the mesh model.

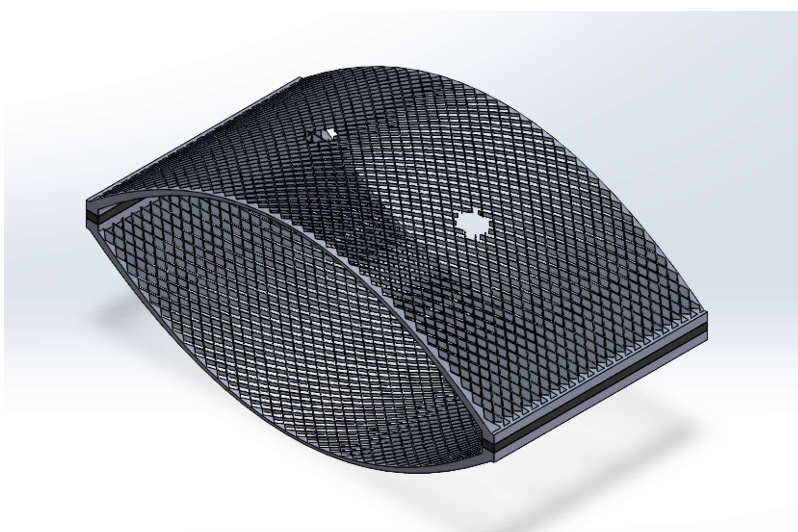

Fig. 9 Isometric view of thin mesh insert

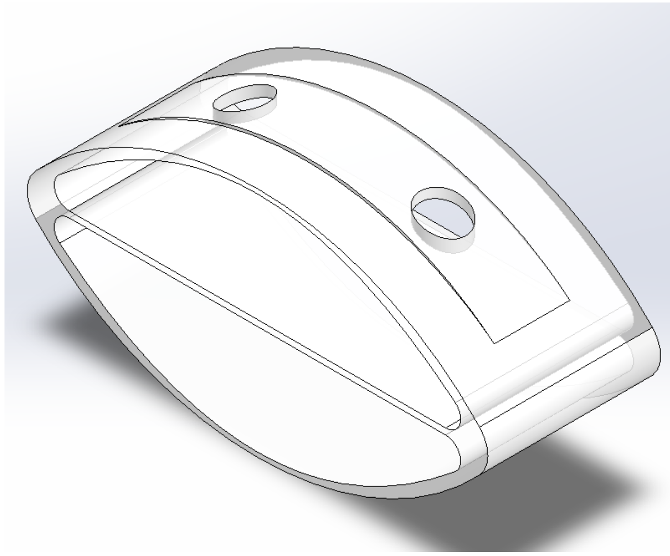

Fig. 10 Isometric view of center bar insert

With the thin mesh structure found to produce a slightly better curve than that of the center bar insert, the mesh design could be optimized. This led to the fourth and fifth prototypes being created. The fourth insert was made slightly thicker than that of the third insert. It was also designed with and without a rubber insert. Both versions of the fourth insert were tested to see if the rubber insert was better or not. The fifth insert design was created without any rubber insert. The basis for this design was to make the insert even thicker. We thought this would add to the amount of absorbed energy due to higher stiffness. The rubber mesh design worked very well, while the thick mesh was extremely stiff. This wouldn't allow for much deformation of the insert. The fourth insert design is shown in Fig. 11 with the rubber inserted while the thick mesh design is shown in Fig. 12.

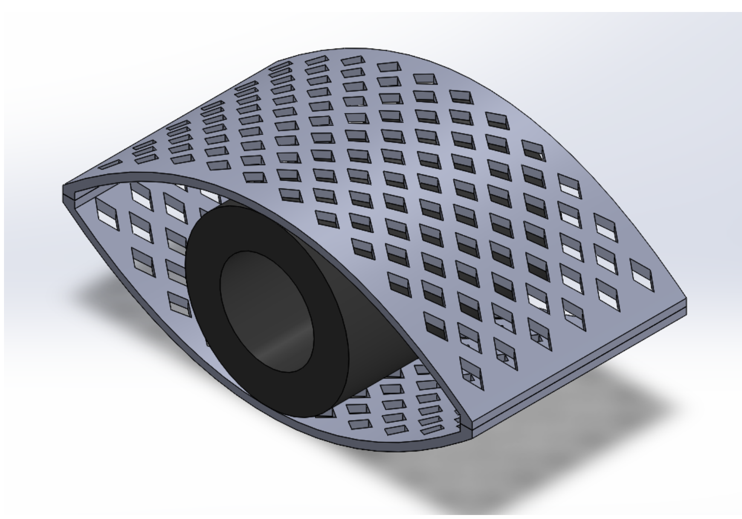

Fig. 11 Isometric view of mesh with rubber insert

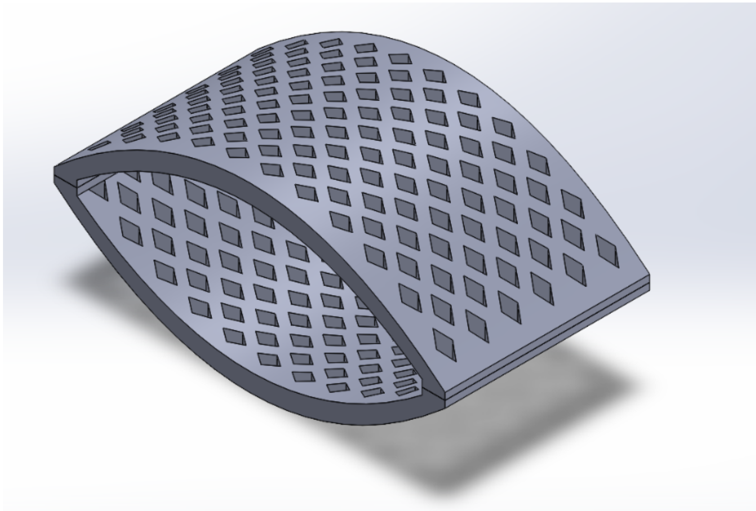

Fig. 12 Isometric view of the thick mesh insert

Calculations

Our baseline data for simulated and experimental results is shown in Fig. 13. It shows our initial test data from the original jumper sole compared to its COMSOL simulation. The simulations were most useful for comparing our designs before printing. We knew the simulations had large margins of error, but by setting all material properties and simulation settings constant, we could see the change in performance based on change in design. Our most significant comparison was that between the thick mesh design and center bar model, seen in Fig. 14. We needed to decide between optimizing the thin mesh design or moving to a solid arch design, and the simulation showed the thick mesh performing better.

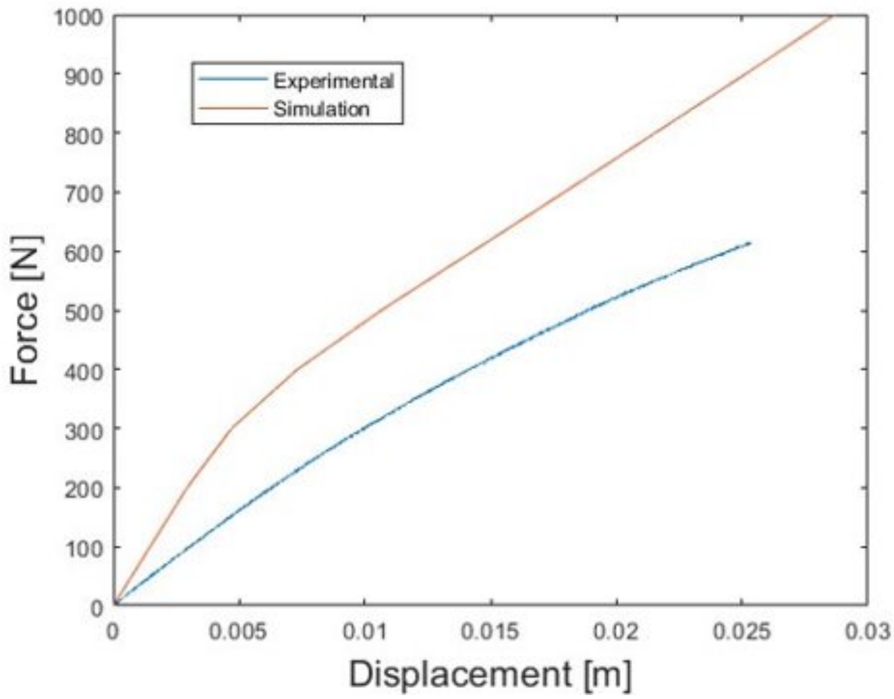

Fig. 13 Simulated and experimental force versus displacement curve for the original sole

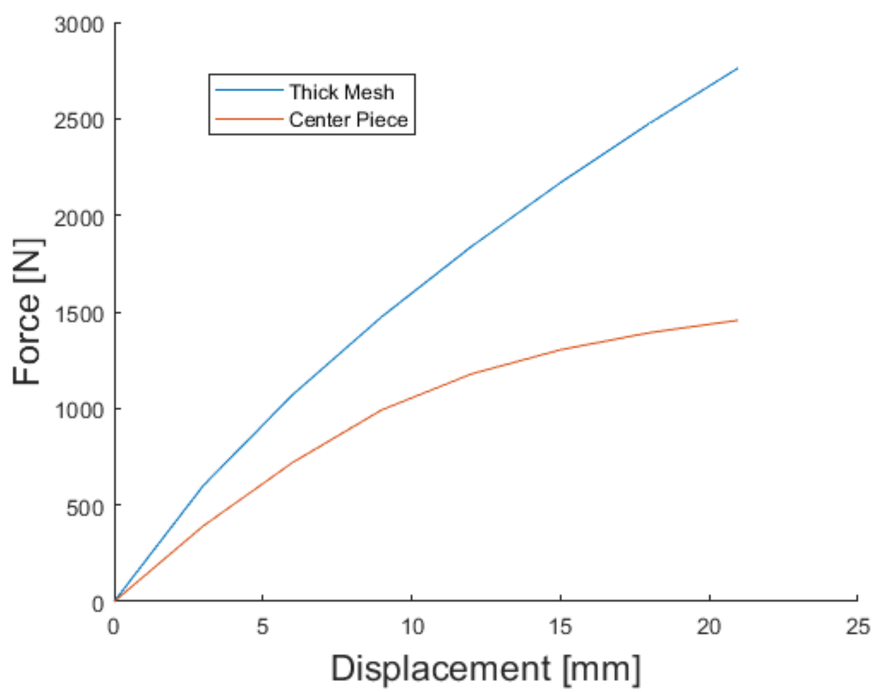

Fig. 14 Simulated comparison of thick mesh and center bar designs

Each prototype was tested within the sole assembly, and the comparison of all the assembled design can be seen in Fig. 15. The thick mesh assembly exhibited the greatest area under the force versus displacement curve. However, it displayed linear behavior, likely because it was too stiff to exit its elastic region with the given force. The thin mesh assembly achieved some improvement over the original sole at higher forces, but it showed a decrease in performance at lower displacements. Adding rubber tubing to the thin mesh assembly showed steady, albeit minimal, improvement in the force versus displacement curve.

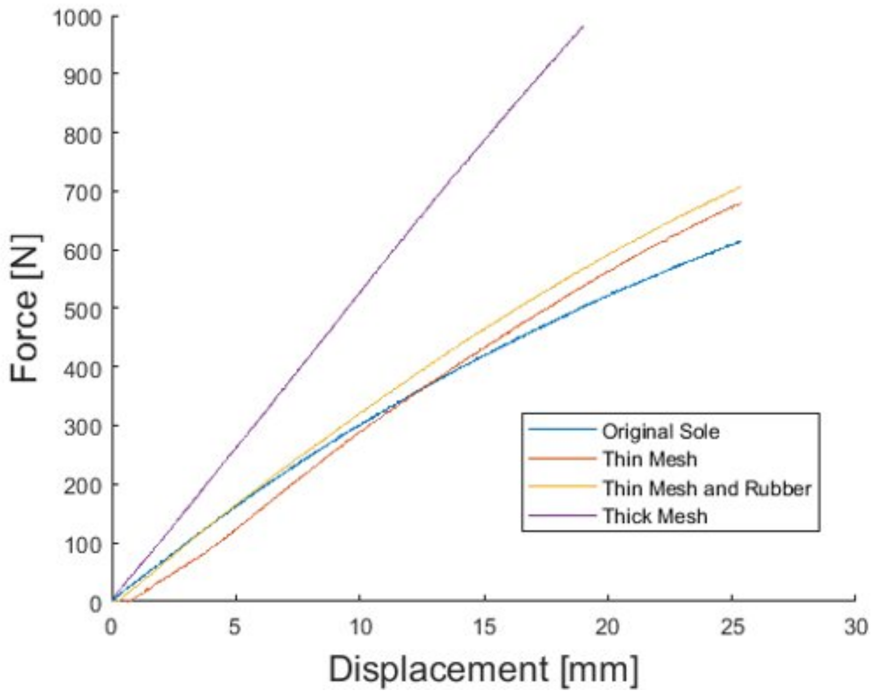

Fig. 15 Experimental force versus displacement data for all prototype assemblies

Final Design

After completing our testing and analysis, we found the best design of our prototypes to be the thin mesh with rubber couplings. This design showed nonlinear improvement over the original sole and withstood preliminary human testing. Though the thick mesh absorbed the most energy, it snapped when subjected to human testing. The part was too stiff to provide the necessary spring effect the jumpers require. The thin mesh was springy enough to achieve the desired bouncing effect, but it needed the additional rubber to provide extra strength to the design.

Results

Our thin mesh and rubber assembly can be seen in Fig. 16. Simply increasing the thickness of nylon was not sufficient for our project parameters. The combination of the thinner, stiffer nylon with the thicker, more elastic rubber proved the most effective design in terms of increasing absorbed energy and maintaining bounce abilities. Further optimization could be done to determine the optimal thickness for each of the materials.

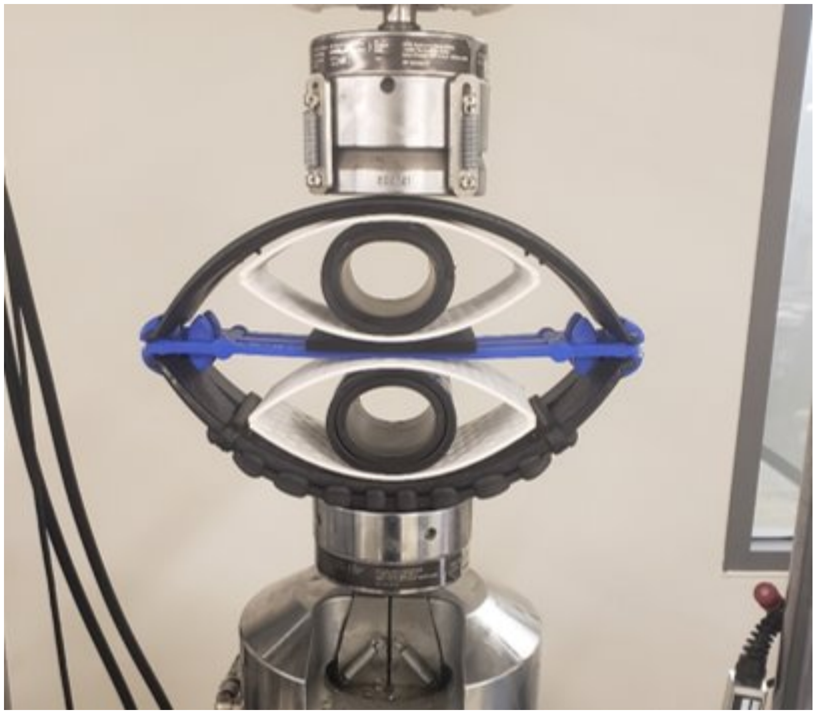

Fig. 16 Final sole assembly with thin mesh and rubber model

Cost Analysis

The driving factor behind the cost of the project was 3D printing of the prototypes. When we printed the first two prototypes, we only printed one of the inserts, so the cost is significantly lower than the last two prototypes. The nylon was used to construct all four prototypes. The material was chosen for its availability and mechanical properties, not its cost effectiveness. The nylon was on the more expensive side because of the way the material was calculated. When looking at our design from a side view, it resembles the outline of a football. When printing with nylon, we must pay for the entire volume that could be contained within the prototype, not just the actual printed material. In other words, instead of paying for the volume of material to make just the outline of the football, we had to pay for material to make an entire solid football.

Table 1 shows the project expenses, coming in on time and under budget with $185.00 remaining. It is also important to note that the initial UltraJump boots were donated, as well as the rubber coupling inserts used in prototype three. Prototype three was our best design, and the second cheapest to 3D print both inserts. When analyzing the cost of production for our design, we acknowledge that this is not practical for a profit-driven business. Our team would advise searching for either a cheaper material or manufacturing process.

Table 1 Breakdown of project expenses

EXPENSES	COST [$]
PROTOTYPE 1	80.00
PROTOTYPE 2	50.00
PROTOTYPE 3	152.00
PROTOTYPE 4	232.00
BUDGET	700.00
EXPENSE	514.00
REMAINING	185.00

Summary and Conclusions

The goal of this project was to design an insert for the UltraJump boots that would increase the absorbed energy of the soles and improve jump height. We created a nonlinear, spring mesh design which we simulated, experimentally tested, and continuously improved. Each model was evaluated on its ability to increase the area under the force versus displacement curve compared to the original sole. The combination of a medium thickness nylon mesh and a rubber coupling was our best design, improving the force versus displacement curve and withstanding human testing. Our total expenses were $514.00, and we stayed ahead of schedule and under budget.

Recommendations for Future Study

When our team reflected on our project and designs that we produced throughout the semester, we also picked out specific points at which we could have changed and gained more insight into the design. One of the points that out team would recommend for the future study of this product would be to use MTS data to find material properties in COMSOL. Once experimental data is obtained, it can be exported into COMSOL and used to optimize the solution. In doing this, one can find the specific material properties and nonlinear coefficients to properly simulate the materials. We opted not to pursue the optimization process this semester because the runs take a significant amount of time.

We would also suggest exploring other material options. One material that intrigued our team was TPU because its mechanical properties align with the goal of the product. It is very elastic, meaning it can store large amounts of energy, but it can be made more rigid when varying the thickness and dynamic loading structure of the object that is being tested. After struggling to increase the stored energy of the product without making the insert too stiff, we would not recommend using nylon. Using different materials along with exploring other design options is sure to yield intriguing concepts, such as springs or a vertical microlattice. Our team would have liked to investigate these possibilities and would recommend further investigation because the combined elasticity of the structure with the stiffness of the material is promising. We also would recommend allocating time to explore different methods to attach the inserts to the soles. Our team selected an epoxy that would suffice, but other methods may prove more effective and lasting.

Project Postmortem

Teamwork

Our team operated effectively and efficiently as a group. We delegated roles based on interest, individual skills, and work ethic. Collaboration was essential to the design process to achieve innovative solutions to issues we encountered.

Technical Communication Skills

Our team communicated frequently via GroupMe messaging, in-person meetings, and virtual meetings with our advisor. We were able to stay organized and up to date throughout the semester, allowing us to stay on schedule.

Project Schedule

As previously discussed, the team stayed on, and even ahead of, schedule throughout the duration of the project.

Ethical Standards

N/A

Industrial/Commercial Standards

The Federal Trade Commission (FTC) is the government entity that regulates and sets forth a system of guidelines upon which developers must abide by. According to the FTC, we must properly label our product for the intended use. The product must be clearly labeled according to the intended use, and well as address any safety concerns. The product must have fair and transparent advertising tactics. If the product is advertised as “made in the USA,” it must comply with the FTC’s enforcement policy statement on US origin claims.

Safety

To ensure that the safety of the consumer is protected and to abide by the regulations set forth in the previous paragraph, we make sure to package the product with the following labels:

1. This product is not OSHA approved.
2. Warning: This product is not intended for use by individuals under the age of 12.
3. Warning: Misuse of this product could result in serious injury.
4. Warning: Not abiding by the weight restrictions could result in breaking of the inserts and flying plastic shrapnel pieces. This could result in serious injury.
5. Warning: Use on slick or uneven surfaces could result in serious injury.

Environmental Impact

Nylon 12 is not the most environmentally friendly or sustainable material. However, with the design’s small size, the environmental impact of this project was minimal. If this product was to be continued or mass-produced, a more sustainable material should be investigated.

Societal/Social Impact

N/A

Multi-Disciplinary Issues

N/A

Bibliography

[1] E. Clough, T. Plaisted, Z. Eckel, K. Cante, J. Hundley and T. Schaedler, "Elastomeric Microlattice Impact Attenuators", SSRN Electronic Journal, 2019. Available: 10.2139/ssrn.3427465.