Thermal Optimization of TLSO

George Deng
John Oraa
Tyler Miracle
Mitchell Moulton

Figure 1. Our teams design a prototype of our optimized TLSO. This is a scaled prototype for testing.

Abstract

A Thoracic Lumbar Sacral Orthosis (TLSO) is a brace meant to provide support for individuals with scoliosis. Traditionally, the brace has been uncomfortable due to its stiffness and inability to dissipate body heat. The goal of this project is to design a new TLSO that can dissipate heat without sacrificing the stiffness required to support the spine. Structural and thermal simulation software will be used to test the design, and a 3D printed prototype will be delivered to the sponsors.

Executive Summary

The main objective of this project is optimizing a Thoracic Lumbar Sacral Orthosis brace (TLSO) for heat dissipation while maintaining support for the spine. Current TLSOs are uncomfortable after extensive wearing due to ineffective heat dissipation.

Through research and interviews with key stakeholders, we have developed a series of functional requirements and engineering specifications to follow when designing our new brace. To reduce heat due to the TLSO, we are looking to decrease the maximum skin temperature by 0.5 ℃. While reducing the skin temperature we are also working to maintain the functionality of the brace by limiting the spot deformation of the brace to 5 mm. As a group, we are also requiring the brace to not create any rashes while to aid in comfortability. The previous brace did not have a weight that was uncomfortable thus we are requiring the new design to not exceed a weight increase of 10%. To ensure we aren't hindering the ability of the wearer to breathe, we are requiring the new design to allow for a circumferential increase of the chest region to be 7.1 cm.

Through concept generation we were able to develop a series of concepts to evaluate for testing. We have evaluated these concepts and have come up with an alpha design that we feel meets our requirements the best. The alpha design we have chosen uses holes in the brace to allow for heat dissipation in areas of high heat.

We have used Hyperworks to optimize our model. We then worked out the flaws of the optimized model so that the brace was usable. We then developed plans to verify our design through computer simulation and testing of a build design. Following the printing of our design, we moved to verification of the design. We were able to verify the full size design for weight, support, and breathing expansion using computer simulation. To verify a reduction in temperature we used a build design to test the difference in steady state temperature between our design and the old design. This temperature test was inconclusive as the difference was not outside the accuracy of the thermometer. We have also tested the relative movement of the build design against a balloon to verify the requirement of not causing rashes when wearing the brace. The only requirement that did not pass was the breathing expansion requirement.

If we had more time we would be able to better optimize the design to increase comfort and mobility while reducing skin temperature as much as possible. We would also try to implement a way to increase the ability to breathe in the brace as we did not pass our original requirement.

Table of Contents

Problem Description

The objective of this project is to optimize the thermal performance of a Thoracic Lumbar Sacral Orthosis brace (TLSO). A TLSO is a brace used to provide support for people with Scoliosis, Kyphosis, spinal fractures, or anyone who underwent a recent surgery [2]. This project is sponsored by Miguel Fuenes, Albert Shih, and Ketut Bagus "Gus" Priambada Putra. The primary stakeholder, Gus, currently suffers from scoliosis and wears a Boston brace. A Boston brace is a type of TLSO which is primarily used to treat scoliosis in the lower thoracic and lumbar region of the spine [2]. It consists of a hard plastic outer shell with an inner layer of compressible plastic material bonded to the outer layer, as seen below in figure 2.

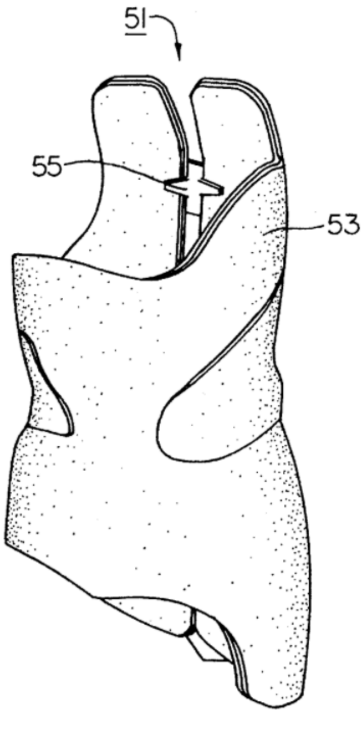


Figure 2. Drawing of Boston brace from patent 5,474,523. As shown in the image, the brace is fit to the body of the patient and is a single piece of continuous plastic joined at the back. This patent was granted in 1995, thus it has since expired [3].

The main problems that need to be solved are overheating and manufacturability. Current TLSOs cause an uncomfortable amount of heat to build up, particularly in high pressure contact areas. In talks with Dr. Moulton, a spinal specialist, we have found this problem to be widespread throughout TLSO wearers [5]. Our sponsor, Gus, has particularly pointed towards his stomach, and under the armpits as points of excess heat [6]. These points can be seen below in Figure 3.

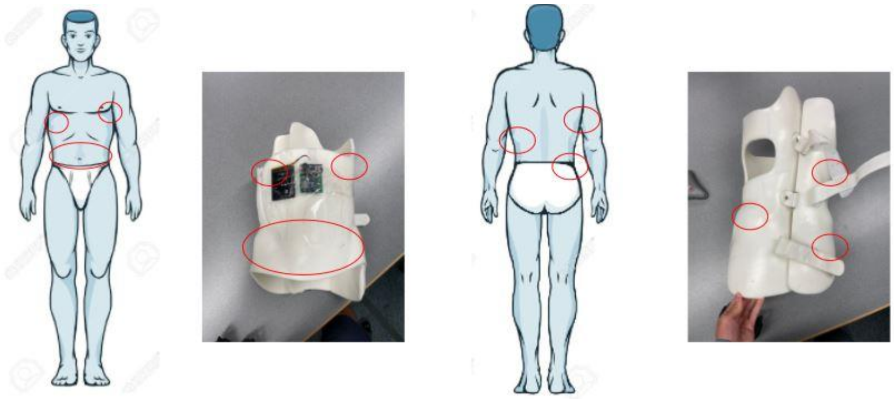


Figure 3. The figure highlights the areas of highest skin temperature for the TLSO wearer.

Our design will attempt to lower the measured skin temperature at these points by a noticeable amount. The areas circled in red are designated as areas of high contact resulting in uncomfortable amounts of heat to build up.

In talks with Anew Life Prosthetics and Orthotics Center, we were told of an old manufacturing process that required the use of a labor-intensive plaster mold [7]. After we visited the University of Michigan Orthotics and Prosthetics Center (UMOPC), we learned that current techniques involve a foam mold instead. This drastically reduces the amount of time and labor required to produce a TLSO. Current methods take about 6-8 hours to create. UMOPC has previously tried to 3D print a TLSO and warned us of shortcomings in the 3D printing method. In their experience 3D printing has taken longer and been more expensive [9]. However, for our project, our sponsors have explicitly asked for a 3D printed model and thus we must accept the anticipated shortcomings.

Figure 4. Pictures showing part of the current manufacturing process for TLSOs

Stakeholder Analysis

Our immediate social impact comes in the form of delivering assistance to our sponsor for whom the brace is being created. Gus, who the prototype will be designed around, is not the only person who could benefit from this project. Current manufacturing methods of this brace are labor intensive and unergonomic; A 3D printed proof of concept could relieve some of these issues. Additionally, anyone who currently wears a Boston brace could see an improvement in their comfort as far as temperature regulation is concerned. There are between six and nine million people with scoliosis in the United States alone [American Association of Neurological Surgeons], and this project, if successful, has the potential to positively impact their lives.

This process could also help 3D printing companies by increasing demand for 3D printers and 3D printed parts. Those negatively impacted would be the suppliers and current producers of TLSOs. These producers would compete with a process that would be less labor intensive and more efficient. The social impact is considered as important as other priorities because once the TLSO printing method is created it could be reproduced for others in need of a TLSO. The current priority is to fit the sponsor with the TLSO using the new method, therefore the social impact will be mitigated. However, a successful development of the orthosis will impact the other stakeholders as mentioned.

Intellectual Property Considerations

There are no intellectual property requirements involved in this project due to the use of open source software and readily available 3D printers. We as a group, did not work with any patented material, processes, or products that would be protected.

Other Contextual Factors

Outside the scope of our project, the end result would be to export our general process for making TLSOs. Our process can directly affect the public health, safety and welfare of those using a TLSO. By increasing heat dissipation we can help everyone who wears a TLSO feel more comfortable while treating scoliosis. This process will be applicable all across the globe. In a global marketplace this process can help increase efficiencies and performance of TLSOs. The use of 3D printing utilizes energy to burn plastic to the desired shape necessary for the printing process. Environmentally, this process releases a small amount of pollution in the form of smoke that over long periods of time could lead to sickness or deaths, as well as using extensive amounts of energy to print the design. The design could be made more sustainable by using less product or a different material. Less sustainable aspects such as the non-reusable plastic can be mitigated by choosing a new material that is recyclable. It will not have a substantial impact on disposal as there will be no change in the method of disposal. Both the old and new TLSO will simply be thrown away. Economically, this process would incentivize increased 3D printing and with that, increased use of energy from the power grid. It would also reduce demand for traditional molding methods. To help characterize our potential impacts we have utilized a stakeholder map as shown below in figure 5.

Figure 5. Stakeholder map used to help assess socio-economic impacts of our project.

We also utilized Life Cycle Assessments and Eco-Audits to assess potential environmental impacts. Finally, we used social and economic impact frameworks such as the one provided by Kühnen and Hahn [19]**.**

Library

Interactions with the library were mainly with online resources. Resources such as MLibrary proved to be very helpful in finding reliable research on TLSO design and performance. It also provided many medical databases such as PubMed that were helpful to find relevant statistical information on humans. Challenges came from attempting to find specific human factors information regarding forces and temperatures of the human body for our report.

Inclusion and Equity

As students within this group, there is an equal power dynamic across the four team members. All four members are students in the same position with no experience in TLSO production. Certain power dynamics exist between the project sponsors and team 18. Because the brace is made for the sponsor, team 18 was limited in its ability to design for others suffering with scoliosis wearing an orthosis. The identity of the members of the team is different from the end users because none of the team members suffer from scoliosis and provide a perspective different from the end user who will be wearing the brace who may have a specific idea on how to achieve the overall solution. Culturally, the team was fairly similar and usually approached problems in similar ways. Generally, decisions were made as a group without substantial friction while reaching a consensus. Differing cultures between the sponsors and the team did not substantially affect the design process. Occasionally, there would be communication errors but they were always corrected immediately afterwards.

Ethics

Ensuring ethical decisions throughout the life of the project are one the major concerns for the TLSO project. As a team, the ethical goal is to do what is correct and create the best possible product for those suffering with scoliosis. Ethical dilemmas that the team anticipates are that all our work is documented correctly and ensuring outcomes and deliverables are calculated correctly. By applying force on the body, team 18 has the ability to injure our stakeholder if forces are incorrectly measured. Because of this, the team's work will be rechecked to ensure that calculations are done correctly. The team will ensure that if the work were to be published the team members would be confident in the calculations and analysis performed to be peer reviewed by others. Personally, our ethics are the same as the University of Michigan in the goal of creating accurate repeatable research to better the lives of others.

Design Process

We have decided a combined stage and activity-based model would be the most effective. We adopted the recommended design process shown below in figure 6. [4]

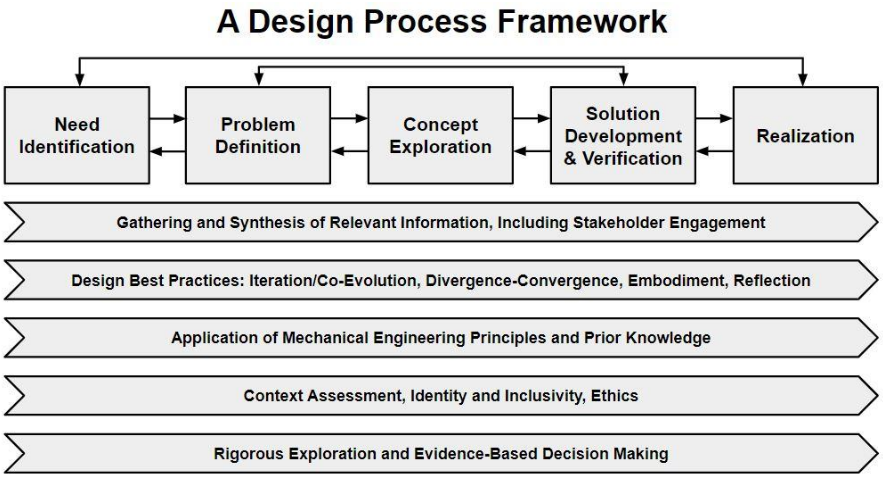


Figure 6. The recommended ME capstone project design process

Each of the blocks on top represent different stages of the process that we will move between. The "Need Identification" and "Realization" stages are out of our scope. Each of the banners at the bottom represent iterative processes that we will do in each stage. This framework allows for us to have clear stages to move to while still utilizing iterative processes between and within stages.

Requirements and Engineering Specifications

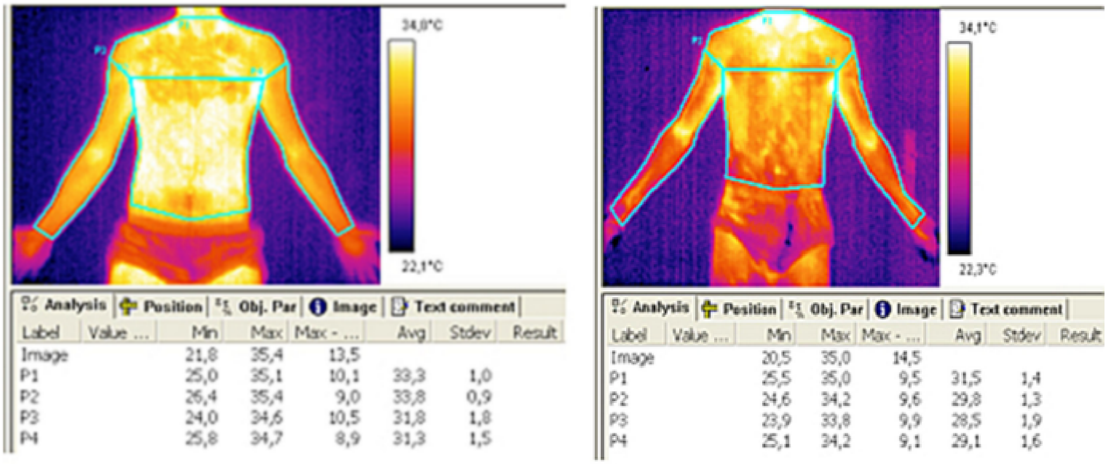
To ensure we address the entire design problem, functional requirements and quantified engineering specifications were developed. These requirements and specifications were developed through synthesizing independent research and interviews with key stakeholders. These requirements and specifications are shown in table 1 below.

Table 1. Functional requirements and their translation into engineering specifications.

Functional Requirements	Engineering Specifications
Reduce Skin Temperature	Must reduce max. Temp by at least 0.5 degrees C
Maintain Scoliosis Support	Spot deformation cannot exceed 5 mm
Must Not Cause Rashes or Rub Against Body	Relative translational movement to body at pressure points is not more that current brace
Remains Lightweight	New brace should not weight more than 10% more than the current brace
Allows Comfortable Breathing	7.1 cm increase in circumference of chest

Reduce Skin Temperature

Reducing skin temperature is our most important functional requirement. Our sponsors made it clear that any improvement in heat dissipation would be acceptable. From this input, we decided to aim for a noticeable change in skin temperature. In research we found that according to Dr. Lynette Jones 0.11 ℃ is a noticeable decrease in skin temperature [9]. However, this temperature reduction is treated as an absolute minimum. After further discussion, we have decided a larger skin temperature change of 0.5 ℃ would be attainable. Despite these temperature differences appearing low, they are quite significant. In cryogenic therapy where athletes stand in a -140 ℃ cooling chamber their skin temperature in the torso region only decreases by 3.2 ℃ [10]. Obviously, we will not be able to achieve temperature differences on the scale of cryogenic therapy and thus have set a more modest 0.5 ℃ target. We plan on testing the heat dissipation ability of the design concepts we generate using thermal simulation software by using the historical skin temperature data seen in figure 7.



Label	Value ...	Min	Max	Max - ...	Avg	Stdev	Result
Image		21,8	35,4	13,5			
P1		25,0	35,1	10,1	33,3	1,0	
P2		26,4	35,4	9,0	33,8	0,9	
P3		24,0	34,6	10,5	31,8	1,8	
P4		25,8	34,7	8,9	31,3	1,5	

Label	Value ...	Min	Max	Max - ...	Avg	Stdev	Result
Image		20,5	35,0	14,5			
P1		25,5	35,0	9,5	31,5	1,4	
P2		24,6	34,2	9,6	29,8	1,3	
P3		23,9	33,8	9,9	28,5	1,9	
P4		25,1	34,2	9,1	29,1	1,6	

Figure 7. Surface temperature of body before undergoing heat treatment [11]. These maximum values will be used to compare each design's ability to dissipate generated heat away from the body.

Maintain Scoliosis Support

The main purpose of any TLSO is to provide support to the spine and prevent further scoliosis development. This is done through providing constant pressure against the spine at key spots. To ensure no reduction in support as compared to the original brace, we must limit the spot deformation to less than 5 mm. Spot deformation was chosen as our metric because of its direct relation to the pressure against the spine. After researching the current Boston Brace TLSO, 5 mm was chosen from a computer analysis of the spot deformation [12]. The simulation is shown on the next page in figure 8 along with the forces used. Note that the max deformation was 4.733 mm, but we are limited by the precision of our instruments and had to round to 5 mm.

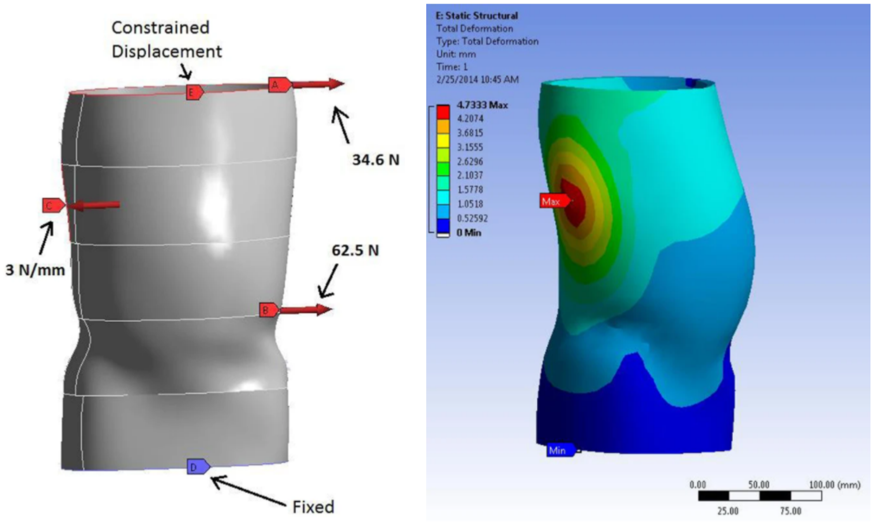


Figure 8. Force Loading of Boston brace model, based on force simulation of curved spine (left). Spot deformation of Boston brace model (right) [12].

Must Not Cause Rashes or Rub Against Body

Another key component of improving patient comfort is reducing rashes caused by the TLSO rubbing against the wearer's skin. As a secondary effect, this may improve the thermal performance as a reduction in rubbing would lessen the heat generated by friction forces. Because the friction threshold that causes rashes is different for each person, we decided that this functional requirement would best be quantified by limiting the relative motion between the TLSO and the user. The sponsors claimed that the current brace did not cause significant rubbing, providing a good benchmark to test our design against. Ultimately, we decided that the relative translational movement at pressure points should not exceed that of the current brace.

Remains Lightweight

Clearly, we cannot create an excessively heavy TLSO. Currently, this is not an issue as said by our sponsor Gus. However, we are concerned the new model may be heavier. This is because many 3D printing materials are substantially denser than the current polyethylene. In further conversations with Gus, we have found that he would feel comfortable with a brace that is heavier than the current one. He expressed that up to a 10% increase in weight would still be acceptable. Thus, our design must not increase the weight by more than 10%.

Allows Comfortable Breathing

Our final requirement is that we must allow the wearer to breathe comfortably. While TLSOs are designed to be tight and restrict bending of the spine they must also allow the wearer to breathe. In our case, we would like to ensure full comfort for the wearer. In researching chest expansions, we found that the average uninhibited circumferential chest expansion was 7.1 cm. This measurement was of the lower thoracic chest expansion around the 10th thoracic vertebrae.[13] This location can be seen below in figure 9.

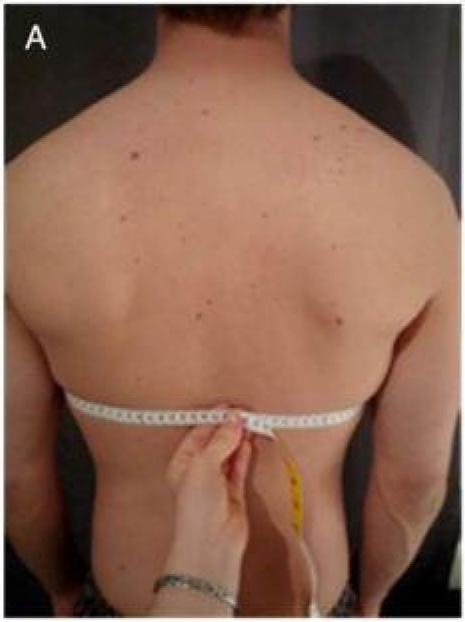


Figure 9. Measurement of the chest circumference to measure the expansion of the chest during breathing [13].

From this we decided that our TLSO must circumferentially expand 7.1 cm around the 10th thoracic vertebrae.

Concept Generation

Following the creation of our engineering specifications, brainstorming began placing an emphasis on creative and unorthodox ideas. A variety of TRIZ creativity triggers were used in our initial brainstorming session such as zooming in to the exact cause of the problem as well as zooming out to get the big picture. Additionally, the prism of TRIZ was used to apply general solutions to our specific problem: TLSO heat dissipation. For example, one of the ways we applied this was by examining ways computer companies dealt with the copious amounts of heat generated by processor chips. Typically, the chips will have a heat sink attached with a fan used to blow off the excess heat. We thought the same concept could be applied by attaching fans directly to the TLSO to blow away heat generated by the body. Following our initial brainstorming session, we used divergent thinking to generate even more concepts that we felt could solve the problem, and then created a handful of iterations. An outline of one chain of iterations can be seen in figure 10 on the next page.

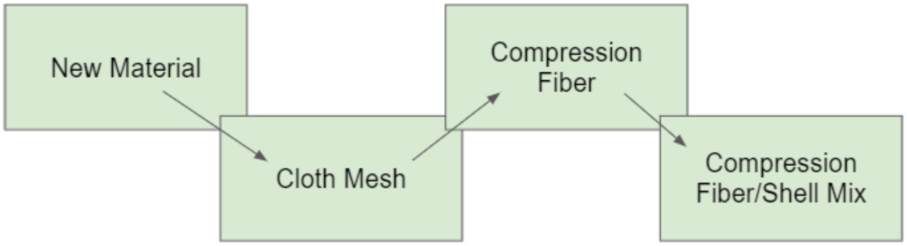
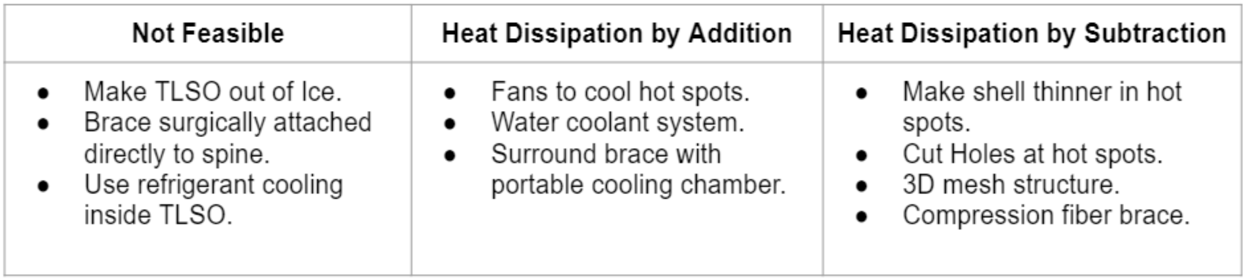


Figure 10. Example of iterative concept generation. Initial concept was new material and the final concept generated was a combination of compression fiber material and the hard plastic shell that currently makes up the TLSO.

In general, the concepts fit into one of the three categories shown below in Figure 11. By sorting through each concept and determining which category it belongs to, we could get a general idea as to which concepts could be used as our final design. By the end, we narrowed it down to just 5 possible concepts. A full list of concepts can be found in Appendix B on page 25.



Not Feasible	Heat Dissipation by Addition	Heat Dissipation by Subtraction
• Make TLSO out of Ice. • Brace surgically attached directly to spine. • Use refrigerant cooling inside TLSO.	• Fans to cool hot spots. • Water coolant system. • Surround brace with portable cooling chamber.	• Make shell thinner in hot spots. • Cut Holes at hot spots. • 3D mesh structure. • Compression fiber brace.

Figure 11. Categorization of a few of the generated concepts into the following categories: Not Feasible, Heat Dissipation by Addition, and Heat Dissipation by Subtraction.

Concept Selection

Our first step in selecting our top design was eliminating any concept that we deemed not feasible. A few of the reasons some concepts were eliminated included weight restrictions, technological limitations, and budget constraints. Then, using general engineering intuition, we determined which five concepts we thought most likely to meet all our specifications. We eventually got the list down to just five concepts and used a Pugh chart to select a few alpha designs.

Concept Breakdown

The five concepts used in the Pugh Chart are shown and described below. The captions explain how the concepts were scored in relation to the baseline TLSO in the Pugh chart.

Concept 1: Bungee Cords

The first concept was the bungee cord design. This concept would allow heat to pass through the center of the torso, but not on the sides where many of the hotspots are located; thus, this concept was given a +1 in that category. Doubts remained as to how much this concept would deform, as the bungee cord, if not tight enough, could allow significant deformation. This meant this concept got a -2 for the structural support category. The reason this value was -2 rather than -1 was to distinguish it from other ideas made of the same material with similar structures to emphasize the doubt concerning structural integrity. On the other hand, this would allow for more chest expansion during breathing, so we gave it a +1 for breathing comfort. We didn't think this design would change the relative movement between the body and brace, so we gave it a 0 in the relative movement category. This design would be lighter than the existing brace due to the large amount of material removed, but the added bungee cords and hooks needed to hold them would add back some of that weight; we gave it a +1 for weight and a -1 for manufacturability as the hooks could prove difficult to attach to the brace. This brace would prove more expensive to manufacture than the current brace as the bungee cords and hooks would be an additional cost in terms of material and labor, so it got a -1 in this category. Finally, we didn't think the aesthetic appeal of this design would be too far off from the baseline, so we just left the aesthetic category at 0.

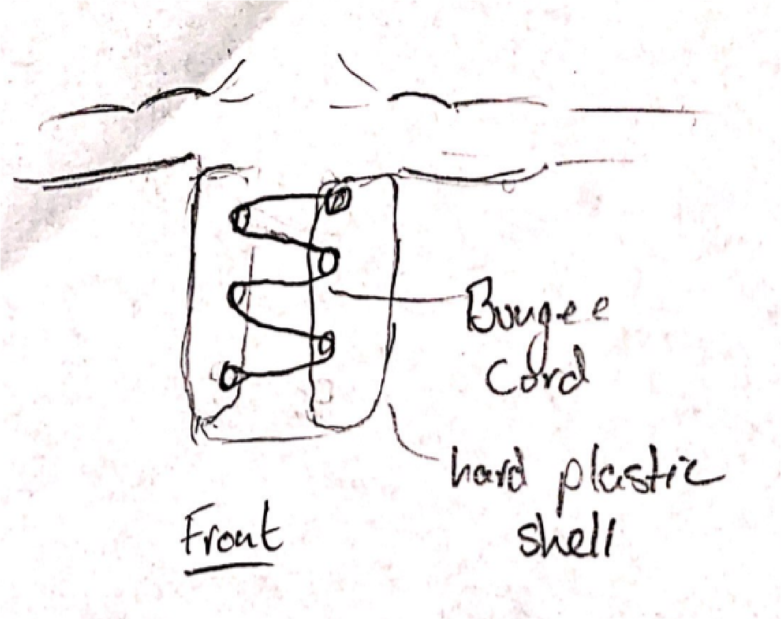


Figure 12. Concept 1, Bungee cord design.

Concept 2: Integrated Fans

The second concept was the integrated fans design. This concept is composed of adding fans to the existing shell for active convection to dissipate excess heat. We think this would do an excellent job at reducing skin temperature, as the fast-moving air would be able to draw a lot of heat from the body, so it was given a +2 for this category. The design of the TLSO would not alter the support of the TLSO and therefore did not differ from the baseline. The same design and shape go for breathing and relative movement. Because the only change to the TLSO is the addition of fans, the basic structure of the TLSO will not change meaning these categories would not differ from the baseline. The addition of the battery cells and fans themselves would increase the overall weight of the TLSO especially with the idea of multiple fans meaning that an increase in weight would not be an improvement from the baseline. Drawbacks from this design are mainly from the cost and manufacturing of the TLSO. The manufacturing of the fans brings many complexities and inconveniences of finding room and locations to house fan parts especially because this would be customized for every TLSO wearer. The cost of the components would be substantial adding to the cost and energy of already printing the TLSO. Finally, it would be difficult to hide the wiring and components of the fans as well as the sound of the fans running could be disruptive causing the aesthetic criteria of this design to be judged negatively.

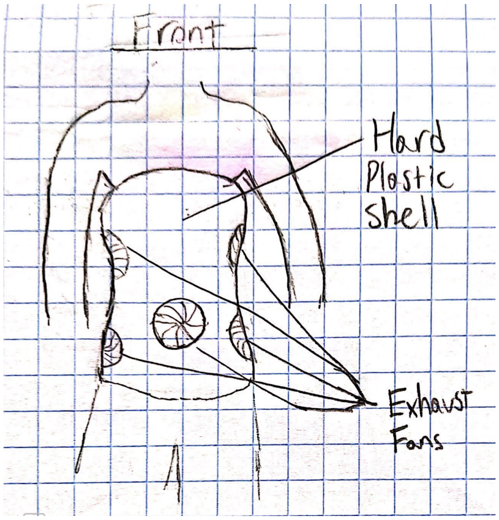


Figure 13. Concept 2. Integrated fans.

Concept 3: Extruded Fins

The third concept was the extruded fins design. This concept would allow air to freely flow along the majority of the skin, allowing extreme amounts of convection, thus scoring a +2 in skin temperature reduction. This design scored -1 in scoliosis support, relative movement, weight, cost, and aesthetics. The extruded fins would likely lead to more deformation, more movement, and add weight. It would also cost more with more material and look quite displeasing. The fins would also require an excessive amount of supports while 3D printing. This would drastically increase print time to an estimated 60+ hours, and thus a score of -2 was assigned to manufacturability. This design received a 1 for breathability as the design wouldn't be as tight around the chest region as the base design.

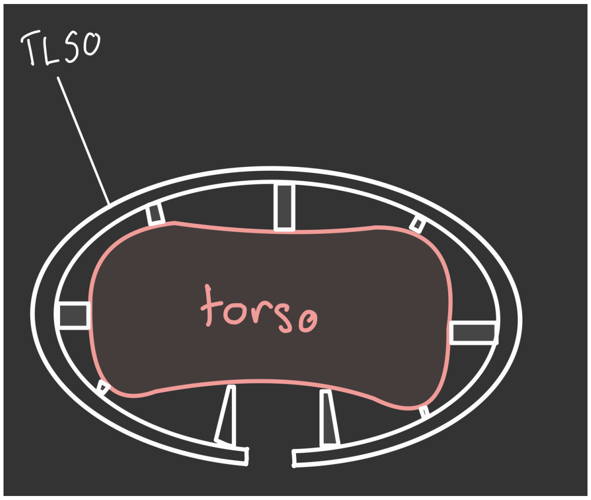


Figure 14. Concept 3. Extruded fins. This concept consists of an outer shell similar to the existing brace but with small fins extending inward to keep the shell away from the body.

Concept 4: Swiss Cheese

The fourth concept was the Swiss cheese design. This concept involves a series of holes throughout the brace to allow for improved heat dissipation. This design would reduce the skin temperature in comparison to the baseline. For that reason, this concept gets a +1 in skin temperature reduction. This design receives 0s in the following categories: resistance to deformation, breathing comfort, and relative movement as it is not making substantial changes relative to the baseline in these categories. This design scored a 1 in the weight category as the holes would decrease the weight of the brace. Scores of -1 were given to manufacturability and cost as this design will be 3D printed and therefore cost more than the conventional method of manufacturing the brace. Finally, it received a -1 in aesthetics as the holes may not look pleasing.

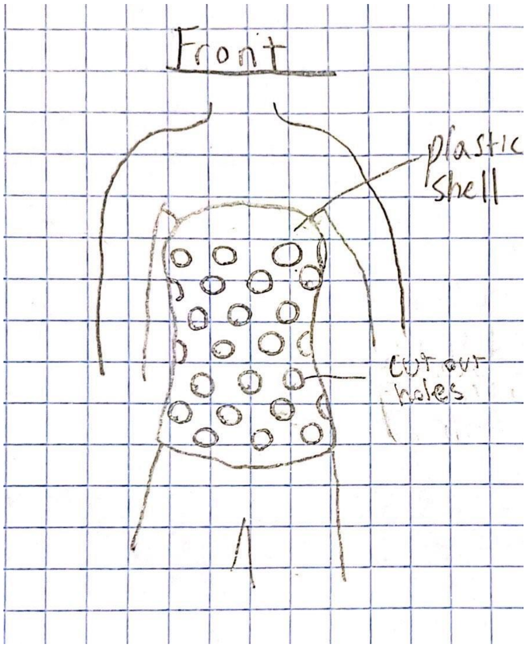


Figure 15. Concept 4. Swiss cheese design where holes are used to increase airflow for heat dissipation.

Concept 5: 3D Mesh

The fifth and final concept was the 3D Mesh. The idea behind this design was that the entire design was breathable and would be able to passively dissipate heat in all locations. This concept scored +1 with heat dissipation because of convection with the air. This score was not +2 because it did not have active methods of cooling or large amounts of exposed skin from heat to be dissipated. The TLSO shape would not change from the current design meaning there was no impact on breathing, support or mobility when compared to the baseline thus scoring 0. This concept did remove a substantial amount of material meaning it was lighter than the baseline scoring a +1. Manufacturability for this TLSO was given a score of -1 because even though it is printed from 3D filament, there is still the need to create holes and ensure the structural integrity stays the same compared to the baseline. The cost of this brace was given a -1 because there would be a need to 3D print this design with added supports to support all the mesh. Finally, this brace could be difficult to clean and not very aesthetically pleasing meaning it was given a score of -1.

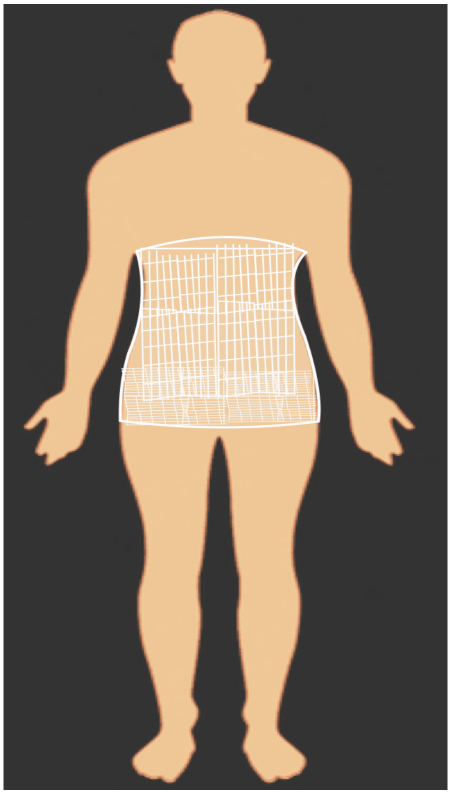


Figure 16. Concept 5. 3D mesh. This design has the same silhouette as the existing shell, but instead of being solid plastic, it would consist of a 3D printed plastic mesh-like structure. This design would help cool the skin, but the degree that it would cool would likely be limited by the density of the mesh required to maintain structural integrity, meaning this concept got a +1 in the cooling category.

Pugh Chart

Our Pugh Chart was set up with eight different criteria. Our five functional requirements plus three practical considerations: manufacturability, cost and aesthetics. Our first functional requirement of reducing the skin temperature was weighted the heaviest at a 5 because it is the main goal of our project. If our design does not meet this requirement, we have failed the main objective. Our next functional requirement of maintaining scoliosis support was weighted highly at a 4 because the main use of all TLSOs is to support the patient's spine. If we reduce scoliosis support our product would be less effective at its main purpose. Next, our comfortable breathing functional requirement was weighted at a 3 above the others that are left. Clearly, we must not prevent the patient from breathing. We are, however, confident that none of our designs will fully stop breathing and it is not one of our main goals. Relative movement, weight, manufacturability, and cost are all ranked at 2 because they are important considerations but not as important as the ones above them. Our initial selection process to converge on five designs has already eliminated non feasible options thus we are confident that we can create all these models using a 3D printer because they do not require any additive manufacturing besides the capabilities of the 3D printer.

Finally, Aesthetics was also considered at a weight of 1 because the patient would prefer the design to look better.

The baseline in this Pugh chart is our sponsor's current unmodified TLSO. All rankings were made relative to this baseline. Note, because many designs scored similarly in comparison to the baseline, we adopted a scale from -2 to +2 for added variability. This added variability would be used to help identify which concept would be the one selected. It should be noted that each design was ranked negatively in manufacturing because the amount of time and labor required to 3D print a TLSO is not as efficient as the current manufacturing method, however it allows for more complex shapes and designs not currently available using the current method. [8]

Table 2. Pugh chart containing our top five concepts.

Criteria	Weight	Baseline	Option 1 (Bungee cord)	Option 2 (Fans)	Option 3 (Extruded Fins)	Option 4 (Swiss cheese)	Option 5 (3D plastic mesh)
Skin Temp. Reduction	5	0	1	2	2	1	1
Maintain Scoliosis Support	4	0	-2	0	-1	0	0
Breathing Comfort	3	0	1	0	1	0	0
Relative Movement	2	0	0	0	-1	0	0
Weight	2	0	1	-1	-1	1	1
Manufacturability	2	0	-1	-2	-2	-1	-2
Cost	2	0	-1	-2	-1	-1	-1
Aesthetics	1	0	0	-1	-1	-1	0
	Total	0	-2	-1	-2	2	1

Alpha Design

The design we chose for our alpha design was a modification of Concept 4: the Swiss Cheese design. It is the highest scoring on our Pugh chart and was also deemed most likely to succeed given our project constraints. Starting from an existing shell, given by our sponsors, we incorporated our Swiss Cheese design in the areas of high temperatures. This was done exclusively in areas of high temperature to maintain structural rigidity. We are looking to optimize the air flow by altering the size, shape, and exact locations of the holes while maintaining the same support. Our holes will be finalized following finite element analysis to best optimize the size, shape, and location. In addition, we have included two slits at the top of the brace to allow for more deformation around the chest. This will allow the wearer to breathe more comfortably. The cutout beneath the stomach is made to accommodate the wearer's legs when sitting. Finally, the cut down the back is made for ease of entry. The back will be closed using Velcro straps as is standard in the industry.

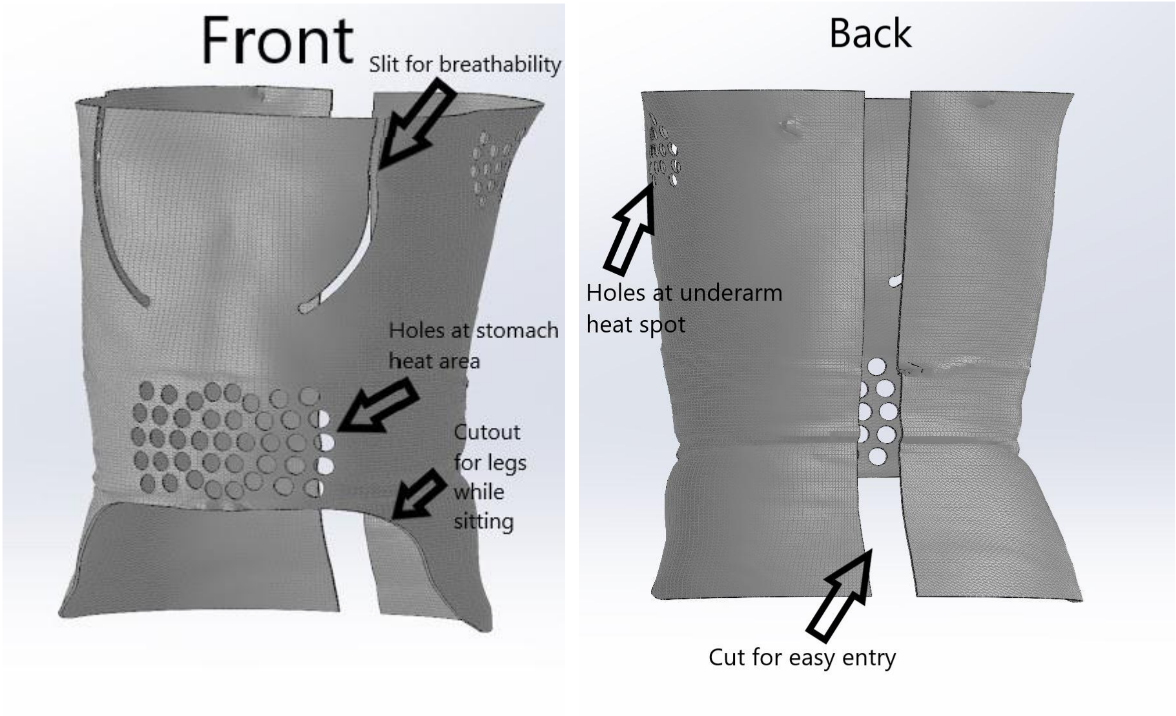


Figure 17: Initial Alpha design. This design has holes for heat dissipation in the stomach region and the underarm areas. The design also includes two cuts in the chest area to allow for breathing when worn. This is not an accurate representation of what the final design will look like, as it will heavily depend on the simulations that we will run in the coming weeks.

Engineering Analysis

In order to refine our alpha design we analysed whether or not holes in the TLSO would be able to achieve an acceptable skin temperature drop. We also ran a structural optimization analysis to precisely decide the holes' shape, size, and location.

Thermal Analysis

Initially, our thermal analysis was going to be done using FEA methods in either Hyperworks or Ansys. However, this proved to be more challenging than expected. The main issues we faced were a short timeline to learn completely new aspects of FEA software and trouble using very complex geometry. After many failed attempts we realized that FEA analysis was not necessary. We could conduct a simple first principles analysis to assess the holes' thermal performance. Our analysis was done by comparing two cases of natural convection with uniform heat flux from the body. The two cases we analyzed can be shown below.

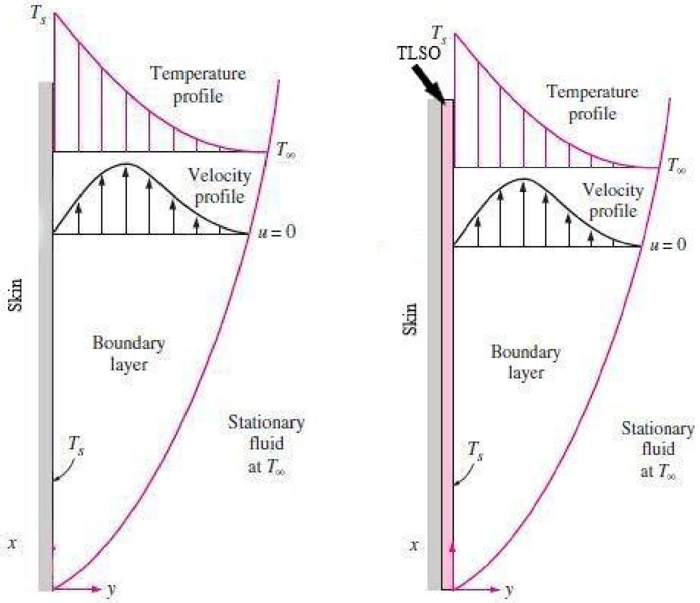


Figure 18: On the left, case 1 diagram of natural convection analysis with no TLSO. On the right, case 2 diagram of natural convection with TLSO in between body and air. [15]

In the diagram above, T_s is the skin temperature and T_∞ is the temperature of the ambient air. In both cases, we assumed the patch of skin and TLSO to behave like a flat plate, steady state conditions, and for there to be identical flow conditions and plate lengths across cases. We also applied a uniform heat flux of 94.4 W/m^2, as that is the average heat flux across the torso for adult men [10]. The ambient air was also taken to be at a standard 1 atm of pressure and 20℃ room temperature.

In the first case, left on figure 18, we found that the average person's skin temperature is 35℃ in room temperature conditions [12]. Then we applied the standard heat convection equation to find the heat transfer coefficient: h. The heat convection equation can be seen below.

$$q'' = h(T_o - T_\infty) \qquad (1)[15]$$

In this equation, q" is the heat flux, h is the heat transfer coefficient, T_o is the temperature at the contact between the plate and the air, and T_∞ is the temperature of the ambient air. In case 1 T_o is the skin temperature T_s because the skin is directly contacting the air. This heat transfer coefficient was then converted to the non-dimensional Nusselt number. The definition for the Nusselt number is shown below.

$$Nu = \frac{hL}{k} \qquad (2)[15]$$

In this equation, Nu is the Nusselt number, h is the heat transfer coefficient, L is the length of the flat plate, and k is the thermal conductivity material in contact with the air. In this case the k was the thermal conductivity of skin. This value was 0.21 W/m-K and was found from the *Fundamentals of Heat Transfer* [15]. The L was left in the equation to be canceled out later.

Because the Nusselt number is a non-dimensional description of the flow we can apply this same Nusselt number to case two.

In case 2, right on figure 18, we analysed the body with a TLSO in between the skin and the air. We assumed the flow conditions to be identical to the first case. Thus the Nusselt number was the same. Using equation (2) for case 2 we were able to cancel out the Ls in the equation as we assumed the same length across cases and the k was found from the *Fundamentals of Heat Transfer* for polyethylene [15]. This left us with a new heat transfer coefficient h for case 2. Using this heat transfer coefficient we used equation (1) to find the temperature at the outside of the TLSO: T_o. We then used Fourier's law of heat conduction, shown below, to find the skin temperature, T_s, with the TLSO on.

$$q" = \frac{k}{d}(T_s - T_\infty) \qquad (3)[15]$$

Finally, we compared the skin temperature in each case and found that there was a 1.2℃ drop when the skin is directly exposed to the air. This 1.2℃ drop at the holes is more than enough to satisfy our specification of a 0.5℃ max temperature drop. This analysis however, is limited by the assumption that the patch of skin or TLSO will act like a flat plate. In actuality the body has many complex curves that would make the thermal analysis far too complex for us to complete. Full calculations can be seen in Appendix D.

Structural Optimization

Our plan originally was to use Altair Hyperworks to run many structural analyses using a guess and check method for locating the holes, however this method would have proven too time intensive and imprecise, so other methodologies had to be formulated. Hyperworks' topology optimization proved an effective way to locate the holes efficiently, thus it was used. We started with a body scan of our sponsor that had been touched up in Blender and used this to generate our shell. This proved difficult initially, as the .stl scan file had multiple layers of duplicate elements, which went unnoticed. Many attempts were made to get a working analysis running with no luck; Eric Nelson from Altair was able to help get a single layer of 2D elements that we could use to generate our shell [16]. From there, a pshell component with Nylon-12 properties [17] was generated using the geometry of the scan. This scan was loaded as shown below in figure 19. The pshell consisted of triangular 2D elements and had an assigned thickness of 5 mm. Both the thickness and material were recommended to us by Jeff Weinsman during our visit to UMOPC [8]. Nylon-12 was a good choice because it had a higher elastic modulus without a significantly higher density than polyethylene. The added stiffness would allow us to remove material while maintaining the structural integrity of the TLSO. PLA was another considered material however, it's density was much higher than both polyethylene and Nylon - 12 leading it to be too heavy.

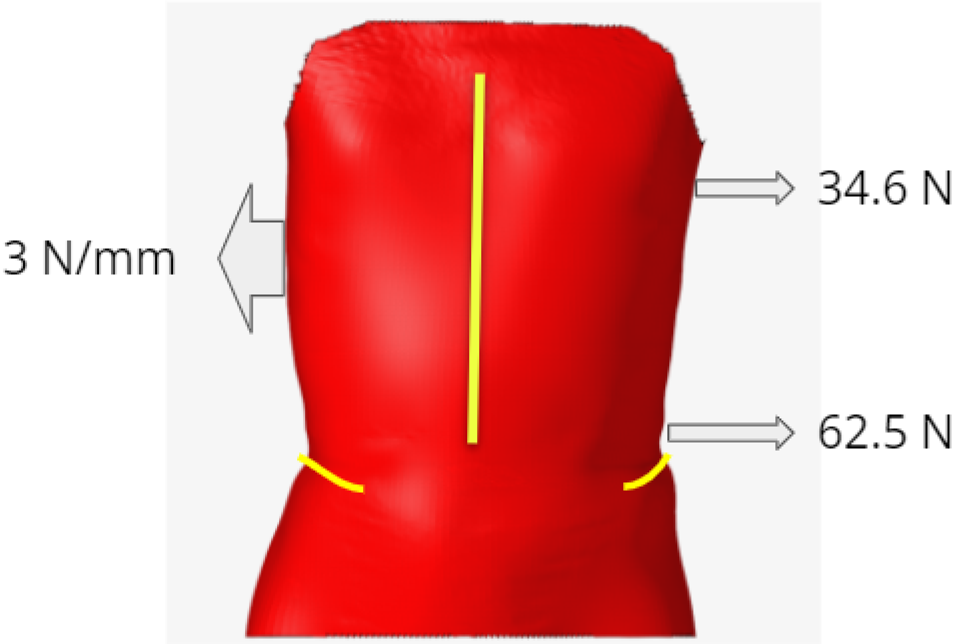


Figure 19. Loading of the brace in Hyperworks. The yellow lines indicate where the brace was constrained. Note that this is different from how the brace was loaded in figure 8, as that simulation was constrained in a manner that did not translate to how the brace performs in reality. Instead, we constrained the brace vertically (Z) along the hips, and laterally and into/out of the page (Y and X) along the centerline of the chest. This better matched the behavior of the brace when it is on the body.

However, upon testing this did not accurately mimic the behavior of the brace on the body, as it failed to account for the straps that hold the brace closed onto the body. So, two straps were modeled on the back of the brace using a pshell with nylon material properties, a material commonly used for straps [18]. These straps were attached onto the back of the brace using RBE2 elements. Finally we were ready to begin our optimization. Our no design area consisted of the straps and the region surrounding their mounts on the back of the brace. This would ensure that the optimization program left enough material on the back to attach the straps once we had our model printed. The topology optimization consists of three types of variables: responses, constraints, and an objective. The responses we used were mass fraction, compliance, and total displacement. The constraints were that massfrac had to be below 0.7 and the total displacement of any given node on the shell had to be less than 5 mm. Finally, the objective was to minimize compliance. This would provide us a good idea of where the holes could go as well as what shape they would have. The results of the optimization are shown below in figure 20.

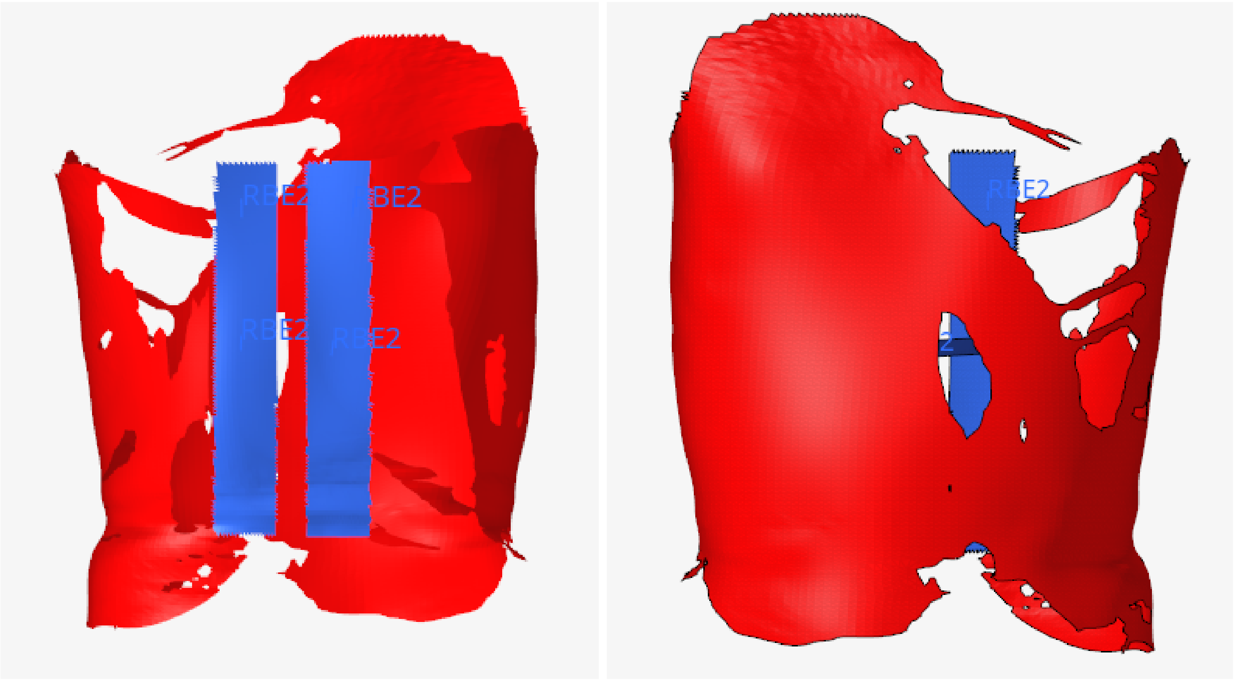


Figure 20. Results of topology optimization program. The no design area is shown in blue.

After we cleaned this up as described in the next section, we ran a reanalysis with the same loads and constraints as shown above in figure 20. We used this simulation to check the spot deformation at the locations the loads were applied. The result of this test is shown below in figure 21. The maximum deformation is required to be less than 5 mm and the maximum deformation that we found was 2.4 mm in our design, so this design would provide the required support.

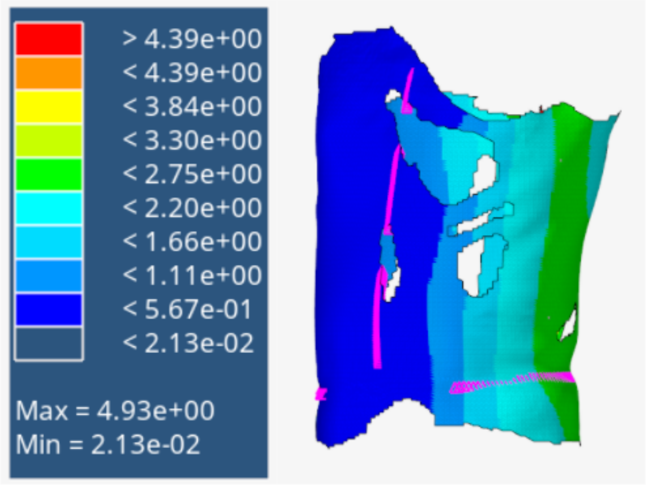


Figure 21. The results of the linear static simulation. What is shown is the total displacement in the brace under the applied load.

Final Design

By running the structural optimization in Hyperworks, the team was able to identify areas of integral structural strength and areas that could be removed to allow for heat dissipation from the surface of the skin. The final result of the structural optimization however, produced the minimum amount of coverage needed to meet displacement requirements and would not be suitable as our final product without risking injury to our sponsor as shown in Figure 22. Because of this, the topology optimization was used as a framework for the final TLSO.

The process of building the final design began with using a body scan of the sponsor, Gus. This scan was imported into a kinematic animation software called Blender and extruded to a thickness of 5 mm along its normals, the thickness of our studied TLSO. While still in Blender, this new shell was smoothed and would serve as the base for an optimized TLSO. The optimized topology and the smoothed scan were then perfectly overlaid in blender and holes were cut to the shape of the optimized topology as shown in figure 22.

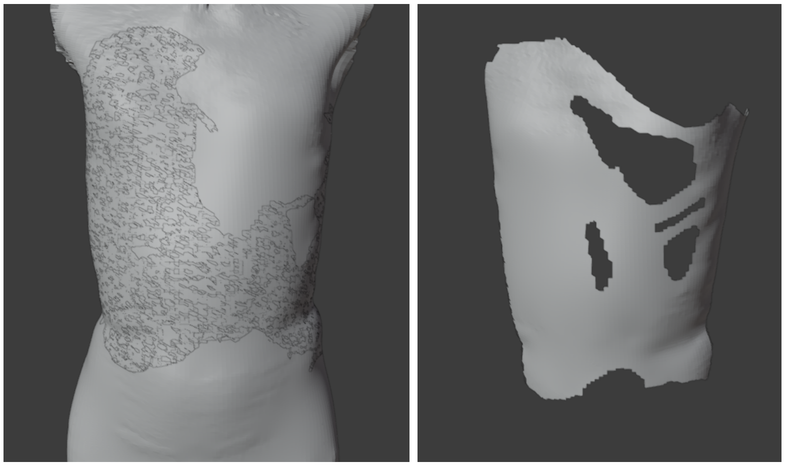


Figure 22. showing the overlaid optimized topology on the extruded scan of our sponsor. The TLSO on the right is a cut version of the scan shown on the left.

The final output from Blender was very jagged and the team was not satisfied with roughness and quality of the holes. This TLSO model was then exported to a software called Inspire, created by Altair. From here the TLSO holes were shaped more uniformly so that no hard edges or sharp corners could injure the sponsor.

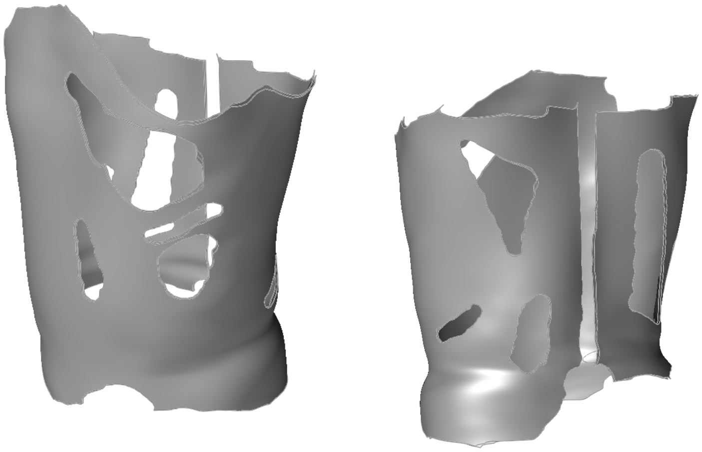


Figure 23. Above is the model following the smoothing function in Inspire. The edges on both the outside and inside were smoothed.

The TLSO was then exported to a software called Meshmixer which allowed for the edge of the TLSO to be manually smoothed. The final design is shown in Figure 24:

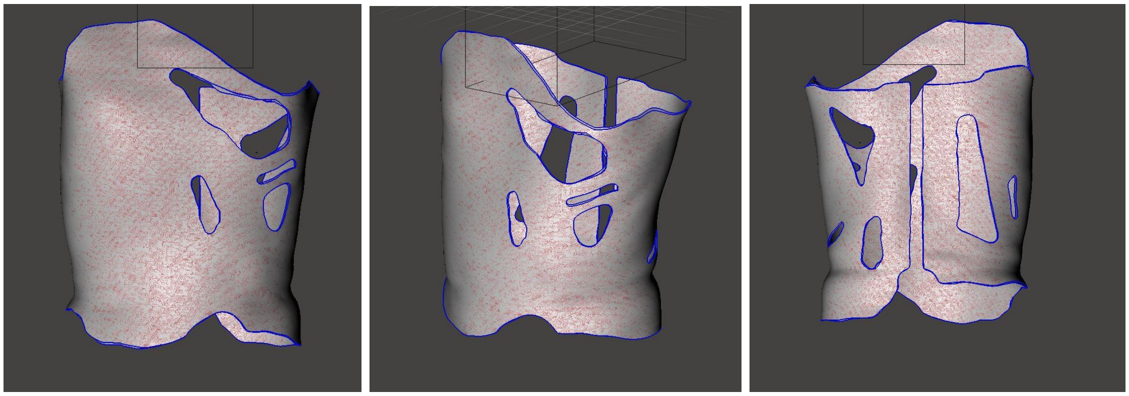
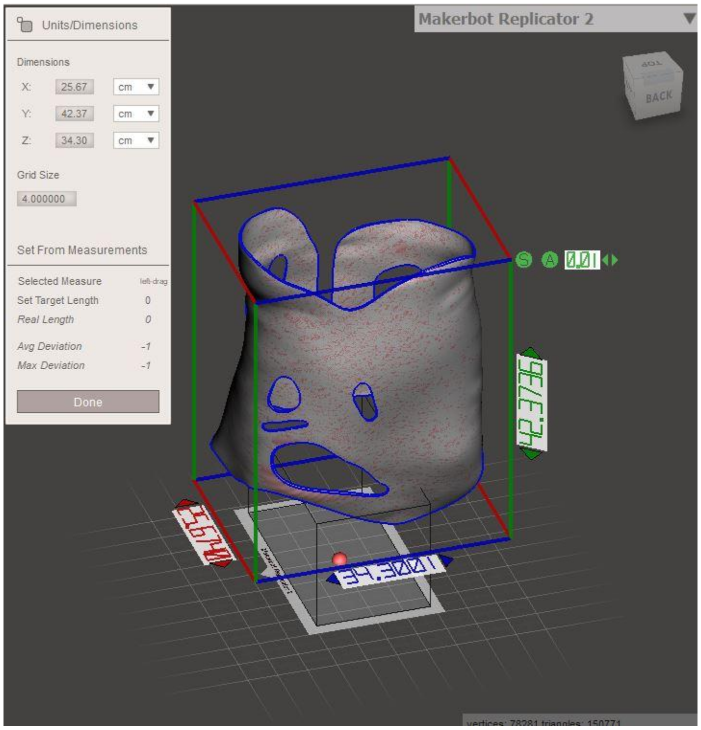


Figure 24. The Final Optimized TLSO is shown with views of the Front, Isometric, and Back



Units/Dimensions

Dimensions

X: 25.67 cm

Y: 42.37 cm

Z: 34.30 cm

Grid Size

4.000000

Set From Measurements

Selected Measure left-drag

Set Target Length 0

Real Length 0

Avg Deviation -1

Max Deviation -1

Figure 25. Final optimized TLSO on 3D printer bed. Bounding box dimensions are shown in cm.

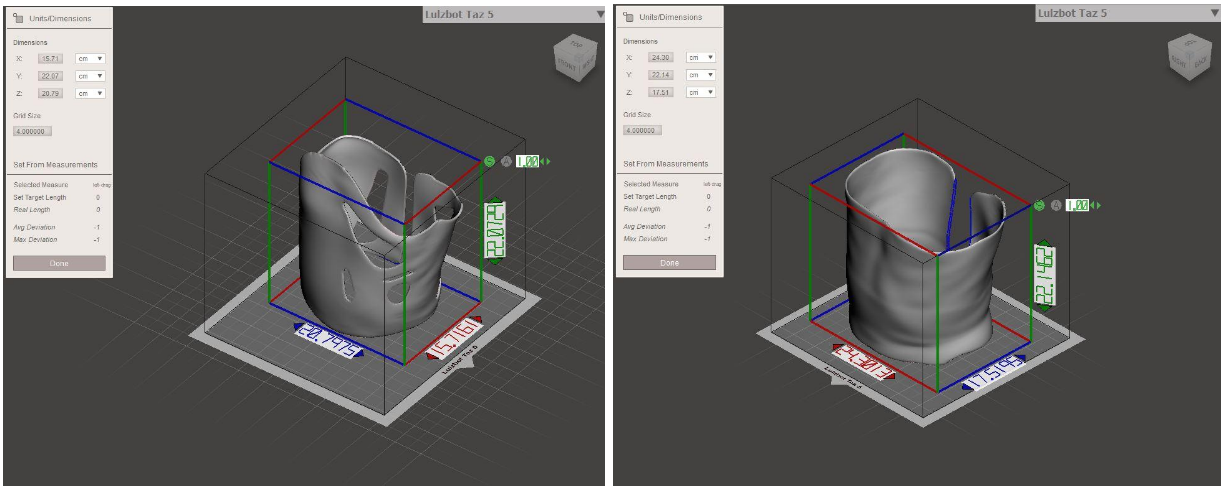
As seen in the engineering analysis, the holes should allow for direct convective heat transfer leading to a 1.2℃ skin temperature drop. In addition after the design was finalized another structural analysis was done in Hyperworks. We found that the maximum spot deformation of our final design was 2.4 mm, well below our 5mm specification.

As stated before we have chosen to create the TLSO out of Nylon - 12. This was due to Nylon - 12's similar density to the current brace's polyethylene and its increased stiffness. Along the back there will also be Velcro straps riveted into the brace to allow for tightening after entry. A full bill of materials can be found in Appendix C.

The use of the TLSO is the same as with any other TLSO. The user will approach it from the back pulling the two sides apart to enter the brace. After that they can tighten the brace by connecting the velcro straps behind it.

Build Design

The build design for the TLSO is a 52% scaled version of our final TLSO model. It has been iterated through with input and advice from our sponsors based on previous designs. The current model was sculpted in Meshmixer with the help of the sponsors. The TLSO was scaled to the print size of the bed to ensure verification tests could be run. The sizing meant that the full scale brace was printable by a commercial FDM printer our sponsors had access to. A second model of the original brace was printed to the same size to act as a baseline for verification testing. Both scaled designs can be seen in figure 26.



Units/Dimensions
Dimensions
X: 15.71 cm
Y: 22.07 cm
Z: 20.79 cm
Grid Size
4.000000
Set From Measurements
Selected Measure left-drag
Set Target Length 0
Real Length 0
Avg Deviation -1
Max Deviation -1

Units/Dimensions
Dimensions
X: 24.30 cm
Y: 22.14 cm
Z: 17.51 cm
Grid Size
4.000000
Set From Measurements
Selected Measure left-drag
Set Target Length 0
Real Length 0
Avg Deviation -1
Max Deviation -1

Figure 26: The figure above shows the scaled model of the brace fit to the size of the printing bed.

The brace is printed using Nylon-12, the same as the full scale model. The brace is then finished with the use of 6 rivets and 3 straps of velcro all of which are found in the BOM. (Appendix C) These build designs will be used for the verification of the temperature and relative movement requirements. These prints are the exact same design as the full sized brace meaning that the scaled brace will have a direct relation to the full sized. The most important element of our build is the heat dissipation. The scaled models allow for verification testing of the TLSO to prove that the optimized model improves heat dissipation. The other functional requirement tested by the build model is the relative movement of the brace. By twisting the balloon 45 degrees and identifying how far the brace has deviated from the original position we can directly measure the relative motion. This value would be the same between a full scale and build scale test and is thus valid to compare directly.

Verification and Validation

Verifying our design is critical to ensure that all engineering specifications have been met. Validation plans were created as future considerations for if we had enough time to validate.

Reduce Skin Temperature

If we were able to print a full sized model our verification would have been a direct measurement of the temperature difference between wearing our model and the current TLSO. We would ask our sponsor Gus to wear each TLSO and identify areas of highest heat. We would then use a temperature probe to directly measure the skin temperature. This method would be extremely easy to assess and would only require a temperature probe.

Because we were unable to print a full size prototype, a scaled build design of both the original and our optimized TLSO was printed. We were unable to use our sponsor as a baseline for the verification testing. To replace our sponsor, a plastic bag filled with 2.5L of water was used to fill the shape of the TLSO. A 7.5 Watt fish heater (*Aqueon Flat Submersible Heater 7.5 Watts)* was placed inside of the bag and allowed to sit for 1 hour to reach the steady state temperature. This simulated a human body producing uniform heat flux. The surface of the “skin” temperature was recorded using the *DoQaus digital thermometer* at the end of this time and shown in Figure 27.

Figure 27: The steady state temperature of the TLSO was captured using a temperature probe on the surface of the skin. The resulting temperatures can be seen and were recorded: 80.4∘F for the optimized TLSO and 79.5∘F for the baseline TLSO.

The final steady state temperature of the original brace and our optimized brace were 80.4∘F and 79.5∘F respectively. Converting these to celsius they are 26.9∘C and 26.4∘C respectively. This means we observed a 0.9∘F or 0.5∘C drop between the original and our optimized TLSO. This meets our functional requirement of a 0.5°C. However, when considering the accuracy of our thermometer there is no noticeable difference between measurements. Our thermometer has an accuracy of +/- 1°F. Since our measured difference of "skin" temperature is only 0.9°F there is no real difference between the two. Hence our temperature verification was inconclusive. Our specification was numerically met but it is well within the error for our specification to have failed. If we were given more time, a full scale model with testing on a longer time frame would be done to further verify thermal performance.

Despite our inconclusive results we are confident that a full scale model of our optimized TLSO would dissipate heat better than the original. This is due to our first principles analysis and intuition. The only major difference between our optimized TLSO and the original is the inclusion of structurally optimized holes which will allow for more convective heat dissipation.

Maintain Scoliosis Support

We have verified our final design to maintain scoliosis support through finite element analysis (FEA). Because we don't have access to the type of equipment that would allow us to test the prototype, we elected to run an FEA analysis in hyperworks. This would allow us to check if our brace met the deformation requirements without having a full scale prototype or access to the force gauges and deformation probes a physical test would require. As mentioned before, spinal forces acting on a TLSO were found from Rizza, R., Liu, X., Thometz, J. et al [12]. These forces, shown in figure 19, were applied to our final design using the same deformation tests used for engineering analysis. The test resulted in a maximum spot deformation of 2.4 mm. This passes our engineering specification of a maximum spot deformation of 5 mm.

Allows Comfortable Breathing

Because we did not have access to a full scale prototype to test on the body, an FEA stress simulation was run. This would allow us to check how the brace would perform by simulating the expansion of the chest when breathing. A displacement was applied about the 10th thoracic vertebrae such that the circumference increased by 7.1 cm. [13] Due to limitations of the software, we could not precisely displace the nodes normally outward from the center of the brace. We had to approximate it by displacing them along the normal axis of the face they were on. For example the front was displaced in the +x direction and the back was displaced in the -x direction. Each node was displaced outward by 113 mm; this was the radial increase required to increase the circumference of the brace by 7.1 cm. The stresses were then analysed to ensure the brace would allow for the expansion of the chest when breathing. The results of this simulation are shown below in figure 28. Unsurprisingly, the stiffness of nylon 12 means that this amount of chest expansion would break the brace, however the human chest is not capable of exerting forces large enough to actually achieve this much displacement. The design does not meet specification in this regard.

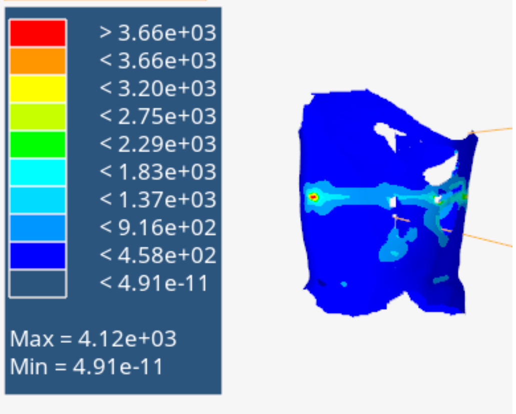


Figure 28. Results of breathing simulation. The maximum recorded stress value of approximately 4.12 GPa which far exceeds the yield strength of Nylon - 12.

Must not Cause Rashes

To verify the full scale model, we would directly measure the relative motion of the optimized TLSO. This would be done by measuring how far the brace moves relative to the body when twisting the torso 45 degrees left and right of center. This data will be recorded at every twist to ensure the brace is not correcting itself when the sponsor returns to anatomical position. To verify that our optimized TLSO has no increase in relative movement, the distance will be collected with calipers using a mark on the body and the TLSO.

Because we were unable to print the full scale model, our tests were run on the scaled build model. In this case, we used a blown up balloon to fill up the space within the TLSO. The original location of the balloon relative to the brace was marked. The balloon was then twisted 45 degrees to the left and right of center (marked on counter) before returning to the middle 0 degrees. From there, the offset distance from the original balloon was collected using a set of calipers. This experiment was conducted with 3 separate trials in 5 sets. The before and after photos for one trial are shown in figure 29.

Figure 29. The photos show the relative movement of the optimized TLSO (top) and baseline TLSO (bottom) after twisting 45 degrees left of center and 45 degrees right of center and positioned back at 0 degrees.

The average absolute distance was calculated to be 1.2 mm off center for the optimized TLSO and 1.7 mm for the baseline TLSO. This difference fulfills our requirement of no increase in relative movement between the optimized TLSO and the baseline. The difference between the two results is very minimal (0.5 mm) meaning there was almost identical relative movement. This verification is therefore conclusive and the new TLSO does not move more relative to the body.

Remains Light Weight

The weight was analysed using SolidWorks CAD software. In SolidWorks, we assigned Nylon - 12 as the material of our full scale TLSO. We assessed the weight based on the volume of the part and the density of Nylon - 12. Our optimized brace's mass is 1.14 kg based on a Nylon - 12 density of 1020 kg/m^3 [15]. In order to compare this to the original brace's weight, we imported the original brace into SolidWorks and assigned the original brace's material: polyethylene. The original brace's mass is 1.46 kg based on a polyethylene density of 950 kg/m^3. [15] This easily passed our requirement for the new brace to be at most 10% more heavy than the baseline. In fact, our brace was actually 22% lighter than the original.

Validation

We would validate a full scale brace as an adequate solution to the design problem by using sponsor input. Validation would come from the use of a quality of life survey, typically conducted for long term users of TLSOs. This survey would highlight thermal performance as compared to the original brace through a series of qualitative questions. Validation of maintaining scoliosis support would need to come from a medical professional who could compare the original cobb angle and the current cobb angle of the spine. This validation would occur after extensive use of the TLSO to ensure it is properly supporting the spine.

Discussion.

Problem Definition

The functional requirements, while far from being all encompassing, boiled down the problem pretty well. If we had more time and resources we could have conducted testing on the current brace. Those results could provide a more specific set of specifications that cater more to each stakeholder. No two bodies are the same so this would provide an exact metric against which we could compare our prototype. Insead of testing the current sponsor's TLSO, we collected research that referred to average values and specific criteria that were representative of a global population. While these metrics address a general population, there is no way for us to tell if they were specifically accurate for our patient's anatomy. For example, we found that the average male chest expansion during breathing is 7.1 cm, however this number could vary for our specific patient. It would have been better if we were able to actually formulate our specifications around our patient instead of referring to literature values.

Design Critique

We believe this design does well to provide support for the spine as well as dissipate heat effectively, however we are concerned that it will be uncomfortable for the patient. As stated above, the stiffness of nylon-12 does not allow for significant chest expansion. This could potentially be alleviated by running a topography or gauge optimization to make certain areas thinner - specifically the chest region. Our time constraints did not allow for this as it would have involved generating a new model and learning the intricacies of new optimization variables. Another way this design could have been improved would be to filet the interior of the holes inside the software. This would provide more consistent filets, use less material, and save time during post processing of the print. Also, consulting with someone who is an expert in patient comfort would probably have helped us identify what factors to consider when trying to improve the comfort of orthotics. However, we think that our brace is still an improvement over the current sponsor's brace because it is significantly lighter and allows for better heat dissipation. The decrease in weight should offer more mobility when the brace is worn for an extended period of time. Our greatest strength is establishing a method for removing material in regions of low stress to allow heat to exit the shell more efficiently without impacting the structural performance of the brace.

Recommendations

We have recommendations regarding both the design and manufacturing methods of the brace. Our first recommendation is to look into ways to improve the amount of deformation when breathing. One relatively simple way would be to cut a slit in the brace along the ribcage on the front of the torso. This would allow the chest region to expand without sacrificing the overall structural integrity. If this were done, structural reanalysis would have to be conducted to ensure no critical loss in rigidity. Another option would be to explore variable thickness via gauge or topography optimization. This would optimize the thickness of our TLSO in specific spots to allow increased deformation in chosen areas while maintaining rigidity where needed. Another recommendation would be to explore more material options. In our project, we were fairly limited in what materials were available to us. Other options such as Acrylonitrile Butadiene Styrene (ABS) has a similar density to Nylon - 12 but is more flexible. This flexibility would allow the wearer to breathe more easily and still provide the support needed. The Nylon - 12 was chosen in an abundance of caution to provide more support than needed. Our final recommendation would be to print the brace vertically as shown below in figure 30.

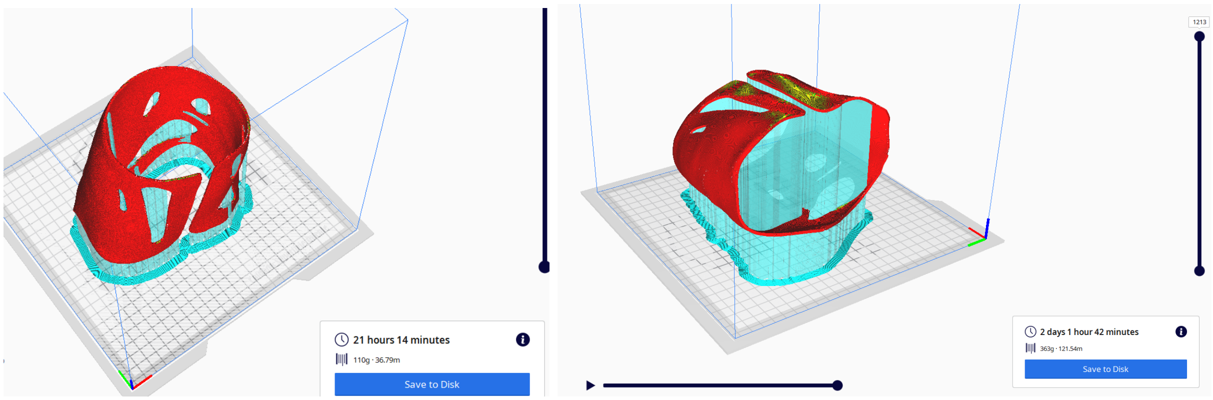


Figure 30. Comparison of two printer orientations for the scaled down part. Supports are highlighted in blue. As you can see the vertical orientation (left) uses less material and prints significantly faster than the horizontal orientation (right).

By printing it vertically, you dramatically reduce the amount of support needed to print the part, which drastically reduces both print time, and post processing. This would also save money by eliminating a large amount of plastic waste and reducing the active print time.

Conclusions

The main goal of this project is to improve the thermal performance of a TLSO while maintaining its ability to support the spine. We 3D printed a TLSO prototype as it is the easiest way to manufacture our complex geometry.

Through conversations with stakeholders and research, we devised a list of functional requirements and quantifiable engineering specifications. We hope to decrease the maximum skin temperature beneath the TLSO by 0.5 ℃. However, we do not want to sacrifice the TLSO's ability to correct scoliosis, thus we will limit spot deformation to less than 5 mm [12]. Additionally, the new brace should not cause rashes from rubbing or have more translational movement relative to the body than the current brace. According to the sponsor, the weight of the brace was not a significant factor to his discomfort, so an allowable increase in weight of 10% was deemed reasonable. To make sure the wearer's ability to breathe is not compromised, the chest region of the brace should be allowed to expand 7.1 cm circumferentially [13].

We were able to generate a final design using optimization software on Hyperworks identifying areas of critical structural support and removing material where unnecessary. We were then able to clean up the design removing any sharp edges. The design was then printed and tested to ensure it met our requirements. The design passed weight and support requirements using computer simulation. The breathing requirement did not pass computer simulation for the chest expansion. Using a printed scale model, the temperature and relative movement requirement were tested. The temperature test resulted in an inconclusive result as our final temperature drop was not outside the accuracy of the thermometer. The model passed the relative movement test with insignificant change in displacement.

Overall, our design was able to pass most of the requirements given. The group has concerns regarding the inconclusive temperature test but is confident a full scale model would perform well. The main area of concern is in restricting breathing from a failure in verification. If we had more time, we would consider adding slits in the TLSO and optimize variable thickness. We would also work to remove more material from the brace so that we could have larger reductions in temperature. In the end, we have developed a complete process for the optimization of material reduction in TLSOs.

Acknowledgements:

As a group, we would like to thank Miguel Funes and Gus Putra for their role as sponsors for our project this semester. Without their continuous guidance and expertise on the matter, we would not have been able to successfully complete our goal of optimizing the TLSO. We would also like to thank our professor Gregory Hulbert for his guidance and help especially with the use of FEA and creative solutions to our unique optimization questions. We would also like to thank Eric Nelson for his help in structural optimization. Without his help, we would not have been able to optimize our TLSO resulting in an incomplete project. We would like to thank Chris Casteel from New Life Prosthetics for helping us get started with understanding TLSO production and showing us around his facilities. Finally, Jeff Wensman for his willingness to teach us about current TLSO construction and showing us the production of orthotics at UMOPC (University of Michigan Orthotics and Prosthetics).

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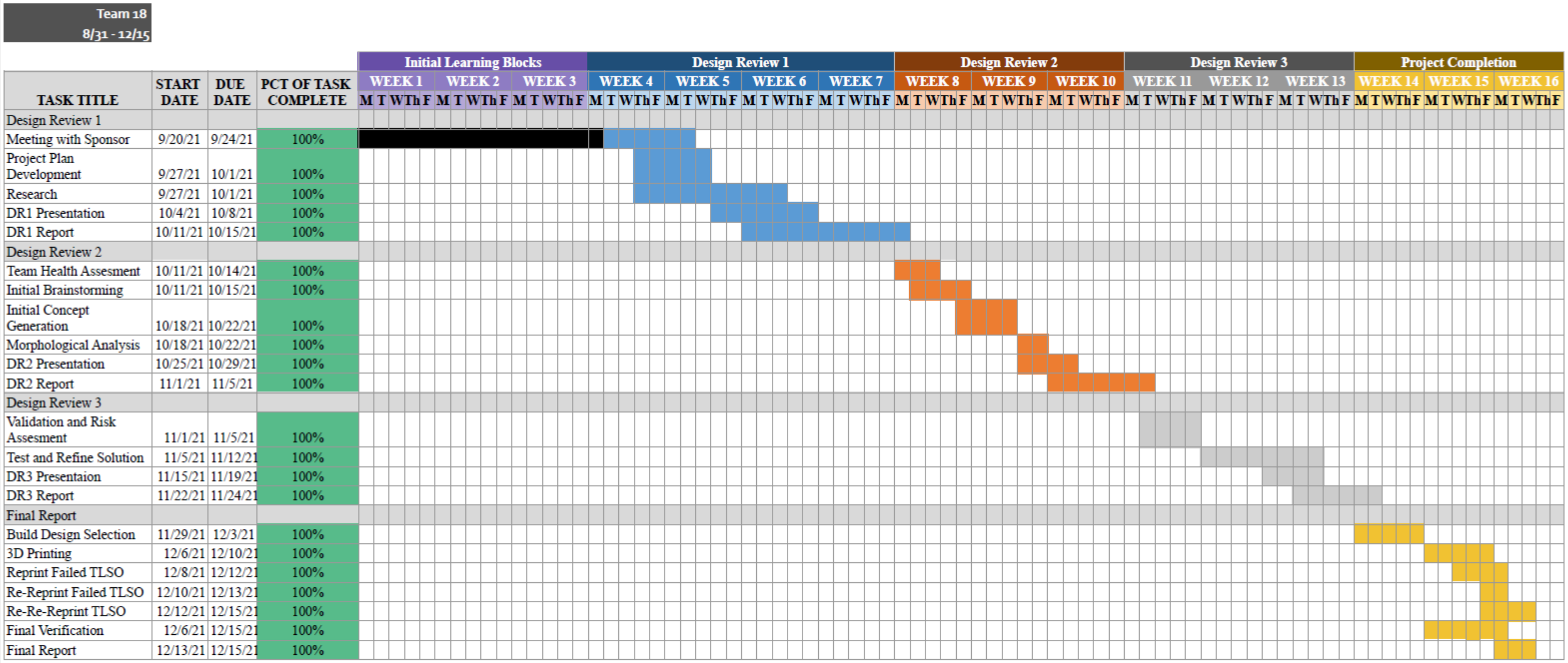
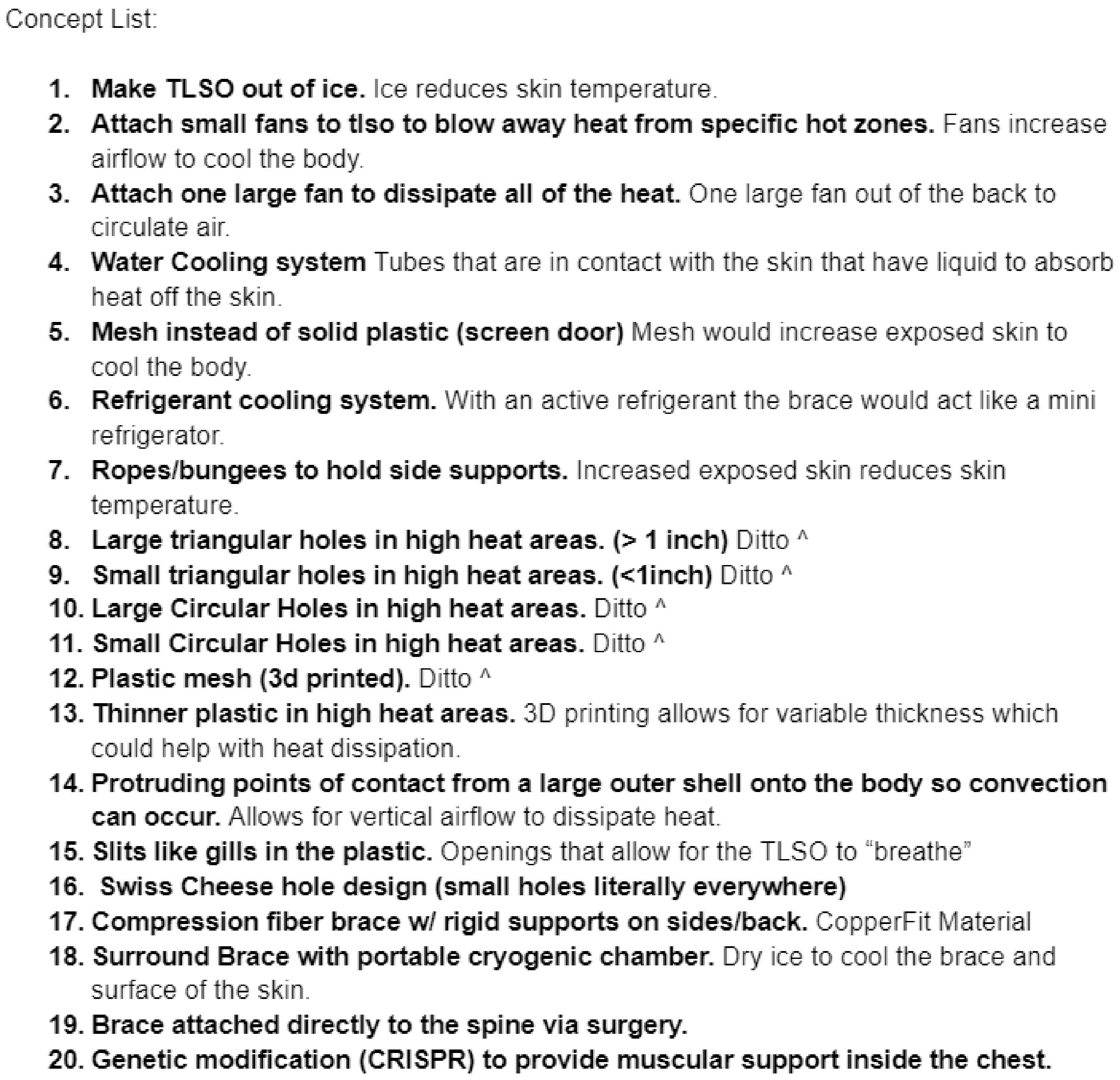
Appendix A



Team 18
8/31 - 12/15

TASK TITLE	START DATE	DUE DATE	PCT OF TASK COMPLETE
Design Review 1			
Meeting with Sponsor	9/20/21	9/24/21	100%
Project Plan Development	9/27/21	10/1/21	100%
Research	9/27/21	10/1/21	100%
DR1 Presentation	10/4/21	10/8/21	100%
DR1 Report	10/11/21	10/15/21	100%
Design Review 2			
Team Health Assesment	10/11/21	10/14/21	100%
Initial Brainstorming	10/11/21	10/15/21	100%
Initial Concept Generation	10/18/21	10/22/21	100%
Morphological Analysis	10/18/21	10/22/21	100%
DR2 Presentation	10/25/21	10/29/21	100%
DR2 Report	11/1/21	11/5/21	100%
Design Review 3			
Validation and Risk Assesment	11/1/21	11/5/21	100%
Test and Refine Solution	11/5/21	11/12/21	100%
DR3 Presentaion	11/15/21	11/19/21	100%
DR3 Report	11/22/21	11/24/21	100%
Final Report			
Build Design Selection	11/29/21	12/3/21	100%
3D Printing	12/6/21	12/10/21	100%
Reprint Failed TLSO	12/8/21	12/12/21	100%
Re-Reprint Failed TLSO	12/10/21	12/13/21	100%
Re-Re-Reprint TLSO	12/12/21	12/15/21	100%
Final Verification	12/6/21	12/15/21	100%
Final Report	12/13/21	12/15/21	100%

Appendix B



Concept List:

1. **Make TLSO out of ice.** Ice reduces skin temperature.
2. **Attach small fans to tlso to blow away heat from specific hot zones.** Fans increase airflow to cool the body.
3. **Attach one large fan to dissipate all of the heat.** One large fan out of the back to circulate air.
4. **Water Cooling system** Tubes that are in contact with the skin that have liquid to absorb heat off the skin.
5. **Mesh instead of solid plastic (screen door)** Mesh would increase exposed skin to cool the body.
6. **Refrigerant cooling system.** With an active refrigerant the brace would act like a mini refrigerator.
7. **Ropes/bungees to hold side supports.** Increased exposed skin reduces skin temperature.
8. **Large triangular holes in high heat areas. (> 1 inch)** Ditto ^
9. **Small triangular holes in high heat areas. (<1inch)** Ditto ^
10. **Large Circular Holes in high heat areas.** Ditto ^
11. **Small Circular Holes in high heat areas.** Ditto ^
12. **Plastic mesh (3d printed).** Ditto ^
13. **Thinner plastic in high heat areas.** 3D printing allows for variable thickness which could help with heat dissipation.
14. **Protruding points of contact from a large outer shell onto the body so convection can occur.** Allows for vertical airflow to dissipate heat.
15. **Slits like gills in the plastic.** Openings that allow for the TLSO to “breathe”
16. **Swiss Cheese hole design (small holes literally everywhere)**
17. **Compression fiber brace w/ rigid supports on sides/back.** CopperFit Material
18. **Surround Brace with portable cryogenic chamber.** Dry ice to cool the brace and surface of the skin.
19. **Brace attached directly to the spine via surgery.**
20. **Genetic modification (CRISPR) to provide muscular support inside the chest.**

Appendix C

Bill of Materials:

BOM Number	Item	Quantity	Source	Catalog Number	Cost	Contact	Notes
1	Velcro Strap	3	Amazon	VC-HD18X2005-BK	$16.99	Amazon.com	
2	Rivets	6	McMaster-Carr	97447A145	$12.43	mcmaster.com	
3	Nylon 12	n/a	Amazon	606110283908	TBD	Amazon.com	KODAK 3D printer filament NYLON 12 NATURAL color, +/- 0.03 mm, 750g (1.6lbs) Spool, 1.75 mm. Lowest moisture premium filament in Vacuum Sealed Aluminum Ziploc bag. Fit Most FDM Printers

Appendix D:

Calculations for thermal engineering analysis.

$$\frac{q''}{(T_s - T_\infty)} = h_1$$

$$Nu = \frac{h_1 L}{k_1}$$

$$Nu = \frac{h_2 L}{k_2}$$

$$T_o = \frac{q''}{h_2} + T_\infty$$

$$\triangle T = T_s - T_o$$

$q'' = 94.4 w/m^2$, $T_s = 35$℃, $T_\infty = 20$℃, $k_1 = 0.21$W/m-K, $k_2 = 0.33$W/m-K

The final change in temperature between having and not having a TLSO on was 1.2℃

Appendix E:

Manufacturing Plan:

The conventional fabrication process does not apply to this project as it includes using subtractive manufacturing methods in a manufacturing workshop to create a final product. Our fabrication process focuses mainly on the use of a scan of our stakeholder and using different software namely: Blender, Hypermesh software, Inspire and Meshmixer to 3D print the TLSO. The following is an in-depth procedure to create an optimized TLSO.

Step 1: Scan the stakeholder of interest's body with spine in neutral position.
Step 2: Open Blender through Caen and import the scan as a mesh by selecting:
    File > Import > STL > scan.stl
Step 3: Move to the Modeling tab on the toolbar and hit A on the keyboard.
Step 4: Select Face on the sub-tool bar and then extrude the scan using "Extrude Faces along Normals" and then typer 0.005 for 5 mm of thickness.
Step 5: Export the scan to Meshmixer.
    Export the scan from Blender and save as an .STL
        Mesh Mixer is an open source software that can be downloaded.
    Import the .STL into mesh mixer

Step 6: Import extruded scan as .STL into hyperworks.
Step 7: Select top both top and bottom edges and delete elements. This should leave you with two separate shells.
Step 8: Delete interior face of shell, sometimes there are multiple shells on top of each other so make sure you are left with a single shell of 2D elements.
Step 9: Create load collector, two loadsteps, a material collector, and a pshell property collector.
    Assign the properties of nylon-12 to the material collector and set the pshell thickness to 5mm.
Step 10: Load the shell as pictured in figure 19 on page 26.
Step 11: Move the 2D elements into the pshell property collector and assign material.
Step 12: Model straps as 2D elements on back of brace.
    Create a new material collector and assign nylon strap properties.

Step 13: Create a new component collector titled ‘no design region’ and assign the straps and the elements in the region they connect to the brace to it. This should have identical material and pshell properties to the rest of the shell.
Step 14: Create optimization design variable, set design area to be the component collector not named ‘no design region’.
Step 15: Create 3 optimization responses:
Massfrac
Displacement (Total)
Compliance
Step 16: Create 2 optimization constraints:
Constrain displacement to a maximum of 5 mm
Constrain Massfrac to a maximum of 0.7
Step 17: Create optimization objective (minimize compliance)
Step 18: Run Optimization.
Step 19: Import results of optimization.
Step 20: In the contour menu, select the last iteration of the optimization and click the bubble next to isosurface.
Then select value based and set the lower bound for the density to 0.43 and click assign. If this does not look right, change the density cutoff until it does.
Step 21: In the post panel, select OSSmooth and use the current file. Then set parameters to none and select the results file (.sh). Then choose the FEA reanalysis option. Check the box next to iso surface and set the threshold to the same density used above. Click the green OSSsmooth button.
Step 22: Once this is done export the new geometry as a .STL file.
Step 23: Import the optimized .STL file into Meshmixer over the extruded shell.
This optimized TLSO will act as a cookie cutter so you can cut out parts of material.
Step 24: Identify the areas that need to be removed.
Use the toolbar on the side of the screen and hit Select > and then highlight the areas that need to be removed (this will highlight orange).
Once you are satisfied with the covered area, hit X on the keyboard.
Repeat this process until all the holes have been cut.

This will result in a pretty rough cut out with non-uniform holes.

Step 25: Export the scan and import the scan into Inspire.

Step 26: Use the smooth tool in Inspire to smooth edges while making sure to not remove too much material. This is for rough smoothing, the finer smoothing is done in a later step.

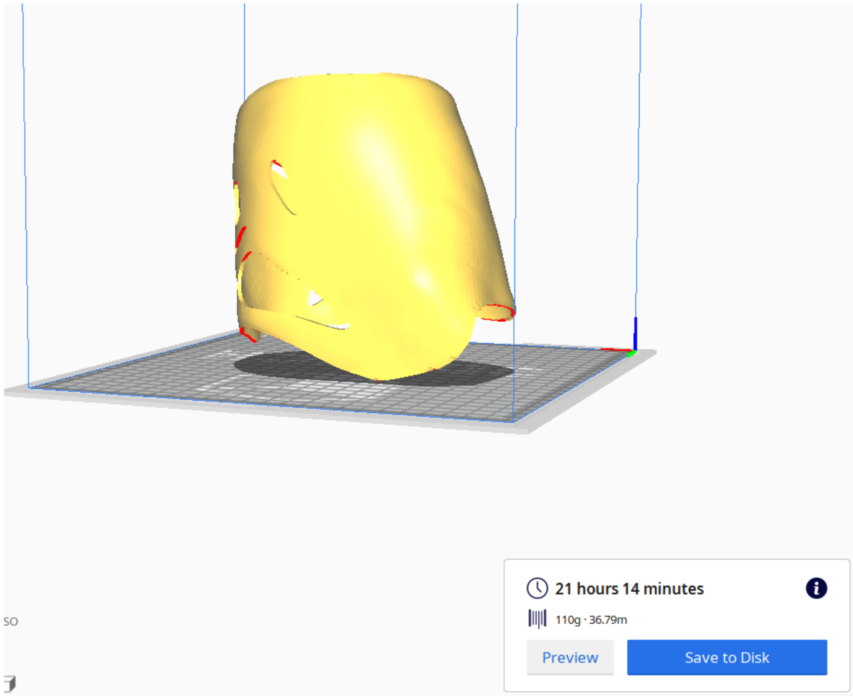
Step 27: Export the .STL back into Meshmixer using the select tool smooth the surface of the TLSO by selecting the rough areas and going to Select > Deform > smooth > accept.

Repeat this process until smooth and then export to your chosen 3D printing software.

Step 28: Size your TLSO to the size of the printer bed you are using by importing the .STL file into the program CURA.

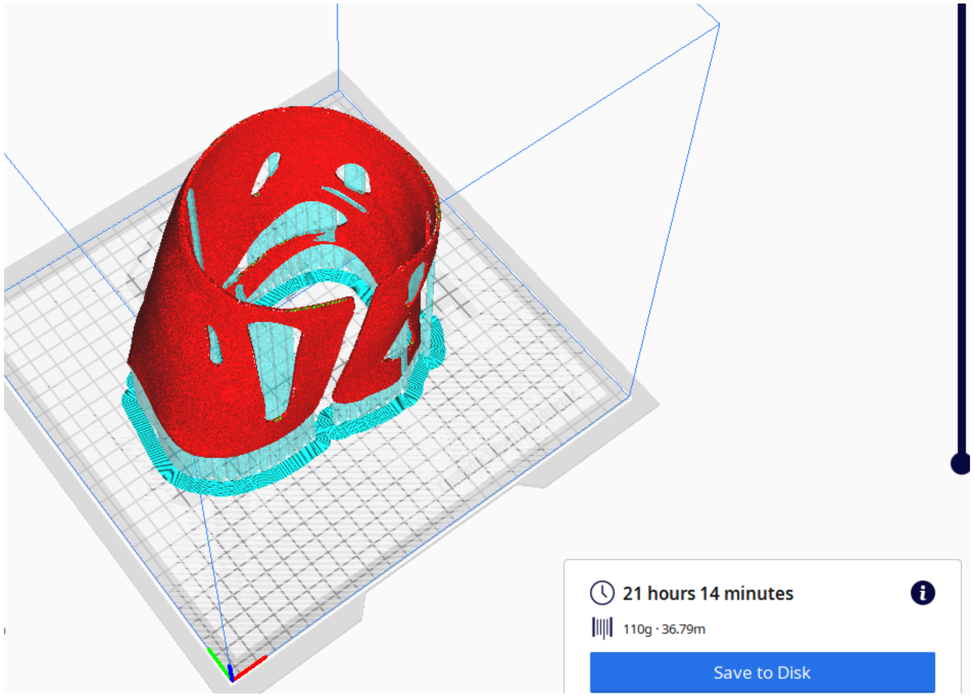
Step 29: Based on guidance from our sponsor, it is incredibly important to account for the orientation of the print. Changing the orientation of the print can cause the print to go from 20 hours to 60+ based on the amount of support needed to be used.
The ideal orientation is so that the “top of the TLSO” is pointed towards the bed. This orientation will use the least amount of Nylon 12 saving time and money.

Step 30: Once you have correctly accounted for the orientation of the model, scale the model to your desired size and then submit the .STL file for printing.
Shown below is an example of the part ready for printing shown with and without supports.



21 hours 14 minutes

110g · 36.79m



21 hours 14 minutes

110g · 36.79m