Investigations into the Form and Design of an Elbow Exoskeleton Using Additive Manufacturing

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ABSTRACT

The commercial exoskeletons are often heavy and bulky, thus reducing the weight and simplifying the form factor becomes a critical task. This thesis details the process of designing and making a low-profile, cable-driven arm exoskeleton. Many advanced methods are explored: 3D scanning, generative design, soft material, compliant joint, additive manufacturing, and 3D latticing. The experiments on TPU kerf cut found that the stress-strain curve of the sample can be modified by changing the cut pattern, it is even possible to control the linear region. The TPU TPMS test showed that given the same volume, changing the lattice parameters can result in different bending stress-strain curves. This thesis also provides many prototypes, test data, and samples for future reference.

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GENERAL AUDIENCE ABSTRACT

Wearing an exoskeleton should be easy and stress-free, but many of the available models are not ergonomic nor user-friendly. To make an exoskeleton that is inviting and comfortable to wear, various nontraditional methods are used. The arm exoskeleton prototype has a lightweight and ergonomic frame, the joints are soft and compact, the cable-driven system is safe and low-profile. This design also brings aesthetics to the exoskeleton which closes the gap between engineering and design.

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Contents

Table of Figures

1. Introduction

1.1 Background and Motivation

The exoskeleton is being commercialized in recent years, in the field like industrial assembly lines, post-stroke rehabilitation, and powered prosthetics. [1] But many of the exoskeletons currently focus only on the functionality and forgo other important aspects such as comfort and aesthetic. As a result, the user often chooses not to wear an exoskeleton for an extended period of time or look for other more user-friendly solutions. [2] To give a few examples of said exoskeletons, some of the most successful commercialized products are listed below.

Figure 1. 1 Guardian® XO® Full-Body Powered Exoskeleton. Image downloaded from https://www.sarcos.com/products/guardian-xo-powered-exoskeleton/

The Guardian XO is a battery-powered full-body exoskeleton that is clearly designed for industry workers. It emphasizes strength and endurance, the large motors provide good lifting force and the side armor plates provide injury prevention. But some common undesired characteristics of this kind of exoskeleton include: Out-of-body offset rotation joints, a high number of joints and degrees of freedom (DOF), complex control system, limited movement, high weight and volume, low operating time.

On the other hand, there are lightweight exoskeletons, or technically, exosuits like the EksoUE which is designed for shoulder and arm rehabilitation.

Figure 1. 2 EksoUE is a wearable, upper-extremity exoskeleton designed to assist a patient's affected shoulder and arm during rehabilitation. Image downloaded from https://eksobionics.com/eksoue/

Unlike the Guardian XO, this kind of exosuit is often not actively powered by battery, but instead passively powered by springs or other compliant mechanisms. Common characteristics include close fit to the body, simple compliant joints, low weight, and volume, adjustable and customizable. Although this approach is more user-friendly compare to traditional exoskeletons, it loses some important functionalities like a rigid body, self-support, and powered joints.

One common aspect of these two kinds of exoskeletons is that they are targeting specific user markets in specific environments: Works in factories or patients during physical therapy. They are not designed for long-term use and daily activities.

Many patients who suffer from reduced motor function due to spinal cord injury or stroke require to assist for daily activities and need a long-term recovery period. [3] The same care is needed for children with a bone disorder or gait abnormalities. [4] Thus arise the need for an exoskeleton that is user-friendly, retains full functionalities, and also has a low profile for day-to-day usage. To insure the user-friendly nature of said exoskeleton, this thesis project will include an aspect often overlooked by many engineers—aesthetic. A great example is Sophie de Oliveira Barata's ALTERNATIVE LIMB PROJECT. [5] As an incredible artist, Barata designs beautiful prosthetics in various themes for users with different needs.

Figure 1. 3 Anatomical Leg, a leg prosthetic made for Ryan Seary, ex-serviceman for explosive ordnance disposal. Image downloaded from https://thealternativelimbproject.com/limbs/anatomical-leg/

As shown in the picture above, the plates around the leg prosthetic do not provide any functionality but instead elevate the aesthetic. As a result, the user is more willing to wear the prosthetic and even show off the design rather than hiding it. Thus improve the overall user experience and bring extra value to the product.

1.2 Objective

This research is to design and test a lightweight arm exoskeleton that strikes a balance between functionality, power, comfort, and aesthetics. The goal is to explore aspects of design often overlooked by mechanical engineers such as the human factor, user experience, and material manufacturing. The project also explores and experiment with serval innovative design and manufacturing tools including generative CAD design, 3D scanning, Additive manufacturing (AM), compliant mechanisms, 3D latticing, and soft materials. Ultimately, the project may open up new approaches to designing exoskeleton and introduce art and design to the next generation of engineers.

1.3 Outline

This thesis will break into three main chapters. Each chapter has its own literature review and conclusion. The first chapter focuses on refining the form factor of the frame of the arm exoskeleton, where ergonomic and generative design plays important roles. The second chapter explores different types of joint designs with a focus on compliant mechanisms such as Kerf cut and soft material. Most of the experiment data is shown in this chapter. The third and final chapter talks about the influence of additive manufacturing on designing and making exoskeletons as well as 3D latticing. The last part of this thesis is a conclusion section that paints a big picture of ergonomic design, points out design limitations, and suggestions for future work.

2. Chapter 1: Form Exploration

2.1 Literature review

To determine the form factor of an active arm exoskeleton, there are a few key aspects that need to be evaluated: machine to body interface, articulation method, signal detection method, and joint type. Because one of the goals of this project is to make the exoskeleton low-profile, the out-of-body type of exoskeleton like Guardian XO is not considered. To achieve a low profile, the exoskeleton should extrude from the body as little as possible. Based on this principle, three upper-body exoskeletons/exosuits are evaluated for this section.

First, a 7-DOF cable-driven upper limb exoskeleton from Harbin Institute of Technology. [6] The group claim this exoskeleton is compact, lightweight, and comfortable, and designed for post-stroke patients. The article states that the weight of the exoskeleton is 3.5 kg, but based on the pictures, the frame is clearly too heavy for one person to operate and the cable system is so complex that it relies on external tubing. The RMS signal from main muscle groups also shows that passive modality values are two to three times larger than free modality values, while assistive modality values are only 20~30 % lower than free modality values. This is not ideal in the case of losing power where the user will not be able to support the weight of the system. Even though the cable-driven system is heavy and bulky, the exoskeleton is able to achieve 7-DOF around traditional rotational joints. This begs the question: How to simplify the design and reduce the weight without sacrificing DOF?

The answer is often soft exoskeleton. A Bowden cable-driven upper limb soft exoskeleton from Soochow University is a good example. [7] Instead of using aluminum as the frame, this exoskeleton uses mainly belts and straps around the upper limbs. The cables go through solid ABS plastic blocks, the force bearing points, fixed on the straps, and are powered by motors attached to the back. An important finding from this article is that increasing the number of cables and moving the force bearing point away from the elbow can reduce man-machine interaction force, thus improve comfort. [7] This soft exoskeleton, compare to the previous one, is much lighter and even portable. It suits the need for recovery training but loses the ability to self-support and provide protection.

Last but not least, taking one step closer to light weight and comfort, another soft cable-driven exoskeleton is made by a team from the Technical University of Munich. [8] For this exoskeleton, the focus is to simplify the design and improve comfort at the same time. The exoskeleton/ exosuit is a jacket made from elastic inlets and soft fabric with embedded tubing for cables. The course of the cable is in line with the bicep to mimic the force produced naturally by the muscle. The article states that the cable force required to move the forearm varies from 40 N to 15 N depend on the distance of the cable outlet to the center of rotation from 4 cm to 24 cm. This exoskeleton is on the extreme side of low-profile and light weight, thus loses in the area of power and functionality.

As for the actuation of the cable-driven system, another paper from the 2016 BioRob international conference showed a low-profile design. [9] The system uses a clutch mechanism that clutches onto the Bowden cables to save power in a static configuration. This design can also drive the exoskeleton's elbow joint in both flexion and extension with a single motor. The system has two series of elastic elements to solve the drawbacks and provide extra compliance. The paper states that friction caused by the Bowden cable may be a drawback of this kind of design, but a compensatory control system may solve this problem. Overall, the design of the actuation system is lightweight and small enough to be placed on the user's back, but the frame of the exosuit does not offer any structural support.

Based on recent literature like the articles above, a cable-driven system is often used in a lightweight exoskeleton to simplify the articulation and take advantage of soft frames. But to the knowledge of the author, not many cable-driven, self-supported exoskeleton with solid frame can achieve the level of low-profile like such soft exoskeletons. Thus for the purpose of innovation and closing gaps, this thesis project explores the possibility of making a low-profile, cable-driven, self-supported exoskeleton.

2.2 Methodology

2.2.1 Initial Concept

Based on the literature review, cable-driven is a tried and proven method to articulate a low-profile exoskeleton for rehabilitation purposes. But many of the exoskeletons using this method are whether heavy and bulky or use soft frames which do not offer support. It is understandable because of the limitation of material and manufacturing. But for the purpose of generating the initial concept, said limitation is ignored in order to visualize what an ideal low-profile exoskeleton can be.

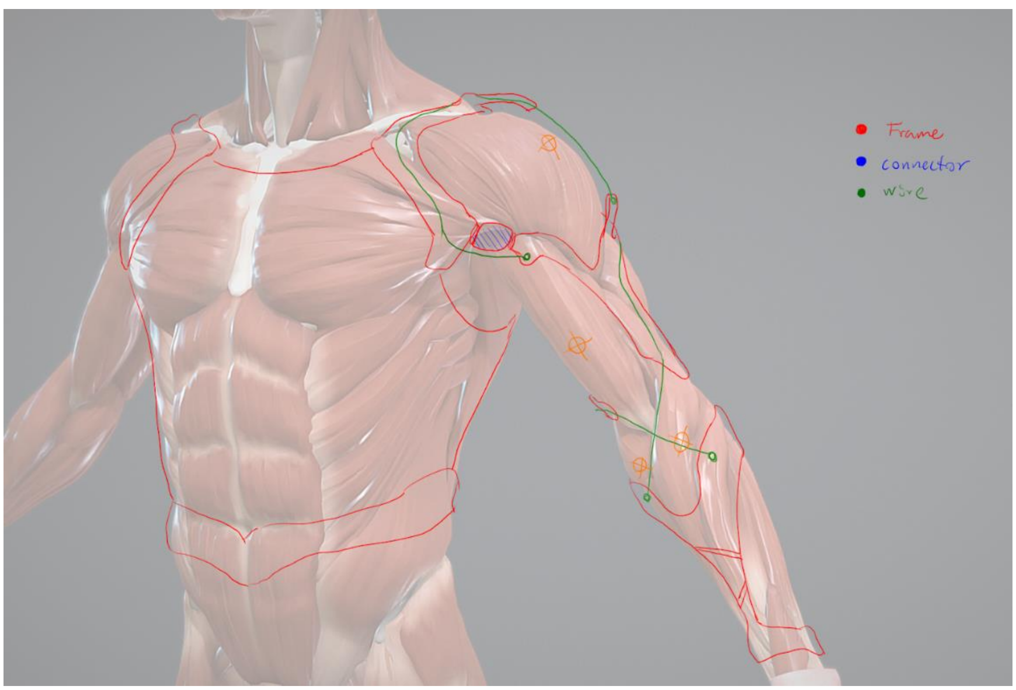


Figure 2. 1 Initial concept drawing, front

Shown above is the initial concept design. A 3D model is used for visualizing muscle groups, and color-coded lines are drawn on top of it. The design is mainly inspired by the exoskeletons from Soochow University and the Technical University of Munich. [7] [8] There are a few key differences: To provide support to the body, a solid frame shown in red is used instead of a soft jacket. The cables are embedded into the solid frame as much as possible to increase comfort and reduce volume. “Connectors” shown in the blue act as soft joints that are multi-directional.

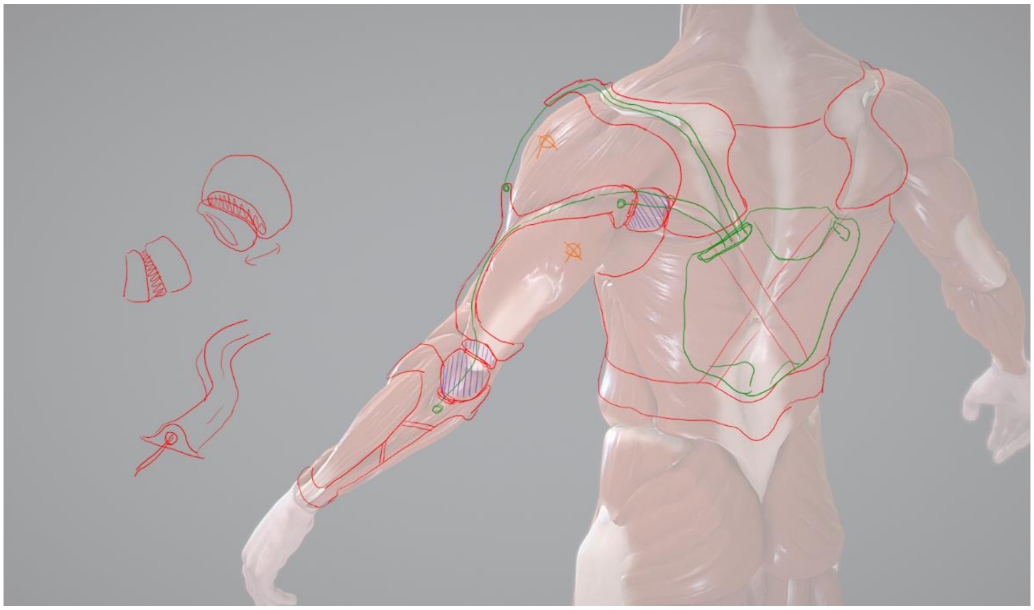


Figure 2. 2 Initial concept drawing, back

As shown in the drawing above, all the cables go through the shoulder frame and into the backpack where motors and batteries are placed. According to [7] , the lower back is the ideal placement for weighty components to distribute the load evenly. Another key aspect of this concept design is the course of the frames. Note that the frames generally follow the gaps between muscle groups. This is because, during flexion and extension, different muscle groups change shapes in different ways, due to the solid nature of the frame, it is best to avoid having solid structures blocking the enlargement of muscle groups. According to a study by Monica Rojas-Martinez [10], during various movements of the arm, three muscle groups give the most electromyographic (sEMG) signals: Biceps, Brachio Radialis, and Pronator Teres. Thus these are the areas the frames need to avoid the most. Another reason for this frame design is to leave space for the EMG sensors potentially used in the control or rehabilitation system.

Moving back to reality, this “ideal” concept design faces many challenges: The compact form factor of the frames is difficult to model and refine, the soft multi-directional joint is still an unknown at this point, and the materials and manufacturing method to support this design is not easy to find. This chapter will focus on solving the first challenge.

2.2.2 3D Scanning

In order to precisely model, the exoskeleton frame based on muscle groups, a 3D model of the user’s arm is needed. The user in this case is the author. The 3D scanner used is Sense 2, a handheld photogrammetry scanner.

Figure 2. 3 3D Scanned Arm Model, scanned using Sense 2

The left picture above shows the raw result from the scanner. By exporting the mesh data to Autodesk Fusion 360, a smooth body type model is generated. Note that during the scanning, the user held his fist tightly so that the muscle groups are more pronounced. Having the model of the arm, the next step is to design the shape of the frame.

2.2.3 Traditional Design

When designing the frame of a cable-driven arm exoskeleton, a common approach is to build a "cage" around the user's arm similar to the picture shown in [6]. But this design leaves a lot of space between the frame and the arm which is not ideal. To achieve a low profile and increase usability, the frame should stay close to the arm while avoiding main muscle groups. The picture below shows two early designs based on said principle.

Figure 2. 4 Traditional CAD design of forearm exoskeleton frame

For these two models, Autodesk Fusion 360 is used as the CAD tool. The point of making these models is to demonstrate what traditional ways of designing ergonomic pieces can achieve. Generally, the designer first needs to have some form of measurement, in this case, the 3D scanned model of the arm. Then based on the measurement, critical points are defined, for example, the elbow joint and whist. Next, ergonomic curves connecting those critical points are designed. Finally, 3D shapes are formed based on those curves. Many artists use this kind of workflow when making 3D models for art pieces because it gives them a lot of design freedom without worrying too much about physical properties. But in the field of the exoskeleton, safety is always the number one concern. With safety, comes a lot of design restrictions such as material strength, durability, and safety factors. Each design needs to be simulated and checked for potential safety issues. Thus it is very difficult to come up with an ergonomic design without many iterations of prototyping, testing, and redesigning. Because of the time limitation and manpower of this thesis project, the traditional design method is not suitable. A faster, more efficient way of ergonomic design is needed.

2.2.4 Generative Design

Although not an entirely new technology, generative design evolved dramatically in the late 2000s due to the improvement of AI and cloud-based computation. Now, designers can send the generative design files to the cloud super computers and the generated results will be done within a day. But the early days of generative design, it was mostly used for complex multi-criteria designs. The system needs a general design, often a CAD, and generates variations of that design by changing its many parameters. [11] The system then filters these variations based on properties like safety factor and cost, finally returns a limited number of designs for the user to choose. It is a very efficient way to generate and down-select designs at the same time. But the downside of this method is that the generated designs often do not deviate too much from the original design because it is simply changing existing parameters. Luckily, this disadvantage is solved by a recently developed new generative design workspace in CAD software like Fusion 360.

Unlike the old generative design, in Fusion 360, the initial general design becomes optional. This means the designer does not need to have an object-based model ready, and instead, only needs to provide the constraints and starting points. To demonstrate this, an illustration is provided below:

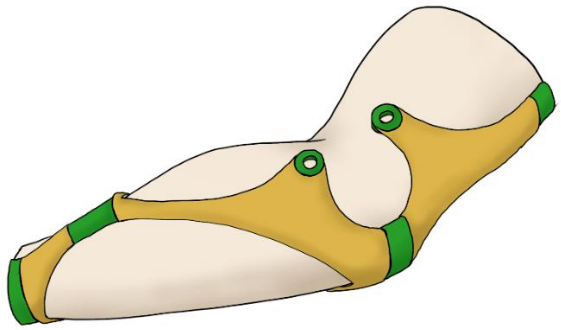


Figure 2. 5 Generative design example, arm exoskeleton

In this case, the goal is to design the arm exoskeleton’s frame without an initial design. The designer can specify the green areas as the starting points and input various load cases and other constraints. When prompted the software will generate the yellow sections connecting the starting points using the constraints. Instead of only changing parameter ranges, this method creates nearly the entire design model. Due to this process, the returned results are often very different from each other and specialized based on constraints, offering design aesthetics that are so intricate and mathematical that a human designer would never generate through an intuitive or manual CAD process.

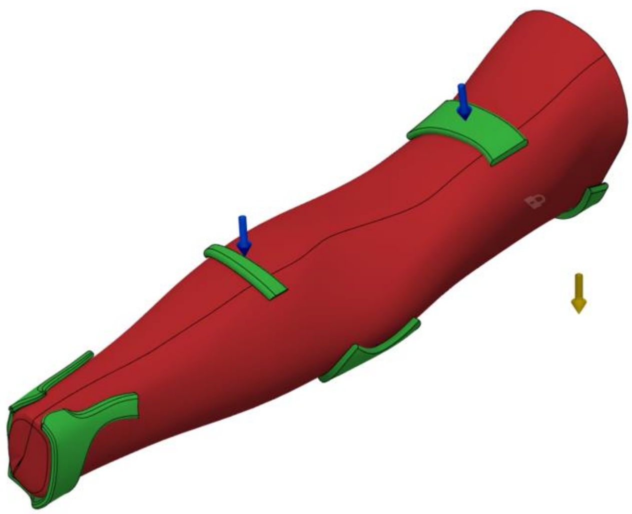


Figure 2. 6 Generative design setup, load case one

The actual generative design setup is shown above. The red part is a slightly enlarged model of the scanned arm with a multiplier (offset scaling) of 1.01. Because the red part (the place holder for a human arm) acts as a guiding obstacle, meaning no structure will be generated within it, how tight the exoskeleton fit can be controlled by changing the offset scaling multiplier to leave space for comfort. This is for the case of skin contact. If the user decides to wear clothes inside the exoskeleton, the multiplier needs to change accordingly. The green parts, just like in the example, are the starting points for the generation process. The returned model will keep the green parts and build upon them. The yellow arrow indicates gravity, which is not necessary for this study but is still shown for the sake of demonstrating the workflow. The lock icon means the surface or part acts as constrain for the loads. For this study, it is assumed the end of the exoskeleton is fixed. The blue arrows are the loads. In a single generative design, it is recommended to have multiple load cases to get the best result. Even include some minor forces to simulate unexpected loads in real life. In this study, six load cases are used based on [7] [12]. The optimized criteria is volume. The materials selected vary from ABS plastic, thermoplastic resin, and metals. Note that the position of the key green part for the upper arm is very close to the base, this is not efficient for torque generation. Also, this position is right on top of the bicep muscle group, it can cause discomfort if pressure is applied here. Later prototypes use a better design where the key part is closer to the center/ elbow joint. After the setup, it is a good practice to use the "preview" function to quickly generate a rough shape of the model to make sure the process is operating as intended. Once the setup is ready, all data are sent to the cloud server to be calculated.

The results are shown below:

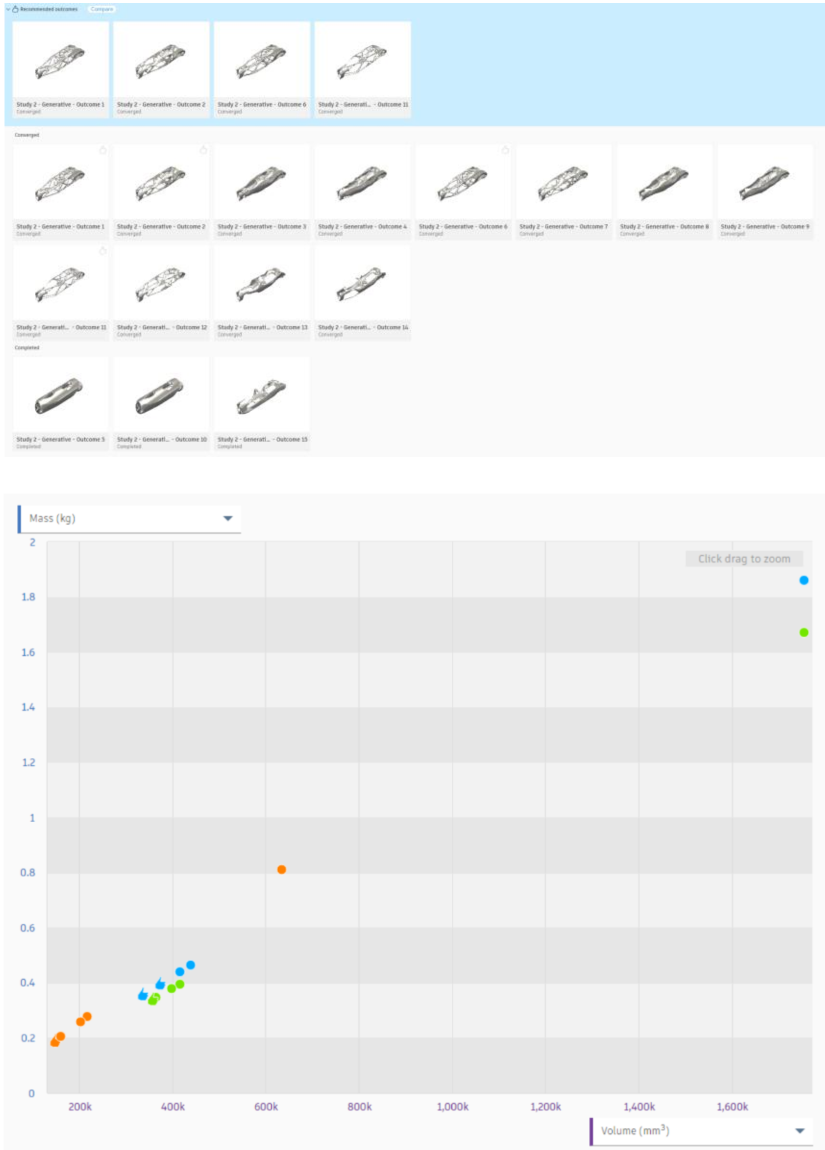


Figure 2. 7 Generative design results thumbnail and plot

On the top of *Figure 2.7* listed all the outcomes. It is difficult to evaluate them just by looking at the thumbnail pictures. In order to choose a specific model, the scatter plot function can be used to compare different parameters of the models. In this case, mass and volume are used as the axis for the plot. The most bottom left model is shown below:

Figure 2. 8 Best generative design model without outer boundary limit

This is the lightest and smallest design generated. Although the structure seems random, it is fascinating to see the similarity of this design to the exoskeleton design in [6]. Some common elements in traditional modeling can be seen: I beam at the end point, usage of triangle structures. The overall shape is very organic, almost looks like something found in nature, for example, tree branches or spider web. This might due to that during the process of generating designs, each iteration is just like the natural selection of creatures throughout millions of years. The process of naturally optimizing toward a general goal instead of improving parts of the design separately results in seemingly biomorphic skeletal designs that seem abstract yet tightly follow basic structural principles like three points support and I beam.

Figure 2. 9 Generative design model examples without outer boundary limit

More examples of generated models are shown above. It is interesting to see the different approaches to each solution. The upper left design uses a spiral structure for the forearm section with smaller beams connecting the main spirals. The upper right one uses large areas of material to cover the top and bottom, connecting them with beams forming many diamond-shaped openings. The lower left design is almost symmetric with curved support structures extending from left to right. The lower right one only generated support on one side, with thicker beams connecting the starting pieces. As shown here, similar to natural selection, there are many solutions that have their own reasons to exist. Generative design can provide solutions other than the textbook approaches commonly used by designers or engineers.

2.2.5 Prototype 1.0

In order to make a wearable prototype using generative design, a critical change is made to the setup: adding an outer boundary. Because all the results shown in the last section extrude away from the body too much, even though they are effectively light and durable, they are not low-profile. The outer boundary shown on the left in *Figure 2.10* will prevent the model to be generated more than 9 mm away from the body. Red blockers are also set at the areas around the triceps and biceps so the exoskeleton frame will not block the enlargement of those muscle groups during movement.

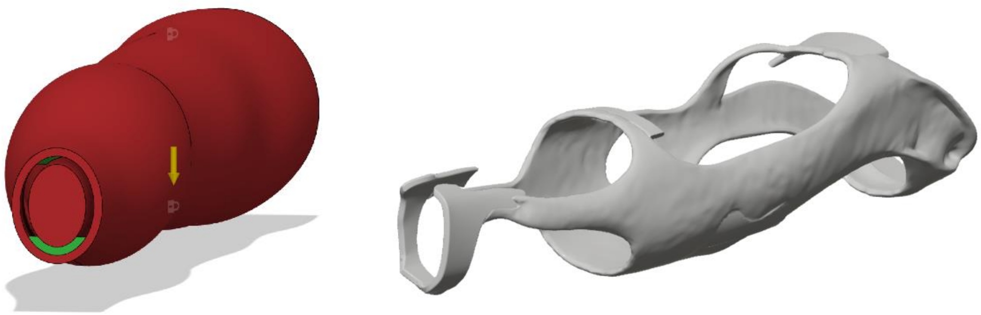


Figure 2. 10 Generative design for prototype 1.0

The best generated result is shown on the right. Because of the limitation of space, this model forgoes the tree branch structure and instead uses a smooth and continuous layer covering and connecting the key/starting points. Using this model as the first prototype is totally viable, but like mentioned before, this project also takes the aesthetic aspects into account. In that regard, this model's rough surface is undesired and unnecessary, some of the curves can also be simplified into three-point curves which are more pleasing to the eyes. Based on these principles, a redesign is made, shown below:

Figure 2. 11 Redesign and render of prototype 1.0

This manually modeled design follows the shape of the generated model, improving the aesthetic without deviating too much from it. One key change is that an opening is added to the elbow area. This is because of the joint design which will be covered in the next chapter. Note that the gray areas indicate solid material, the white areas indicate semi-soft material, and the transparent parts indicate more flexible material. To better visualize this design, an art render is shown on the right in *Figure 2.11*.

Figure 2. 12 Prototype 1.0

Show above is the first prototype. The gray parts are 3D printed using polylactic acid (PLA). The orange parts are cut from a rubber fabric. The purpose of this first prototype is mainly for fit testing, so the rubber part is fixed using short screws which can be removed and reapplied easily for adjustment. The pictures of the author wearing the prototype are shown below:

Figure 2. 13 Fit testing prototype 1.0

For fit testing, the author wore the prototype throughout the day, doing many kinds of activities: walking, lifting boxes, sitting down typing, and even sleeping. Because of the subjective nature of fit testing, all following findings are based on the author's personal experiences. First, the exoskeleton never slipped out of the arm but did sometimes rotated to an uncomfortable angle, especially the upper arm. Second, the orange strip on the upper arm is pushing the bicep noticeably during lifting movements. Third, the solid parts near the elbow joint make connect when the arm is fully folded, which blocks the movement and can potentially damage the exoskeleton and the user. Last, some area of the exoskeleton in the upper arm covers too much skin which is uncomfortable yet other areas are too thin and have the risk of breaking. Based on this feedback from the fit testing, prototype 1.5 is made.

2.2.6 Prototype 1.5

Figure 2. 14 Prototype 1.5 model

Shown above is the model of prototype 1.5, which addresses all the problems found during the fit testing. Detailed comparison to the first prototype is listed below:

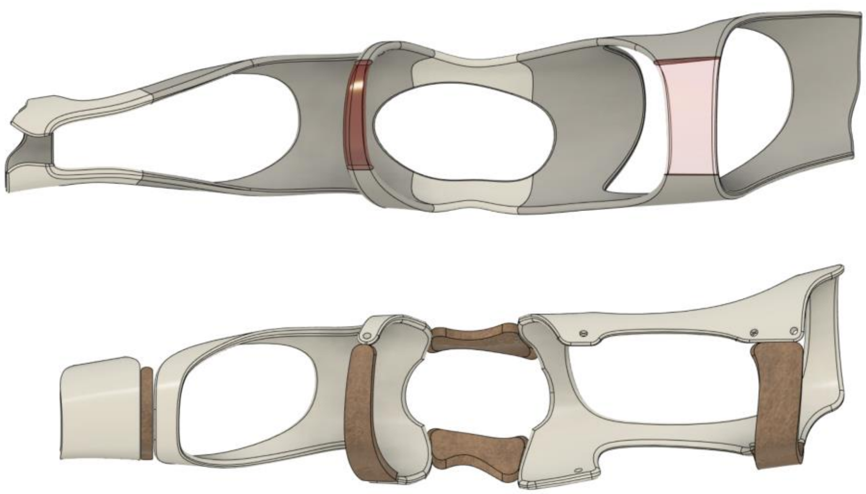


Figure 2. 15 Prototype 1.0 (top) vs 1.5 (bottom). Top view

From the top view, note that the dimeter of the forearm section is increased so that the user will have enough space when rotating the wrist. This section is also connected at the top to better secure the forearm. The flexible strap on the upper arm is moved toward the end to leave space for the biceps. An additional strap near the elbow is optional depending on the types of joints which will be covered in the next chapter. Also, many unnecessary large areas are reduced for better comfort.

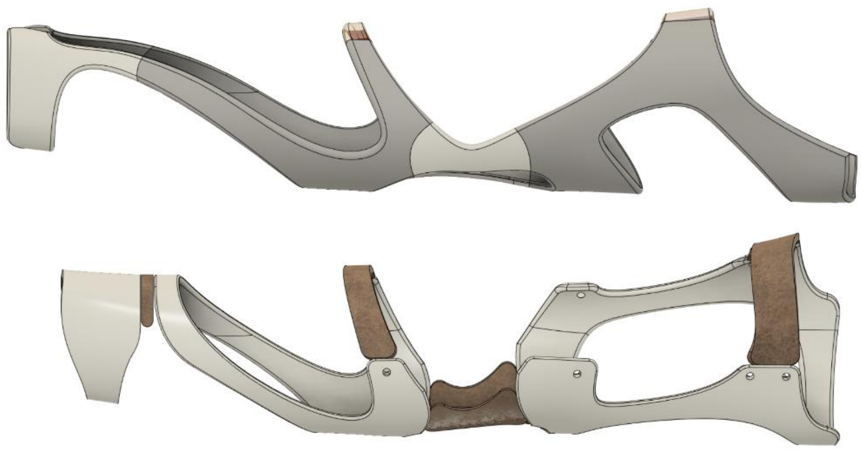


Figure 2. 16 Prototype 1.0 (top) vs 1.5 (bottom). Side view

The side view shows the redesigned shape near the elbow. There are no longer sharp corners near the joint and more space is created for full flexion. Note that the additional area for the optional strap will also act as space for anchor points of the cables.

Figure 2. 17 Prototype 1.0 (left) vs 1.5 (right). Front view

From the side and front view, note that the openings for the straps are increased and the positions of the straps are rotated about 35 degrees for the forearm and 45 degrees for the upper arm. The original angle is more symmetric which looks better but does not agree with the human anatomy, thus created discomfort and the rotational slip during fit testing. The new prototype also removes the wrist guard part due to the time and scope limit of this thesis.

Figure 2. 18 Fit testing prototype 1.5

As shown in the pictures above, prototype 1.5 fits considerably better compared to the first prototype. Note that this version is not connected at the elbow joint for the sake of studying the joint behavior in the next chapter. During the second fit testing, the exoskeleton never slipped. The redesigned straps distributed the interaction force between the body and the frame evenly, greatly improve comfort. The open areas near the biceps and triceps leave space for muscle enlargement and give more room for the skin to breathe. Interestingly, this prototype 1.5 has a lot in common with the generated designs without an outer boundary from *Figure 2.9*. Elements like the U-shaped hoke for the forearm, the unsymmetrical upper arm frame are inherited from those designs. It is fascinating how the generative design foreshadowed some of the design changes.

2.3 Summary and Discussion

In this chapter, the literature review showed promising results using a cable-driven exoskeleton for rehabilitation. But it also showed the lack of a low-profile exoskeleton that can provide support. Thus said exoskeleton became the goal of this thesis. The initial concept design faced many challenges, and this chapter focused on solving the first one: An exoskeleton frame that is compact and ergonomic. Traditional CAD modeling was not suitable for ergonomic designs due to the inefficient redesign cycles. The generative design was used for its ability to meet complex constraints and various parameters. The results from generative design showed fascinating resembles natural structures like tree branches. By adding outer boundary and blockers, a model that suits the need of the project is generated. After some aesthetic and functional modifications, two prototypes are 3D printed and tested for fitting and comfort.

Generative design is a powerful tool if used correctly. Based on the experience of this study, a few recommendations are listed below: First, the starting points are critical to the success of the generating process. Too few points may lead to over-complicated designs or unexpected parameters. Too many points can limit the design freedom and generate fewer designs. A good strategy is to have a manually designed model, only keep the load-bearing parts and cut the rest of the structures. Second, it is a good practice to do a few iterations without setting all the constraints. As shown in this chapter, generated models without all the constraints may not be useable for the final design, but they often provide interesting approaches to solve the problem which can inspire the designers. They can even foreshadow some design changes for the final product. Third, take advantage of the design selection functions like the scatter plots to evaluate and choose the generated results based on different parameters. Last but not least, the generated designs are not often used directly due to aesthetic or manufacturing reasons. Modifications and redesigns are usually required for the final product. But as the technology evolve, maybe aesthetics can be added as constraints or parameters in the future so the generated designs will be suitable for direct production.

Generative design is a relatively new design method. It leaves much space for future studies. For example, mixed material generation. To the knowledge of the author, all generative designs now only offer single material for each design. This means a piece can only contain one material. Another area that can be improved is the load case setup. The current setup is very elementary with mainly forces and pressures. Ideally, constraints like temperature and moisture should be added to the setup. Also, the current generative design is only capable of generating static parts. Thus in this study, the moving joint design had to be done separately without its aid.

In conclusion, generative design has great potential as AI and cloud computation keep evolving. The author encourages more engineers and designers to learn and use this wonderful tool to improve their products in the future.

3. Chapter 2: Joint Design

3.1 Literature review

Following the completion of prototype 1.5, the next step is to design the elbow joint that connects the upper arm and forearm. Based on previous literature review and the concept design, the out-of-body rotational joint is not suited for the low-profile aspect of this project. Thus bag the question: what kinds of joints can have low weight and volume, and at the same time, are comfortable to wear and provide support? To look at some of the solutions, three papers are reviewed in this section.

First, a group from Xi'an Jiaotong University studied arthropod joints and modeled human-robotic joints based on that. [13] This article shows that traditional monocentric fixed-axis joints for exoskeleton do not suit human joints because human joints are polycentric. Based on the article, N-bar linkage can better replicate the bionic motion of humans, but the high number of links can result in loose structure and low stability. To find a better solution, the article shows that arthropod joints and their locomotion can be used for human-robotic joints. Said joint has solid femur and tibia touching each other at conjugate surfaces, with a flexible connecting body on top of the touching surfaces. The curve of the rotation motion can be modified by changing the curve of the touching surfaces. Using this method, a prototype joint model is made and tested. The result shows that the arthropod joint can produce the same motion trajectory as the N-bar model, with the benefit of better structural stability on top. This article shows an interesting approach to exoskeleton joint design, inspired by actual exoskeletons from animals and insects. The combined usage of soft and solid material is also inspiring. The ability to modify the motion trajectory can be useful when designing for different human joints. Even though the prototype made in this paper was not lightweight nor low-profile, using soft material and cable instead of a linear motor may be a solution.

The next paper from Embry-Riddle Aeronautical University studied living hinges using additively manufactured ABS. [14] A living hinge is where bending is achieved by creating a thin section of plastic between more rigid regions. This paper shows detailed tensile test procedures for additive manufactured parts. Based on the testing results, the 3D-printed parts showed brittle behaviors due to micro voids created during the manufacturing. Similar tests are done later in this chapter based on the procedures in this paper. Because most of the prototypes and joint parts are made via additive manufacturing in this thesis project, it is important to know the limit and imperfection of the process.

The last paper is from Acta Mech. [15] This article introduces the idea of kerfing, a relief cutting method that creates flexible freeform surfaces from stiff panels. Interlocked Archimedean spiral patterns are used for unit cells that cover the panel. Physical property tests are done for various patterns and cut densities. The low-density cuts returned the stiffest response. This paper shows the potential of kerf cutting, by varying the pattern and its density, different physical properties can be achieved on the same piece of material. This can be helpful if incorporated into the design of exoskeleton joints or even frames. Because the human body changes shapes while moving, having different stiffness at different areas without using separate pieces or additional material can improve comfort and simplify the design at the same time.

Based on these articles, this chapter will validate and incorporated some of the ideals into the joint design for the arm exoskeleton.

3.2 Methodology

3.2.1 Traditional joint design

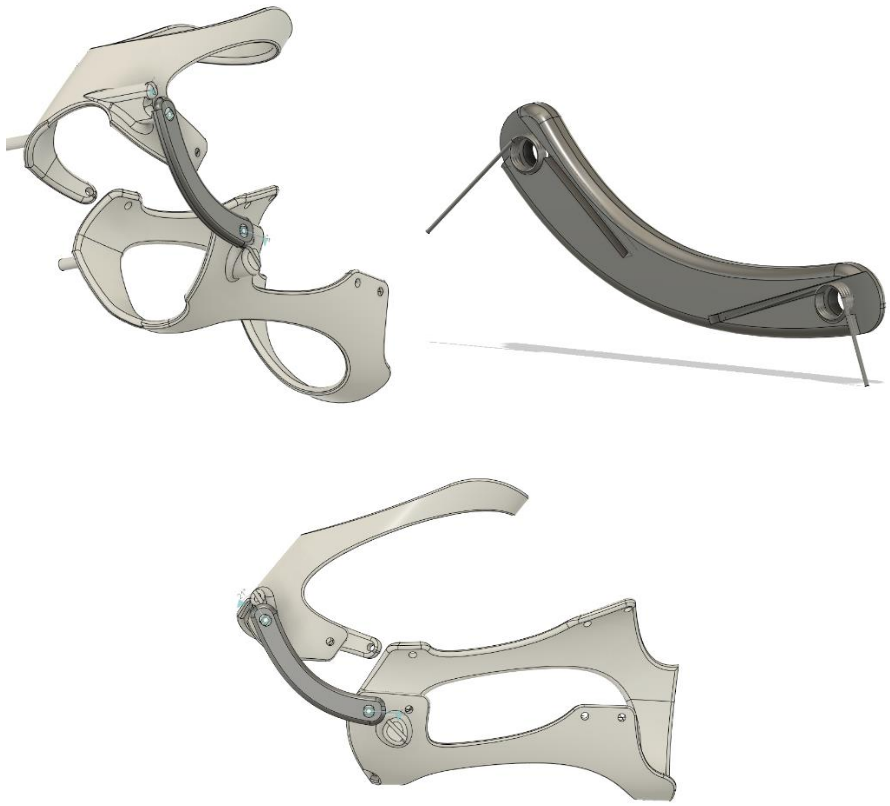


Figure 3. 1 Traditional joint design

Just like the traditional frame model shown in the previous chapter, a traditional joint design is made for comparison. Based on [13], the human elbow joint is polycentric, so a double rotation joint linkage is used. Two weak torsion springs are embedded at the joints in the linkage so the exoskeleton will go back to its natural position when the cables are not powered. The linkage is snap-fitted onto the two exoskeleton frames, securing the torsion springs into the slots at the same time. Note that additional ball bearings can and should be added to the joints but are not modeled. Even with this very compact design, the joint still extrude about 25 mm away from the body which is not ideal. If the user wears the exoskeleton underneath clothes, the fabric can get caught in the joints and create safety issues. Due to these disadvantages of traditional joints, this model is not manufactured nor tested. But if future studies have more time and budget, an improved design based on this model should be fit tested for comfort and safety.

3.2.2 Material for kerf cutting

Figure 3. 2 Common kerf cutting usage, Image downloaded from Google Image

Based on the literature review [15], kerf cutting is often used for small degree plane manipulation or permanent bending as shown above. The material is wood in most cases. In order to make use of kerf cutting in an exoskeleton joint design, redesigns and tests are needed. First, the material. Due to the time and budget limitation of this thesis, the author's interest in additive manufacturing, as well as considering the designs listed in the next chapter can only be achieved via AM, materials commonly used in AM took priority. Because of the repetitive bending nature of the elbow joint, fatigue becomes the number one concern. Based on a recent study [16], softer materials like TPU and PCU are less affected by fatigue. The study also shows that the softer versions of the same material retain better strength under fatigue. Another important finding from this study is that among the printing parameters, the infill raster orientation influences the fatigue life the most. A 45-degree cross pattern infill shows the best result. For strain and stress, a study from RMIT university [17] shows that the linear behavior region of TPU ends around 3 MPa stress and 20% strain. Based on the above literature and the availability of 3D printers and filaments, TPU is chosen for the kerf cut joint design.

3.2.3 TPU printability

Prior to the designing and testing of the TPU joint, the printability for this less commonly used material needs to be tested.

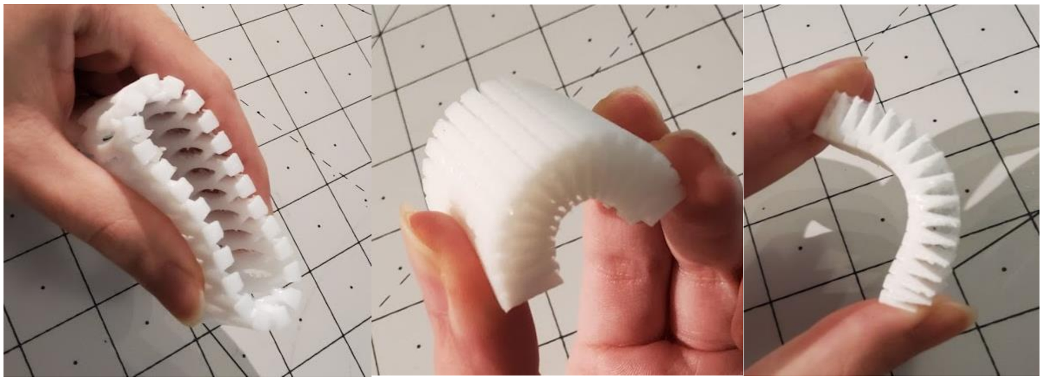


Figure 3. 3 TPU print parameter testing parts

Shown above are some of the test pieces used to refine the print parameters. The printer used is a modified Ender 3 pro, a common material extrusion 3D printer. The author modified the feeding gear and tubing in order to print TPU material. Unlike ABS or PLA, the TPU filament is softer so it can slip out between the feeding gear and tube. It is recommended to monitor the first few prints using TPU in case this slipping happens. The following section will list all-important print parameters and recommendations for future studies to reference. Layer height: This highly depends on the printer, but 0.12 mm is recommend due to the balance between the print time and quality. Shall: This setting can affect the stiffness of the piece dramatically. If the piece has low infill and should act as a uniform soft material, a 1 to 2 wall line count is recommended. But if a good surface finish is required or the piece has a high infill, 3 to 5 wall line count should be used. Infill: The percentage totally depends on the application but different patterns suit different situations. Grids and Lines suit thinner parts where the load is applied on the flat surface. Cubic and Octet suit bigger parts where loads are applied from the XYZ axis. The gyroid is mostly used in organic designs. Temperature: the print temperature for TPU should be between 200 to 230 degrees Celsius, the bed temperature between 60 to 75 degrees Celsius. Decrease print temperature if there is too much stringing. Increase the bed temperature if the part warps at the build plane. Print speed: Infill speed is best set at 30 mm/s which is a lot slower compared to that of PLA or ABS. Wall speed should be half of the infill speed at 15 mm/s. Travel speed needs to be high at around 120 mm/s to reduce stringing. If the base of the part is not secured to the build plane, consider decreasing print speed for the first layer. Retraction is usually not recommended but TPU can cause a lot of stringings, use the following setting only if stringing becomes an issue: retraction distance of 4 mm, retraction speed at 35 mm/s, and retraction prime speed at 15 mm/s. Combing Mode is highly recommended, it will limit the travel to the inside of the part so that most of the stringing happens on the inside wall. This can greatly reduce stringing and improve the outer surface finish. Support, depending on the part but generally, TPU requires lower support overhang angle and higher support density due to its softness. Cooling, print cooling fan should be set to low or disabled, minimum layer time at around 10 seconds depend on how big the part is. This is because TPU should be cooled slowly to reduce layer separation. [17] Note that all recommendations above are based on the authors' limited test pieces and machines. The numbers should be used as references, not guide lines.

3.2.4 TPU arthropod joint

In the study of the arthropod joint [13], the finger model prototype frame was made of hard plastic. In the place of soft tissues of the arthropod joint, a linear motor is used as linkage and also acted as the actuator. This design is far from the organic structure of the arthropod joint and is built only for testing. With the power of printable soft material like TPU, this thesis proposes another design for the arthropod-inspired joint.

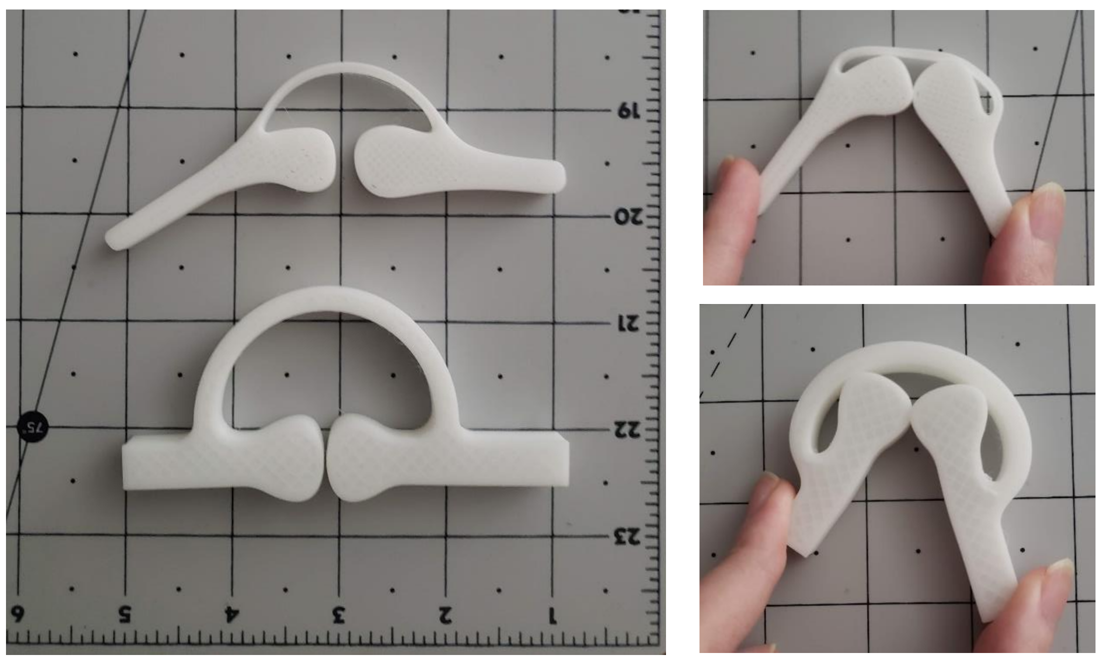


Figure 3. 4 TPU arthropod joint 2D extrusion

Shown above are two simple printed joint models. The top one uses the 2D profile in the paper [13]. The connection bridge is too thin so it does not provide any support, the radius is also so small that it prevents further flexion. To address these issues, a modified profile is used shown on the bottom. By increasing the thickness and radius of the bridge, the joint can now self-support and the flexion angle is also increased. Note that these models are simple extrusions from a 2D profile using TPU to prove the concept, a more sophisticated design is needed.

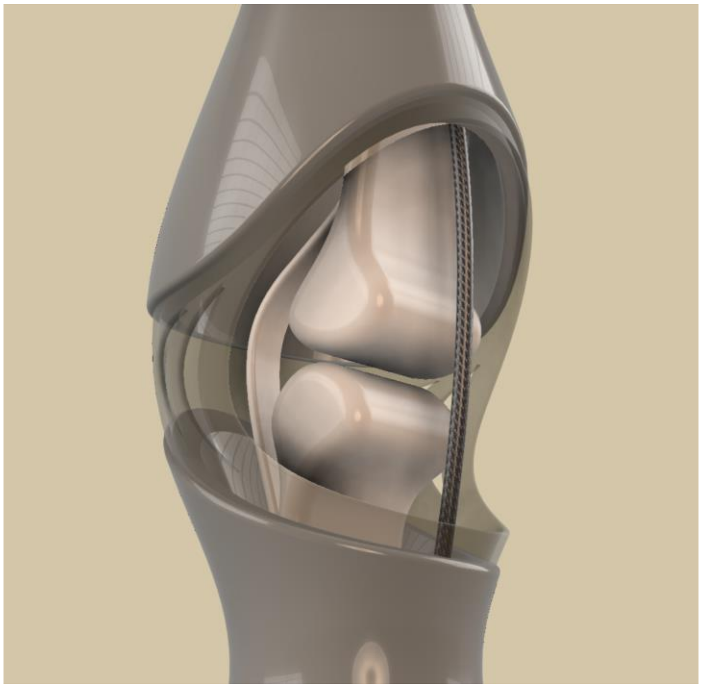


Figure 3. 5 Arthropod joint redesign

Shown above is a potential redesign of the joint. The joint model in light color is surrounded by an exoskeleton just like the structure of a crustacean joint. The transparent middle part indicates soft material like TPU or rubber, connecting the exoskeleton. A cable goes through the opening side for articulation. Because of the requirement of having structures at the center of rotation, this joint design suits the need for lightweight and soft robotic, not so much for the human exoskeleton. Note that it is possible to use the outer shell as the conjugate surface for rotation but that method is not discussed in the paper and is beyond the scope of this thesis. Base on this joint, future studies can focus on the design of an arthropod-inspired exoskeleton for humans.

3.2.5 TPU kerf pattern testing

After the print parameters for TPU are refined, the next step is to test different kerf patterns using 3D printed TPU pieces. Inspired by traditional cutting patterns commonly used for wood work, the TPU test block’s design is shown below:

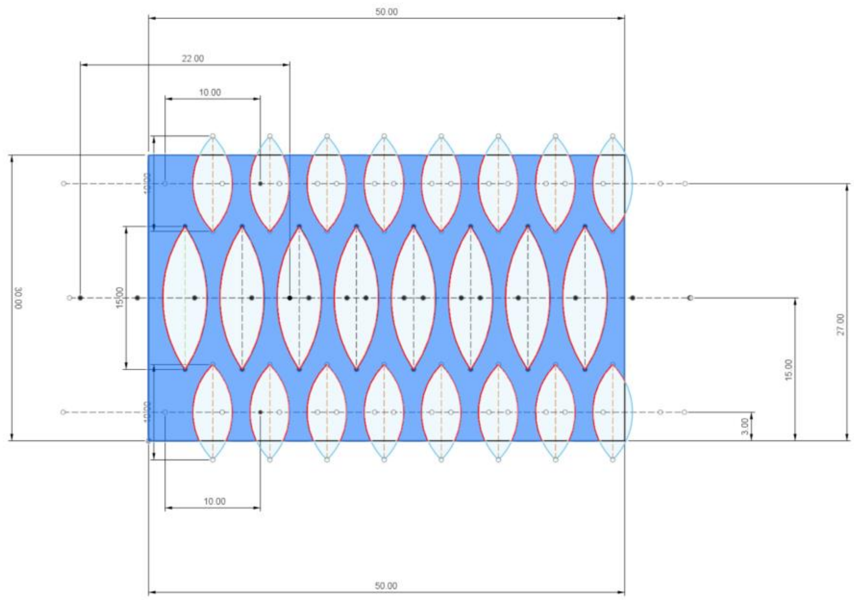


Figure 3. 6 TPU test block base dimension

This 2D sketch acts as the baseline for the testing blocks, all labeled dimensions can be modified including the thickness by extruding this sketch. All numbers are in millimeters. There are three properties of the kerf cut that need to be tested: Cut size, meaning the size of the opening. Note that the position and number of cuts are kept the same. Cut density, in this case, the horizontal distance from cut to cut. Part thickness, the extruding distance of the sketch. Three test pieces for each property are printed using the recommended method from the previous section, with 50% Gyroid infill. Based on the method in [17], tensile strength tests are done using the Instron machine. Note that to the knowledge of the author, there is no suitable testing standard for kerf cut pieces using soft, 3D printed material, so some of the parameters of the test had to be educated guesses from the author. For example, based on the ASTM D638 Plastic Tensile Strength Test standard, the extension rate should be from 0.05 to 20 inches per minute and the break time should be from 30 seconds to 5 minutes. Considering the soft and hollow nature of the test pieces, the extension rate is set to 15 mm per minute. Also, note that the test's goal is to study the behavior of kerf cut on the soft material way before the breaking point. All tests are stopped before breaking when the shape of the kerf cut stopped changing.

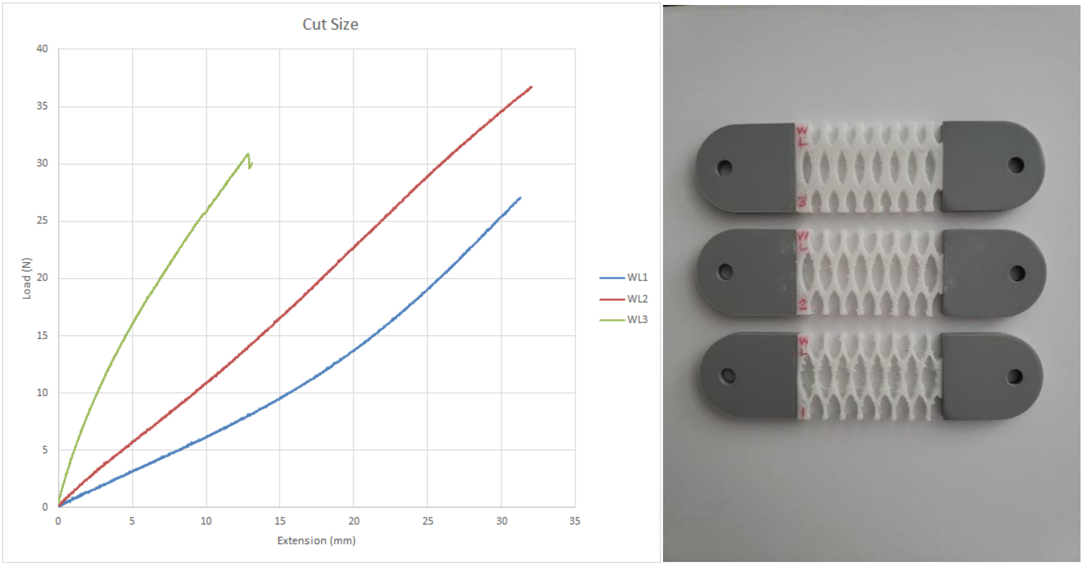


Figure 3. 7 Cut Size tensile test result

The cut size test shows interesting results where the larger cut samples number one and two have similar curves, but smaller cut sample number three behaves differently. It is later found that this is because the middle cuts and side cuts of number three did not bite into each other, creating a line of the area that goes through the entire test piece without affected by the cuts. As a result, the curve is closer to the solid test piece shown later in *Figure #*. Comparing number one and two, number two's curve is almost linear throughout the test while number one starts at a lower angle but becomes parallel to number two toward the end. One possible explanation is that the before the parallel region is where deform caused by the cuts happens, and the parallel region indicates where deform is caused by the extension of the material itself. If this hypothesis is true, one can control the strain-stress curve by modifying the kerf cut which can be useful in many applications.

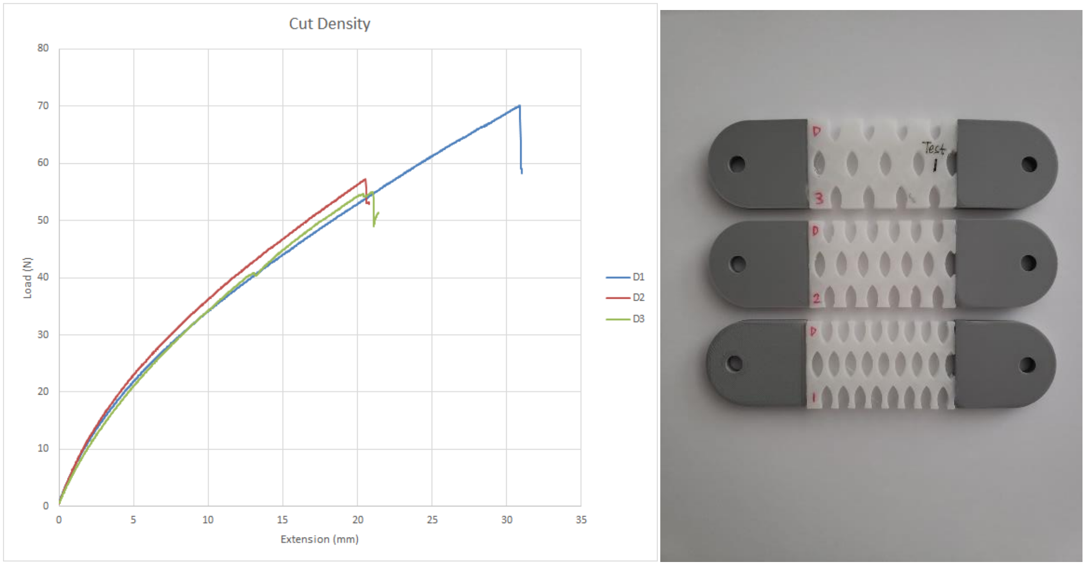


Figure 3. 8 Cut Density tensile test result

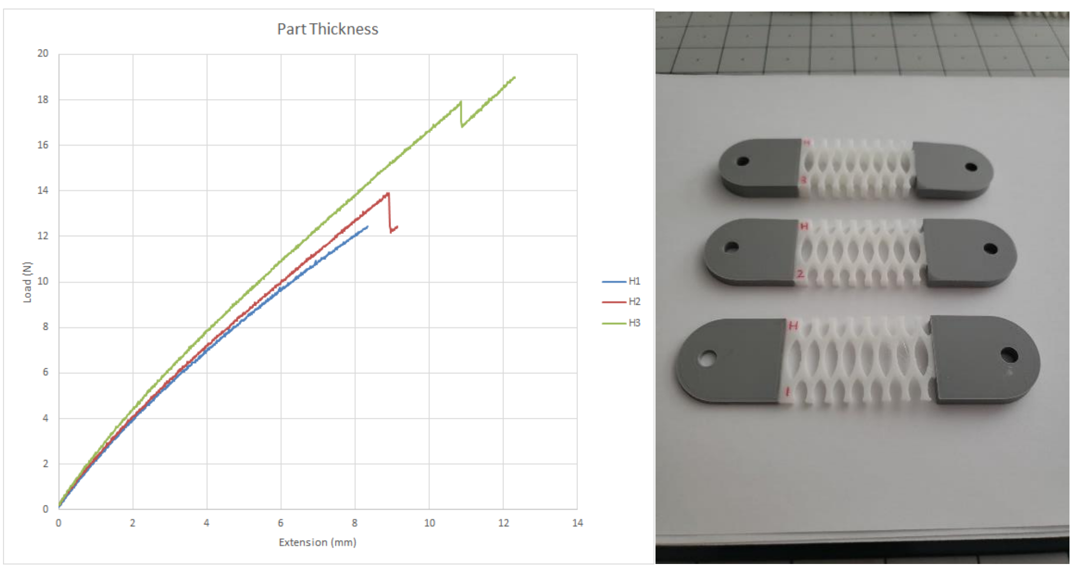


Figure 3. 9 Part Thickness tensile test result

As shown above, the cut density and part thickness have a minimum impact on the stress-strain curve. But this result may be affected by the same fact that the cuts are so small that they do not overlap. To address this concern, an additional test is done.

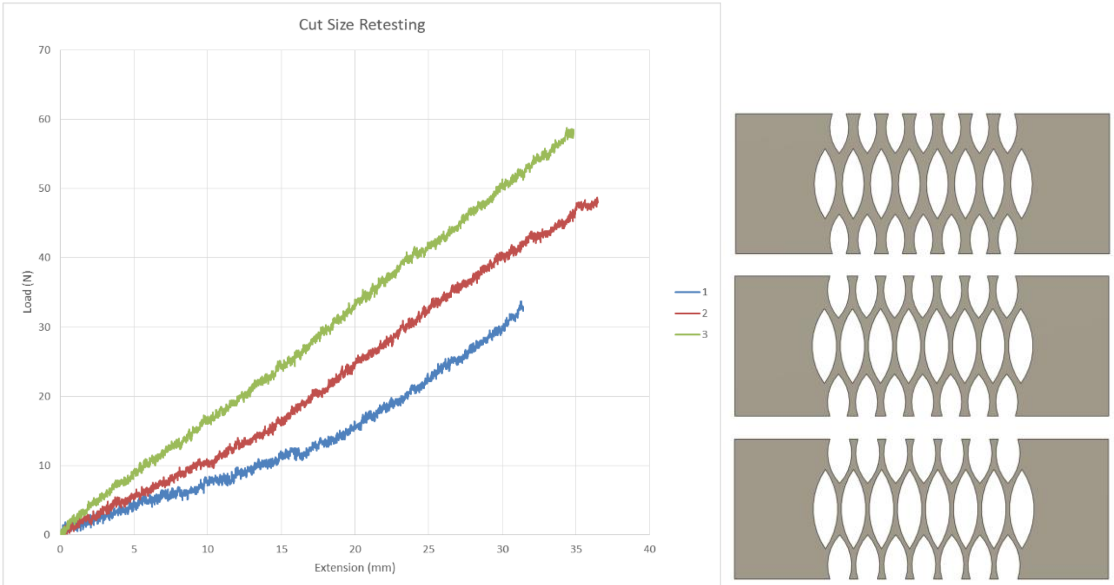


Figure 3. 10 Cut size retesting result

For this retesting, the middle cut is extended slightly vertically so that the tooth overlaps with those of the side cuts. From the plot, it is safe to say that the hypothesis from *Figure 3.5* is correct. The less the tooth overlap, the less linear the stress-strain curve becomes for the initial part but ultimately becomes linear and parallel when the deform is caused by material extension rather than the kerf cuts.

Figure 3. 11 Non-kerf cut comparison plot

To further prove this hypothesis, a solid test piece without any kerf cut is shown above as number five. The non-overlapping piece from the first test is also shown here as number four. From this plot, the stress-strain curve transitioned from the traditional downward curve to the upward then linear curve. The author believes that it is possible to fine-tune the kerf cut pattern to cover the entire range from number one to five.

Another property of the Kerf cutting sample is buckling when compressed. For the compression test, the same samples from *Figure 3.10* are used.

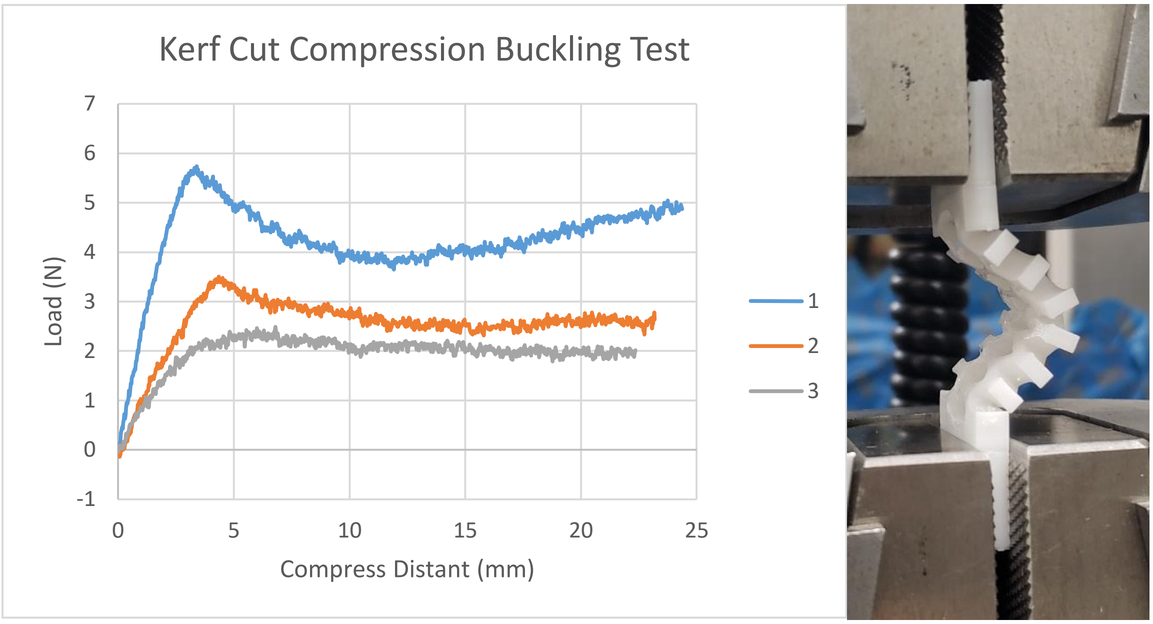


Figure 3. 12 Kerf Cut Compression Buckling Test

For comparison to the extension test, Young's modulus of sample 1 is calculated based on *Figures 3.10 and 3.12*. The Young's modulus is about 0.58 N/mm^2 for extension, 0.73 N/mm^2 for compression before buckling, which suddenly drops and decreases to 0.09 N/mm^2 after buckling. Note that the shapes of the trajectories for all three samples are different. For number 1 and 2, there are clear sudden drops of loads when the buckling reaches the critical point shown in the picture above. While number 3 (the largest cut sample) has a smooth transition. Also, for number 1, the load starts to steadily rebound at around 10 mm of compression while the loads of number 2 and 3 do not. Given the limited scope of this thesis, future study is needed to explain these inconsistent buckling behaviors.

When used as the elbow joint, the sideway buckling of the kerf cut piece can be a good feature to accommodate muscle sideway extension, given the piece is under compression. But it will only be helpful if the sideway buckling can be controlled and limited. One potential solution is by having gradient cut sizes along the y axis, this design may be able to fine-tune the stress-strain curve and limit the direction and degree of sideway buckling.

To simulate the bending when used as the elbow joint. A bending test is done, shown below:

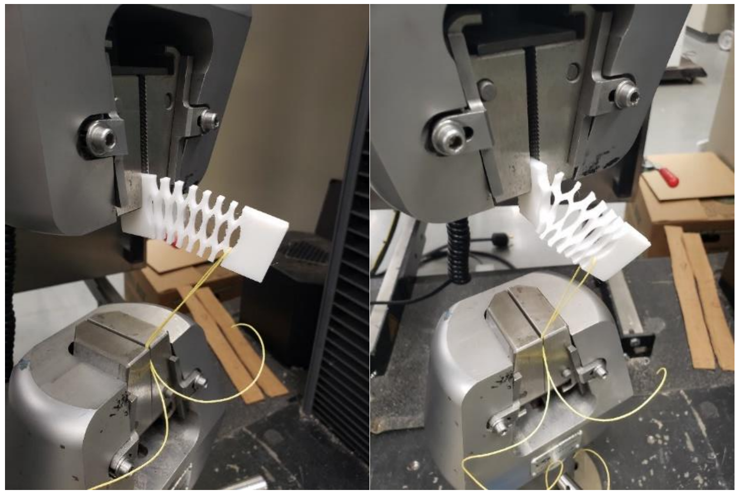


Figure 3. 13 Kerf Cut wide side bending test setup

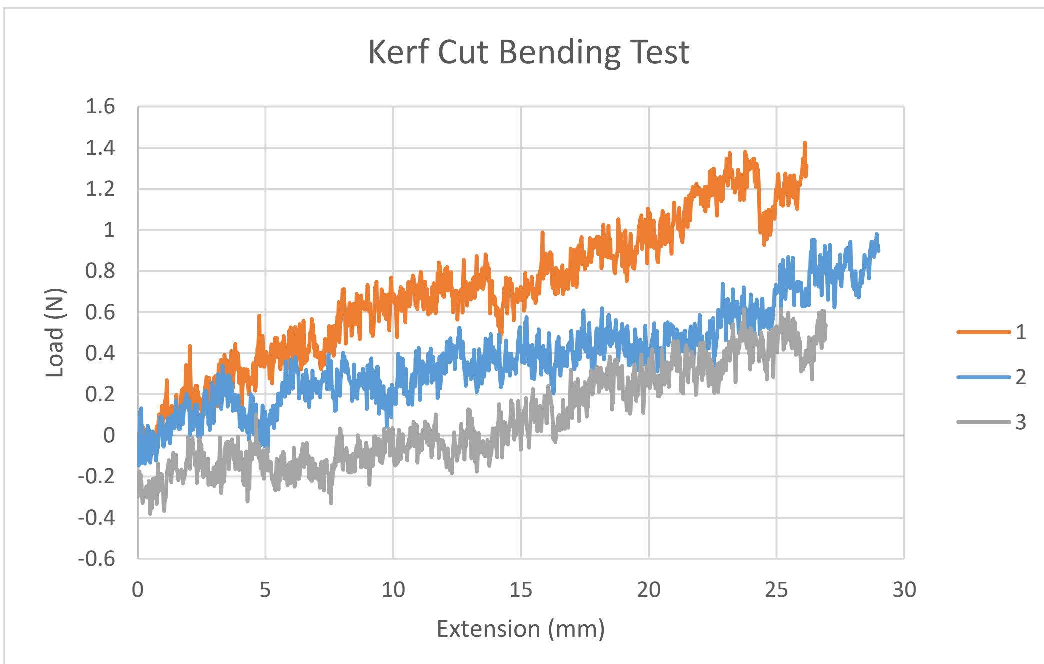


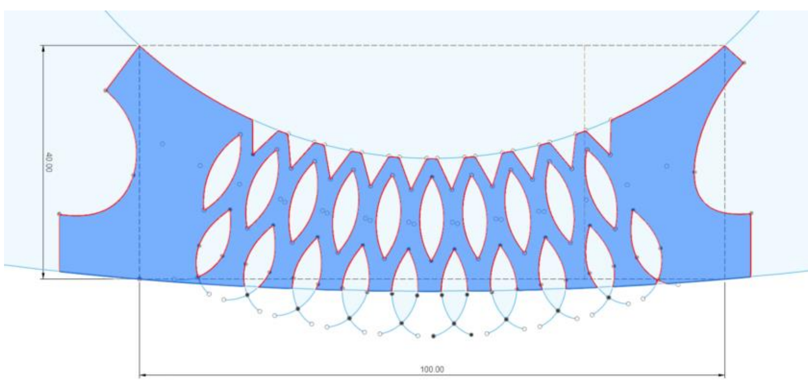
Figure 3. 14 Kerf Cut wide side bending test plot

Note that due to the unideal setup, the test sample bends sideways when pulled by the string. This means the 5mm thick sample does not provide much support in the thin direction. *Figure 3.14* shows a similar result to the extension test, larger cuts result in better flexibility. However, in order to get the bending data solely in the wide direction, future study with a set up limiting sideway bending is needed.

The tests showed the great potential of kerf cutting. The physical property of a material can be modified by changing the cut pattern. The delayed linear stress-strain behavior can also be helpful in the field of compliant mechanisms. But due to the limit of this thesis project, the quantity and quality of the tests are compromised. Future study is recommended to further test different patterns and material combinations.

3.2.6 Prototype 2.0

The purpose of this prototype is to connect the forearm and upper arm frames with an appropriate joint, as well as testing the ability to articulate the exoskeleton using cables. Using the kerf cut tests as references, the joint design is shown below:



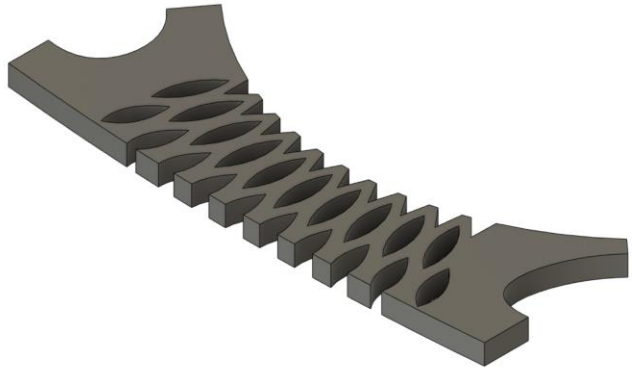


Figure 3. 15 Prototype 2.0 joint design

The natural position of the joint is when the arm is extended at a slight angle. So the kerf cuts, in this case, are arranged along two curves. The inner curve has smaller radios than the outer curve because during flexion, the inner side is under compression and the outer side is under tension. This joint piece can easily bend sideways which may improve comfort but loses the support function in that direction, but when used on both sides of the elbow joint with the cable system, this bending no longer occurs. Without knowing this solution, an alternative joint is designed:

Figure 3. 16 Alternative joint design

This design uses the same kerf cut pattern but adds a slight curve to the inner surface shown on the right. The curve will make it fit onto the exoskeleton frame better because, unlike previous designs, it is a lot thicker to prevent too much bending sideways. This design should use 100 percent infill when 3D printed to provide additional structural support. Although not used in this study, this bulkier alternative can be used in more robust applications like hip or leg joints.

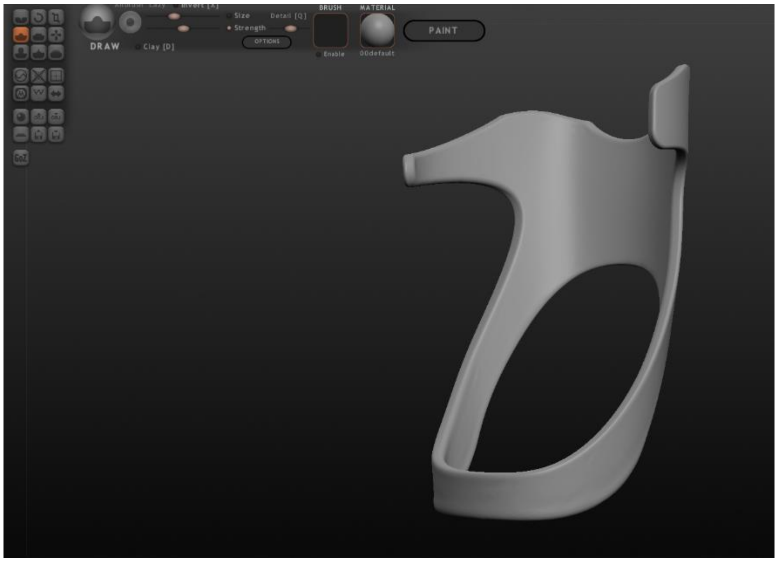


Figure 3. 17 Shape modification using Sculptris

To further improve fitting and comfort, minor adjustments are made to the shape of the frames using Sculptris software. Sculptris is a mesh editing tool usually used for 3D model sculpture. It allows free hand modification which is very difficult to do in CAD software like Fusion 360. The final model is 3D printed using wood PLA:

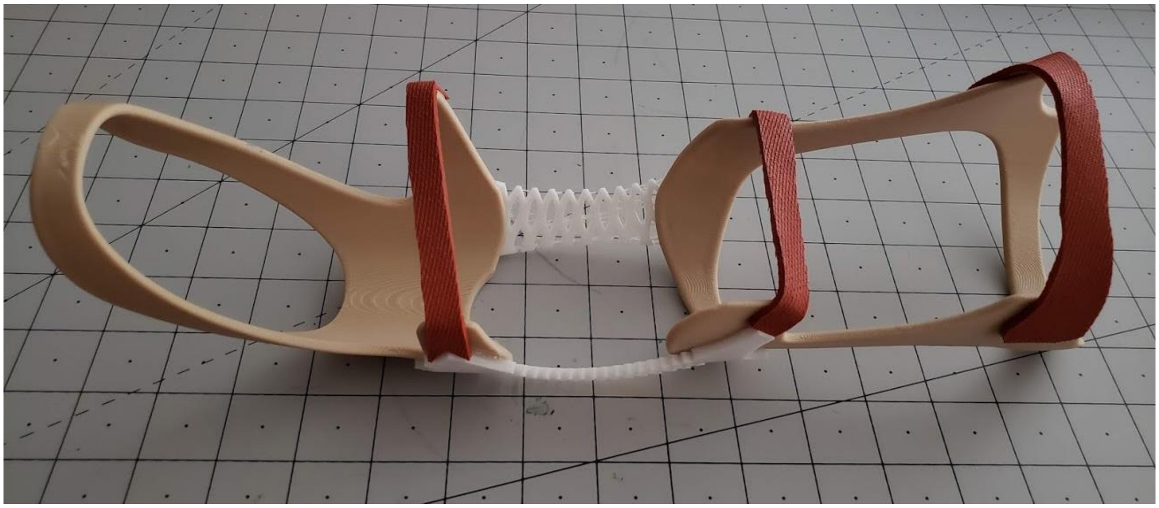


Figure 3. 18 Prototype 2.0 without cables

The set of joint pieces is glued onto the frames while the author is wearing the frames to ensure they are in the correct positions. The same rubber fabric is used for the straps. The wood PLA material is very fascinating, it contains about 70% PLA and 30% wooden fibers. The printed part looks and feels like wood. The part is very post-processing friendly, it can be sanded with minimum melting, unlike normal PLA. It is even possible to use wood strengthener and wood stain to improve the physical property as well as aesthetic.

Figure 3. 19 Prototype 2.0 cable articulation test

With the assembly done, the next step is to install the cable system. To find out where the cables need to be fixed, small blocks with holes are 3D printed and temporarily taped onto the frame. To see how the joint behaves, strings are put through these nodes and are pulled by hand. The positions and angles of these nodes are adjusted so that the joint bend naturally. One problem with this prototype is that the nodes on the inner side joint are too close to the inner TUP joint. As a result, when pulling the string, the inner joint tends to bend sideways and the force required is much greater than that for the outer joint. The design of this prototype frame does not leave enough room for the inner nodes and joint piece, so this issue has to be fixed in the next prototype.

Figure 3. 20 Prototype 2.0 with bicycle break cables

After deciding the nodes' position, those small blocks are glued permanently. Finally, the strings are replaced by bicycle break cables. This cable is semi-rigid which can provide additional structural support for the elbow joint.

Upon further reviewing the design, the position of the cable and joint has created a problem:

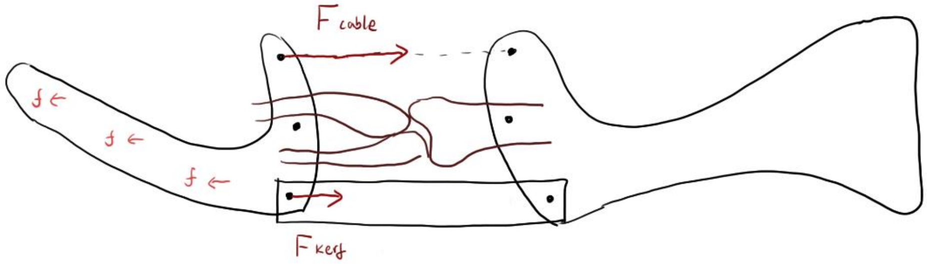


Figure 3. 21 Joint Design Free Body Diagram (lower joint)

Show above is a simplified free-body diagram of the current joint design. Note that in order to increase the distance from the cable to the kerf cut joint, the joint is pushed below the human elbow joint. In this case, the kerf cut joint is under tension when the elbow is bending. With this setup, the forearm frame is being pulled by both the cable and the joint, and the torque is generated by the difference between these two forces. Also because of this, the friction force from the skin to the frame required to balance out the forces are huge which can result in discomfort and stress. This is further proved by the fitting test when the user experienced high friction around both the flexor carpi radialis and extensor carpi radialis. To solve this problem, a potential alternative joint set up is shown below:

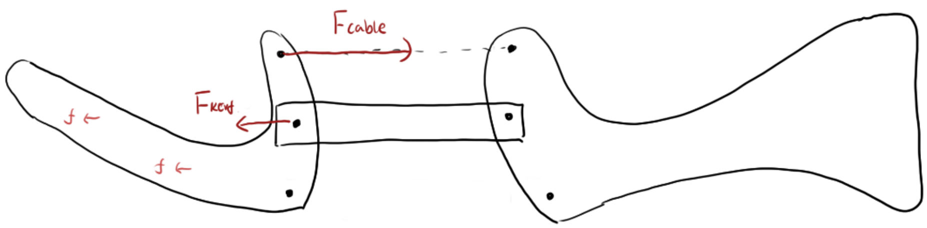


Figure 3. 22 Joint Design Free Body Diagram (higher joint)

In this case, the kerf cut joint is moved to the middle where the human elbow joint is. When pulling the cable this time, the joint is in compression so the force applied to the forearm frame is in the opposite direction of the pulling force from the cable. As for the torque, even though the moment arm is shorter, the forces are opposite so it is more efficient. Also, because the net force in the x-axis from the cable and joint is smaller, the friction force required is much smaller or can be close to zero, thus improving comfort.

Like mentioned before, it is important to have a polycentric exoskeleton joint similar to the human elbow joint. The fitting test shows that these duel kerf cut joints are polycentric and can even deform a little for the rotation of the forearm. Overall, prototype 2.0 with TPU joints is comfortable to wear and the cable system is capable of articulating the elbow joint.

3.3 Summary and Discussion

In this chapter, the literature review showed inspiration for the elbow joint design like the arthropod joints, and testing method for 3D printed material, as well as the less studied kerf cut method. For the prototype, the traditional modeled polycentric joint is too bulky and not aesthetically pleasing. This thesis studied and recommend complaint joint using soft material. The TPU is used in this study due to its printability and superb physical properties. Many tensile tests are done to find the behavior of kerf cut patterns. The result showed that it is possible to control the stress-strain curve by changing the sizes of the cuts. Also, note that the amount of overlapping of the cuts can affect where the linear part of the stress-strain curve starts. Based on the tests, the TUP kerf cut joints are designed and applied to prototype 2.0. This prototype tested the combination of soft joints and a cable-driven system. The result showed a few areas that needed improvement: The kerf cut joint needs to be thick enough so it does not bend sideways. The distance between the joint and the cable system's node should be large enough to reduce the force required for articulation as well as to prevent side bending. When the arm is in full flexion, the muscles around the elbow are pushed to the side, the design of the frame and the joint should take this into account for better fitting and comfort. The cable-driven method asserts a lot of stress to the nodes, if the cables are to be embedded, the end points/ nodes may need extra reinforcement. Similar to the case in both [7] and [8] , it is very difficult for the cable-driven system to provide force during arm extension. Prototype 2.0 showed a potential solution by using a semi-rigid cable so that the cable can be pushed during extension.

The joint designs in this chapter showed a lot of opportunities for future works. The behavior of kerf cut compliant parts can be further tested by using different patterns and materials. The effect of additive manufacturing can also impact the physical properties of the parts. The relation between the compliant joint and the cable system can also be studied further. For example, how the position of the nodes affects the deformation of the soft joint, as well as how to optimize this combination for better articulation and comfort.

4. Chapter 3: Design for Additive Manufacturing

4.1 Literature review

Throughout the previous chapters, 3D printing, or in broader terms, additive manufacturing (AM), is used to make test pieces and prototypes. But the designs of those parts did not really take advantage of this nontraditional manufacturing method. The previous models can be made by laser cutting or CNC machining, though not easy, but certainly doable. This begs the question: Why use additive manufacturing? What are the advantages of using it? The most common answer is that AM is convenient. It allows a designer with no manufacturing background to produce parts straight from a 3D model. But this way of using AM does not bring any additional value to the product compared to traditional manufacturing. If used poorly, AM can result in bad part quality and lengthy build time. The key to successfully utilizing AM is to understand the principle behind different AM methods and design the part that takes advantage of that. "Design for additive manufacturing" instead of "produce using additive manufacturing".

The most common AM method people know and love is material extrusion. Many consumer-grade 3D printers use this method, they simply melt the filament and lay the material layer by layer. Due to the nature of this process, the material used is mostly thermoplastics. Another AM method that is becoming popular is material jetting (MJ). Similar to 2D printers, material jetting printers jet droplets of build and support material to the build plane. Some MJ printers can even do multi-material jetting just like a color 2D printer. In the paper from Rapid Prototyping Journal [18], the effects of orientation and aging in material properties are studied. In the article, multi-material jetting is used to mix polypropylene-like (VeroWhitePlus) and elastomer-like (TangoBlackPlus) materials. The study found that parts have the best tensile strength when printed along the print head travel direction. The aging effect resulted in increased ultimate tensile stress but decreased elongation. The multi-material jetting method provides more design freedom and versatility compares to the material extrusion method. By mixing materials that have different physical properties, a single printed part can have varying properties. This AM method opens up many potential simplifications and improvements to structural design.

Another advantage of AM is that it can produce shapes that are difficult or impossible to make via traditional methods. A great example is 3D latticing. In the research article from Kyungpook National University [19], a mallet finger lattice cast was made using 3D printing. Very similar to the process shown in this thesis, the group 3D scanned the finger to get an STL file. Based on the STL, the MediACE 3D software is used to model the lattice cast. The part is printed using a 3D Edison resin printer which offered great resolution and accuracy. According to the customer feedback, compared to the traditional cast, the 3D lattice casts are more comfortable, light weight, and solve potential health issues like skin necrosis and contamination. 3D lattice cast is becoming more and more popular in the field of the medical industry with the improved AM technology. As for exoskeletons, they share many trades with casts, so the 3D lattice method can be applied and should be studied.

4.2 Methodology

4.2.1 Three design approaches

In the previous chapters, the frame and the joint of the exoskeleton are designed separately. Using solid PLA as the frame and the flexible TPU to make the compliant joint. But there are many other approaches with the help of additive manufacturing.

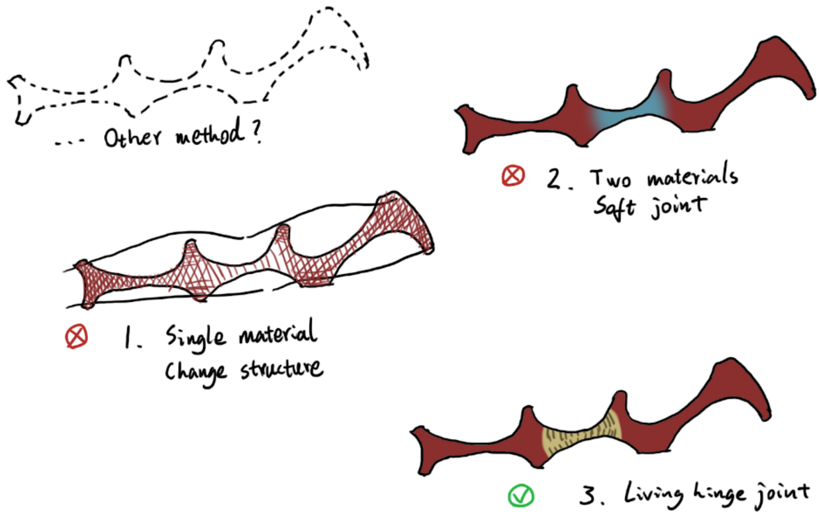


Figure 4. 1 Three design approaches

Shown above are simplified drawings of the arm exoskeleton. Number three represents the separate compliant joint design method used in the previous chapter, but note that kerf cut is just one of the many compliant joint designs. The other two methods rely on the design freedom of AM. The first method is to use a single type of material, but varying the structure at the joint to achieve bending. The challenge of this method is to choose the suitable material and structure combination. The material has to behave like a solid body for the frame part but compliant for the joint. Based on later testing, TPU 95A is a good choice. The "95A" indicates the hardness. Other materials with a hardness of 95A and good fatigue should work for this method as well. As mentioned in the literature review, the 3D lattice structure suits the need of exoskeleton very well, especially for this design method. But manually modeling 3D lattice is very difficult and modeling varying lattice is almost impossible by hand. Specialized software is needed for latticing which will be shown later in this chapter. The second design method in the drawing is to used two materials and fuse them together with a gradient. This can be achieved with the power of multi-material jetting mentioned in the literature review. But the challenge is the material once again. Most of the studies of multi-material jetting [20] [21] use VeroWhite as the hard material and TangoBlack as the soft one. The problem is that TangoBlack has bad fatigue life and low elongation compare to TPU [18]. To the knowledge of the author, TPU is not very compatible with material jetting. But multi-material jetting is not the only AM method that allows the fusion of different materials. It is possible to use material extrusion to combine different layers of various materials [22]. To summarize, additive manufacturing makes a lot of innovative design methods possible. The thesis presents three common methods, but just by combining these three methods, there are many more approaches to design for AM. For example, using 3D lattice for the compliant joint, or gradating the material and structure at the same time.

4.2.2 NTop latticing

The mallet finger lattice cast in the literature review showed the potential of 3D latticing in medical devices. Just like the cast, the low-profile arm exoskeleton also wraps around the human body and contacts the skin, so having a 3D lattice structure can reduce the weight and a lattice surface can allow the skin to breathe better. But modeling 3D lattice is difficult especially on top of a generated organic model. Lucky, the nTopology Platform (nTop) suits the needs for this project perfectly. Ntop is a nontraditional 3D model software that uses an implicit body instead of a CAD body. Meaning the body is not based on surface point data, but based on many simple unit shapes that form the body. With the implicit body, nTop can generate many kinds of lattices and infills efficiently. One disadvantage is that it is difficult to modify the base shape of the model once it is converted to an implicit body. Due to this, another traditional CAD software like Fusion 360 is often used to modify the model before importing it to nTop. To demonstrate the process of making lattice in Ntop, the following pictures show some of the designs using the prototype 2.0 model.

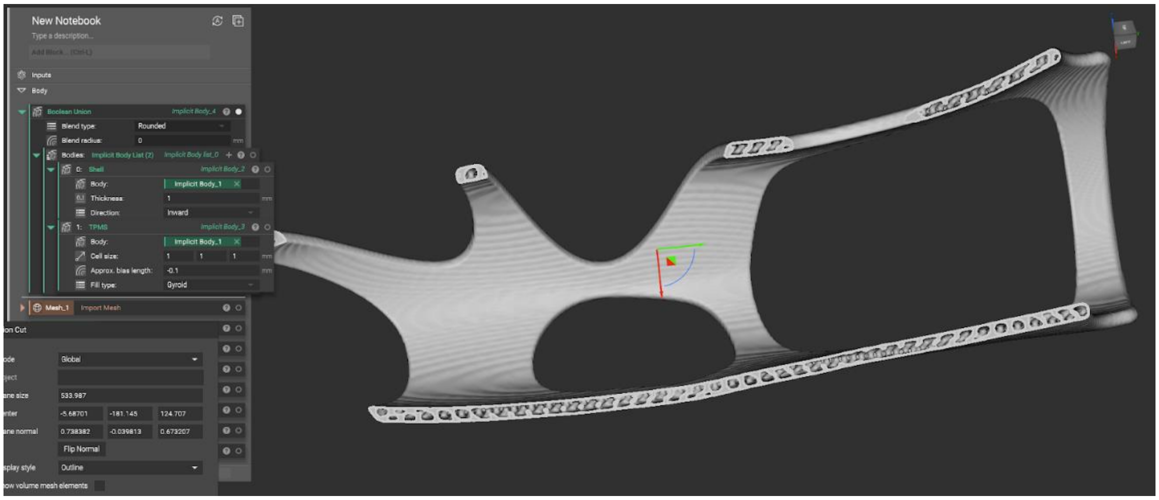


Figure 4. 2 nTop infill

In this example, nTop is used to generate the infill for 3D printing. Shown on the left are the work blocks. Each block has its own function with input and output. Blocks can be chained or embedded into other blocks. This block system works a lot like coding. The benefit of this workflow is that by changing the input within one block, the whole system will update and output the new result quickly. For example, by increasing the “Thickness” input in the “Shell” block, the design will update to have a thicker outer wall. Unlike most 3D printing slicer software, nTop can output the final print model to other CAD software. So simulation can be made using the accurate model before printing. This is very beneficial for robotic designs using additive manufacturing.

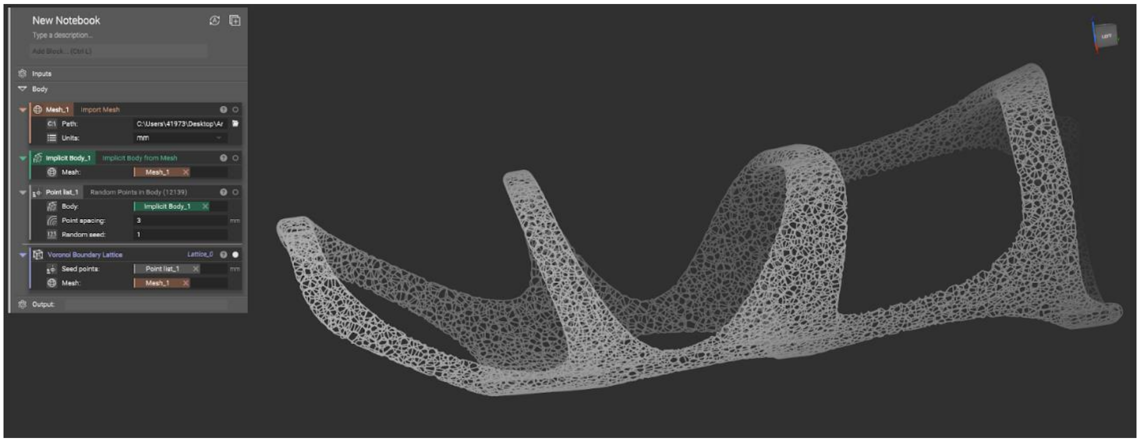


Figure 4. 3 nTop latticing

Shown above is the lattice generated for prototype 2.0. On the left, the first block import the STL file into nTop, the second block convert it into the implicit body, the next block generates random points throughout the body, the last block takes in the points and the body meshes to output the lattice. The result looks similar to the mallet finger lattice cast but instead of a single layer of lattice on the surface, this model has 3D lattice throughout the entire body. This is useful for applications that need to reduce weight but keep the strength of the structure. For 3D printing, nTop can slice the model within the platform and send the print file to the printer directly.

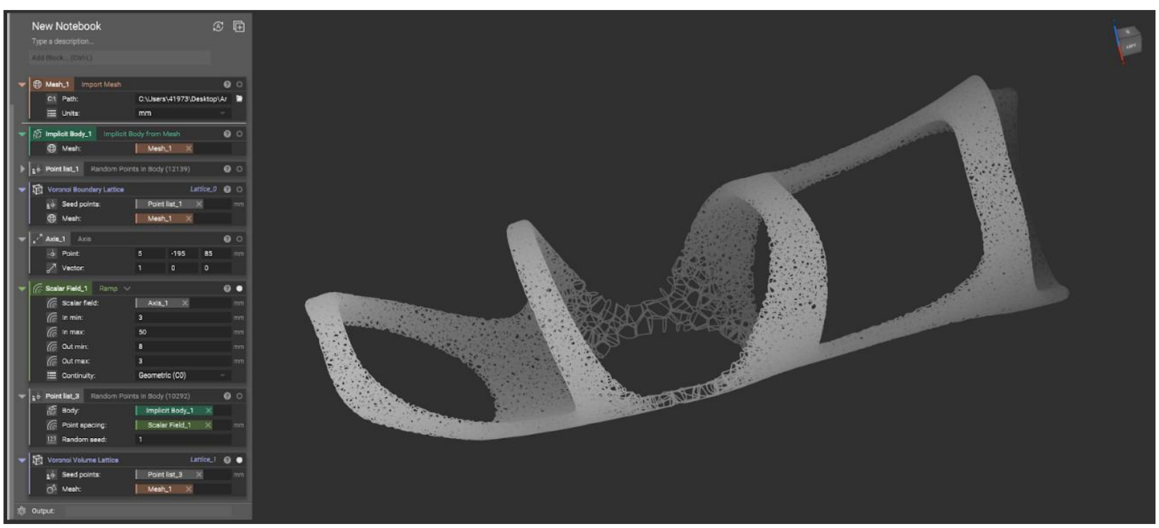


Figure 4. 4 nTop field-driven latticing, point density

The previous example uses uniform lattice, but many designs require different physical properties in different areas. In the case of the arm exoskeleton, if using semi-soft material like TPU 95A, the joint lattice should have a lower density so that it can be bent, and the frame should have a higher density or even solid-body to provide support. To achieve this, the scalar field block is used to modify the point generation block. The scalar field can define a range for the target variable (point spacing in this example) based on a field which is an axis at the joint in this case. As shown in the figure, the lattice has a lower density near the joint and gradually becomes denser moving away from the joint.

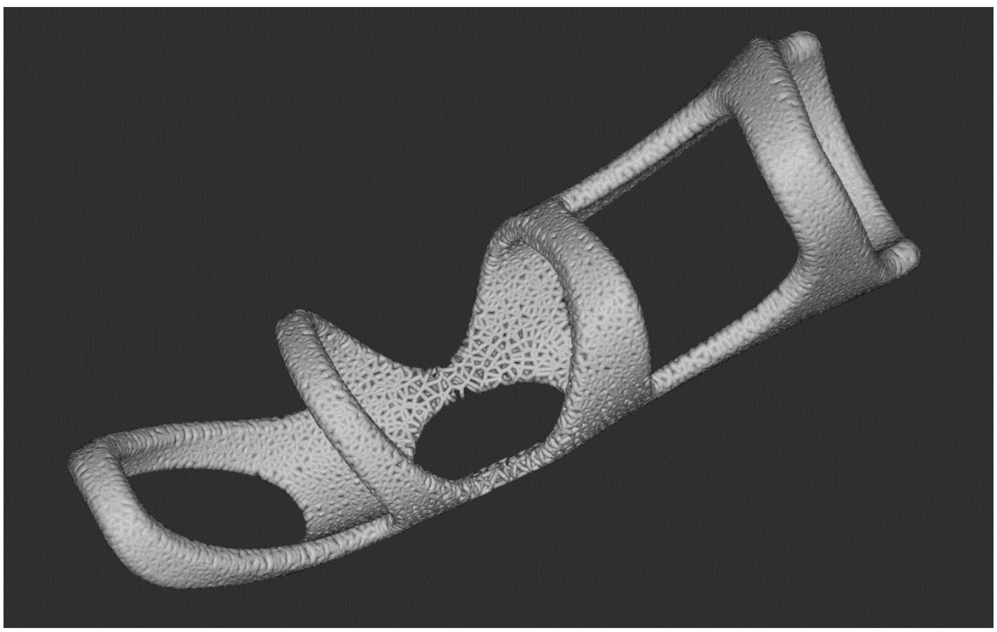


Figure 4. 5 nTop field-driven latticing, lattice thickness

Using the same method with a different variable can return interesting results. For this example shown above, the variable is the thickness of the lattice. The joint area has a lower thickness and the thickness increases moving away from the joint. At some point, the thick lattice simply becomes a solid body. Note that due to the lattice, this model is accidentally thickened and the surface is ruined.

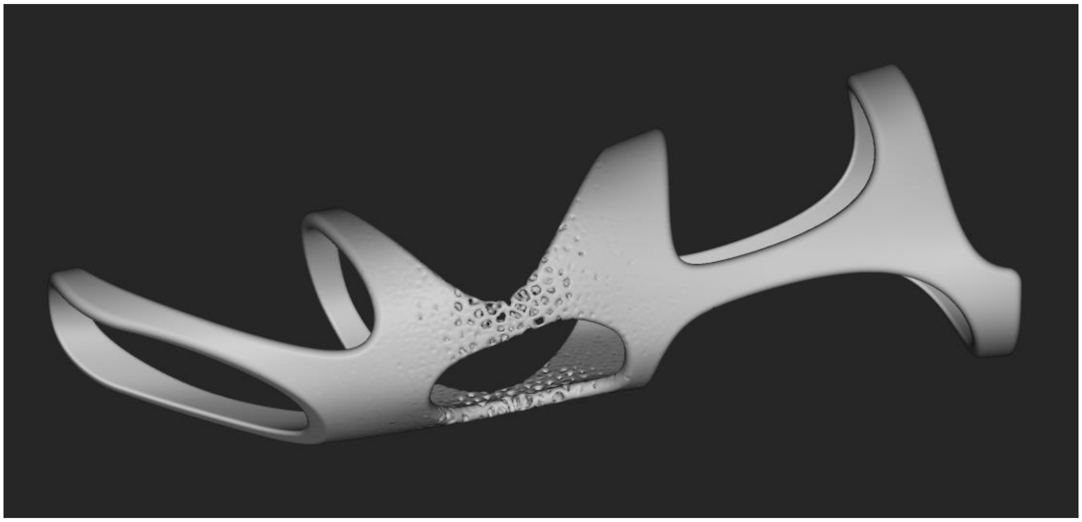


Figure 4. 6 nTop field-driven latticing, Boolean intersect

To keep the joint lattice and the original frame, a Boolean intersect block is used. This block takes two implicit bodies and returns a model where the two bodies intersect, keeping only the overlapping areas. The result is shown above. Note that the Boolean functions in nTop are very efficient due to the use of the implicit body. If the same Boolean intersects with complex lattice is done in other CAD software like Fusion 360, it will take a long time or even require cloud computation.

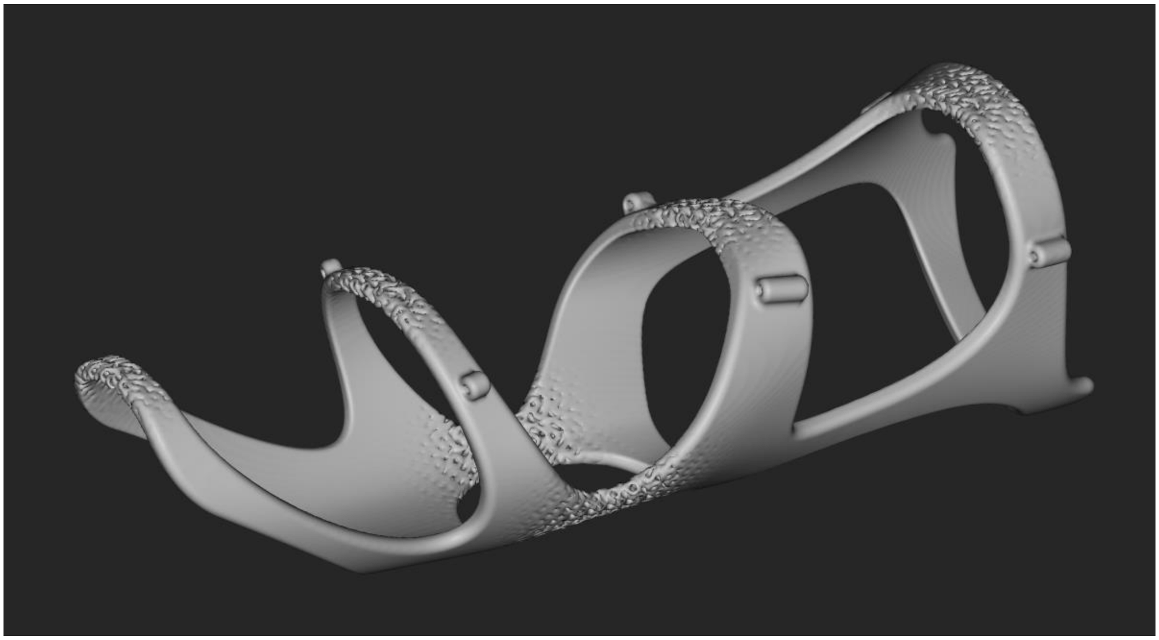


Figure 4. 7 nTop prototype 3.0

Combining the method used in previous examples, the model of prototype 3.0 is made in nTop. The purpose of this prototype is to test the ability to make the exoskeleton using a single material in a single print. Note that for this model, the joint and strap areas used Walled TPMS (triply periodic minimal surface) instead of randomly generated lattices. Because the TPMS structure is well studied and tested, especially for additive manufacturing [23]. It is also a popular infill type for 3D printing. Based on the article from ACS Applied Bio Materials [24], Young's module of the TPMS is almost linear with the relative density, making it easy to control the desired stiffness. The TPMS is also very efficient at reducing volume and increasing surface areas, which can help reduce the weight of the exoskeleton and provide better heat dissipation for comfort. To find out the optimum TPMS density (cell size in nTop) and wall thickness for this exoskeleton design, a study using TPU is required.

4.2.3 TPU TPMS testing

The purpose of this TPMS sample test is to find the behavior of soft TPMS structures and to determine the best parameters for the exoskeleton. Three test blocks are printed using TPU with different parameters:

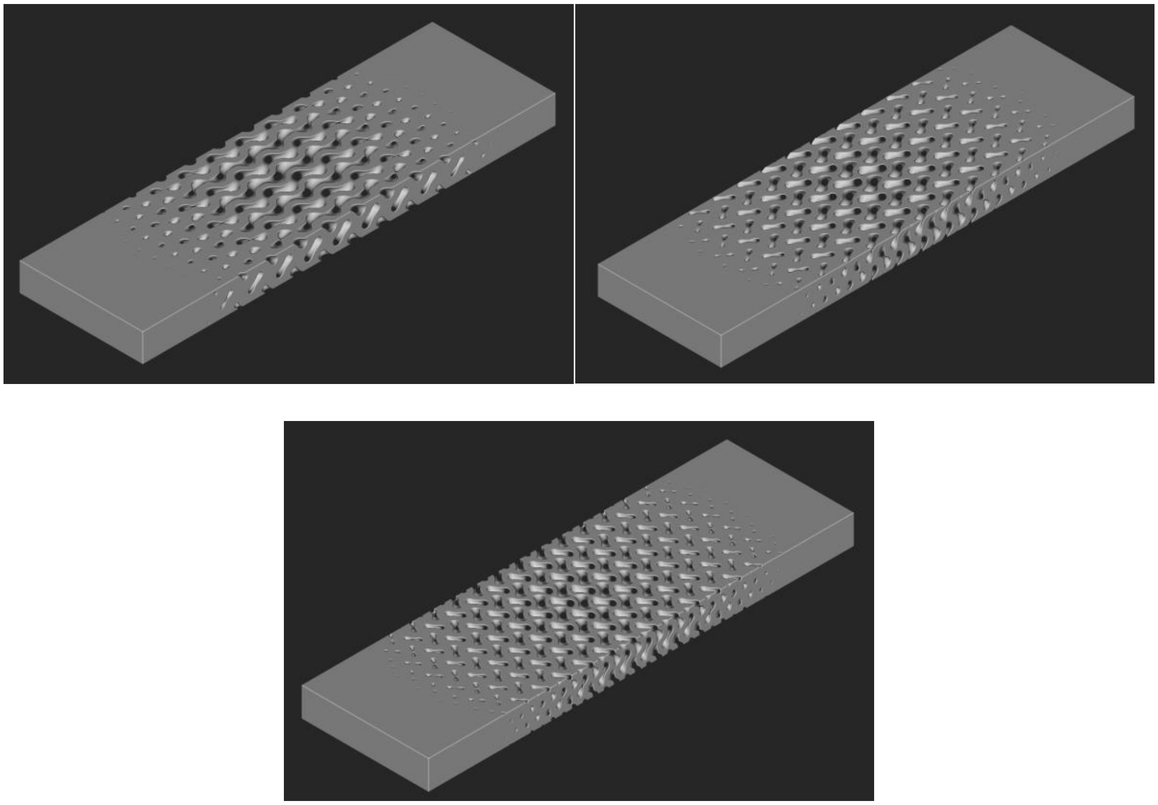


Figure 4. 8 TPU TPMS test samples. (Top left: 1, Top right: 2, Bottom: 3)

As shown above, three TPMS test blocks are designed using the nTop scalar field. Number one has a cell size and max wall thickness of 7 mm, number two uses 6 mm, and number three uses 5 mm. By decreasing cell size (increasing density) and wall thickness at the same time, the volumes of these three blocks are very close. Because weight-reducing is one of the main reasons to use TPMS, it is interesting to find how to change physical properties without changing the weight. The test is run on the same Instron machine used in the previous chapter shown below.

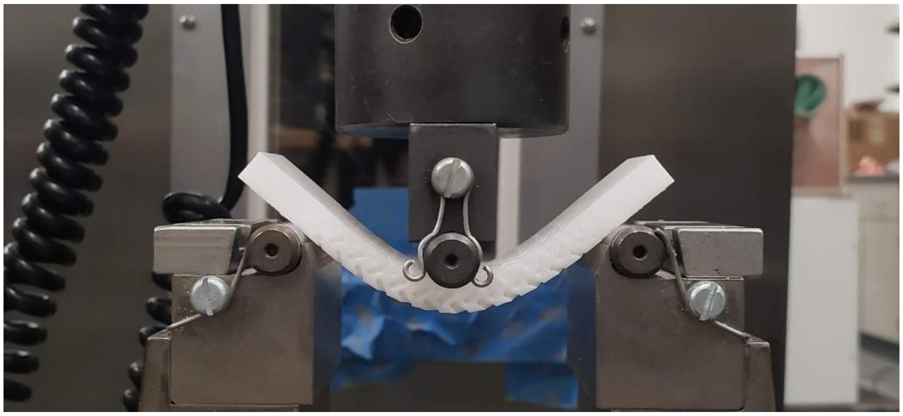


Figure 4. 9 Three-point bending test

The test procedure is loosely based on the ASTM D790-17 standard test method for flexural properties of unreinforced and reinforced plastics and electrical insulating materials. The standard states that it is best suited for a solid material that has a lot higher stiffness than the TPU samples in this test. Because the TPU samples can bend almost 180 degrees without breaking, some of the parameters from the standard are changed to suit the need for this test. The descending rate of the mid-point is set to 5 mm/min which is a lot higher than the standard. The test ended when the sample is bent at around 45 degrees because the sample will slip if pushed further. Note that to the knowledge of the author, no study has been done on the combination of TPU and TPMS. The ideal test procedure should require further study. But for the sake of this thesis, and the purpose of finding suitable parameters for the arm exoskeleton, the test is done is sophisticated.

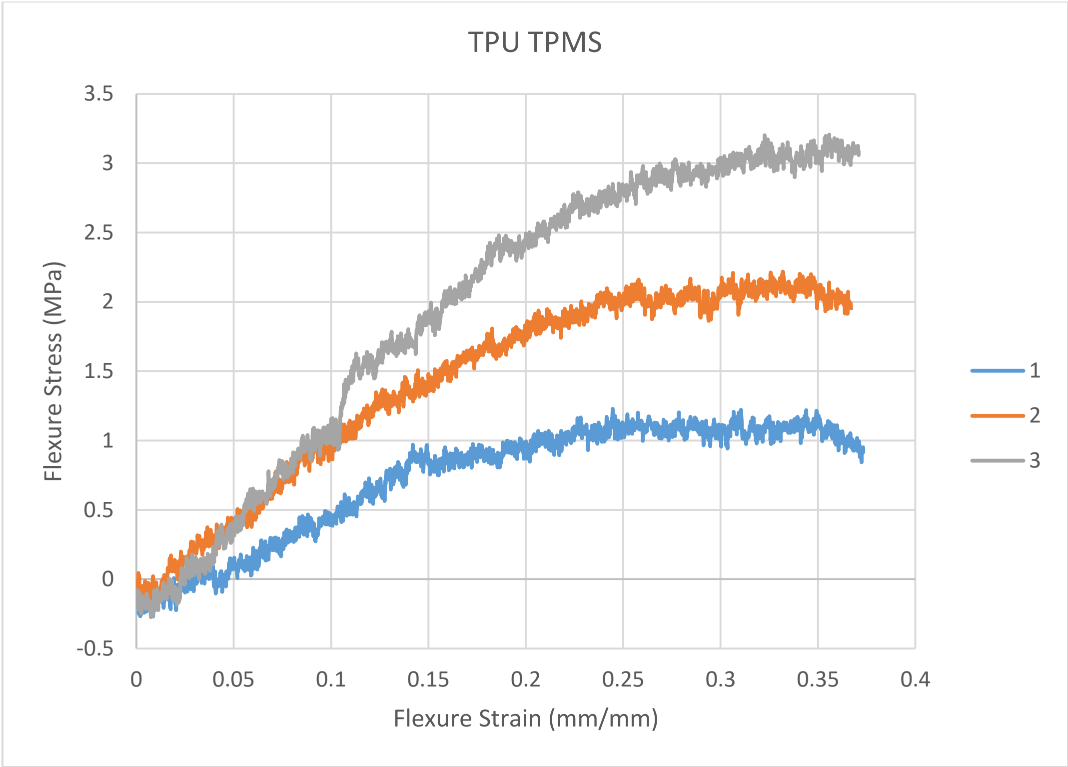


Figure 4. 10 TPU TPMS stress-strain curve

The three test results are shown above. There is a lot of noise in the result because the test sample is too soft and the load cell available for the Instron machine is usually used for the metal bending test. Even with the noise, it is not hard to tell the difference between these three test samples. The parts with higher TPMS density have higher stiffness. Also, though not safe to say with the noise, all three samples seem to have linear regions up until around 0.1 mm/mm strain. As for the exoskeleton joint, the curve of number 1 is the best choice. Because the curve is lower and becomes flat sooner under high strain. This means less force is required to articulate the joint and the force is almost constant in the later stage of bending. The constant force can also make it easier to design the control system for the cable-driven articulation system.

4.2.4 Final Prototype

Figure 4. 11 Final prototype design

Shown above is the design of the final prototype 4.0. The shape of the frame is once again changed based on the TPU TPMS test. The joint area is a lot thinner because TPMS joints do not need as much volume as the kerf cut joints. The elbow opening is also enlarged due to this thinner joint. The cable nodes are replaced by the embedded channels within the frame for a lower profile and better aesthetic. All the connecting parts use hidden dovetail joints, so that the frame has nice-looking curves near the joints on the outside, hiding the dovetail cuts on the inside. As for material, the frames use 3D printed wood PLA with wood stain. The joints use TPU 95A with TPMS lattices. The top straps also use TPU 95A but with low infill for better flexibility. This final design combines many features from previous prototypes and emphasizes more on aesthetic.

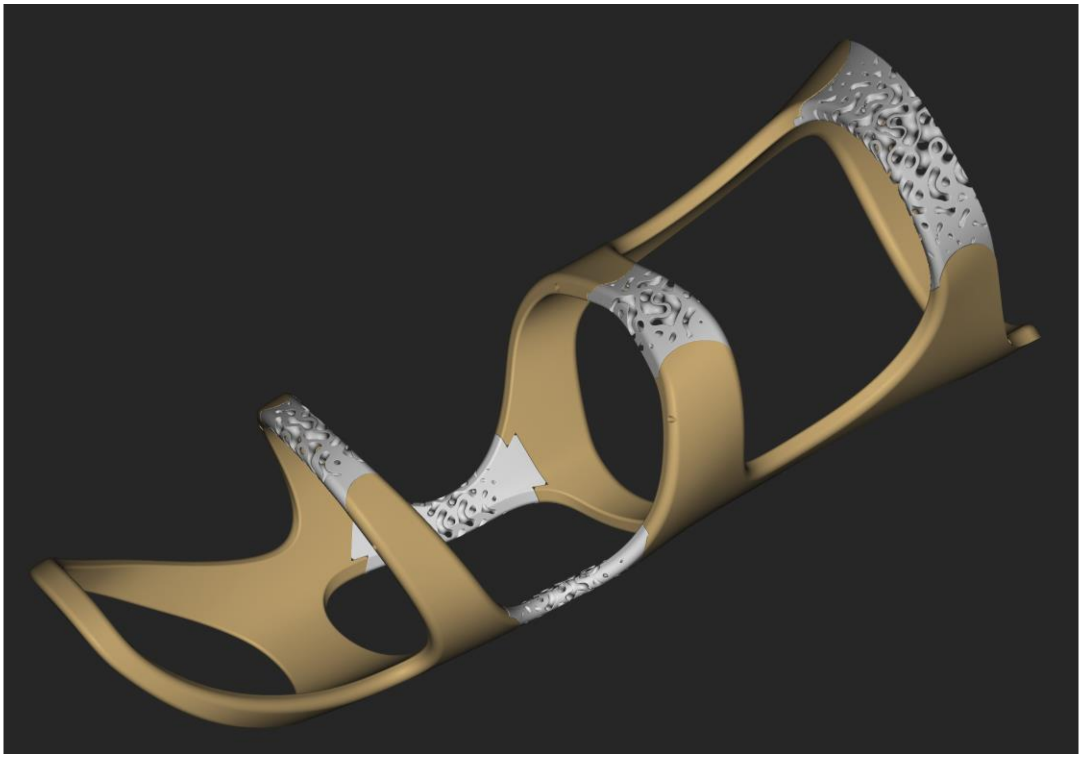


Figure 4. 12 Final prototype nTop model

To add the TPMS lattice to the joints and straps, the model is imported into nTop. Based on the TPU TPMS tests, the joints use a cell size of 10 mm, wall thickness from 1.5 mm to 10 mm. The straps also use 10 mm cell size but the minimum wall thickness is reduced to 1 mm for more flexibility. Shown above is the final model from nTop before exporting into STL files for printing.

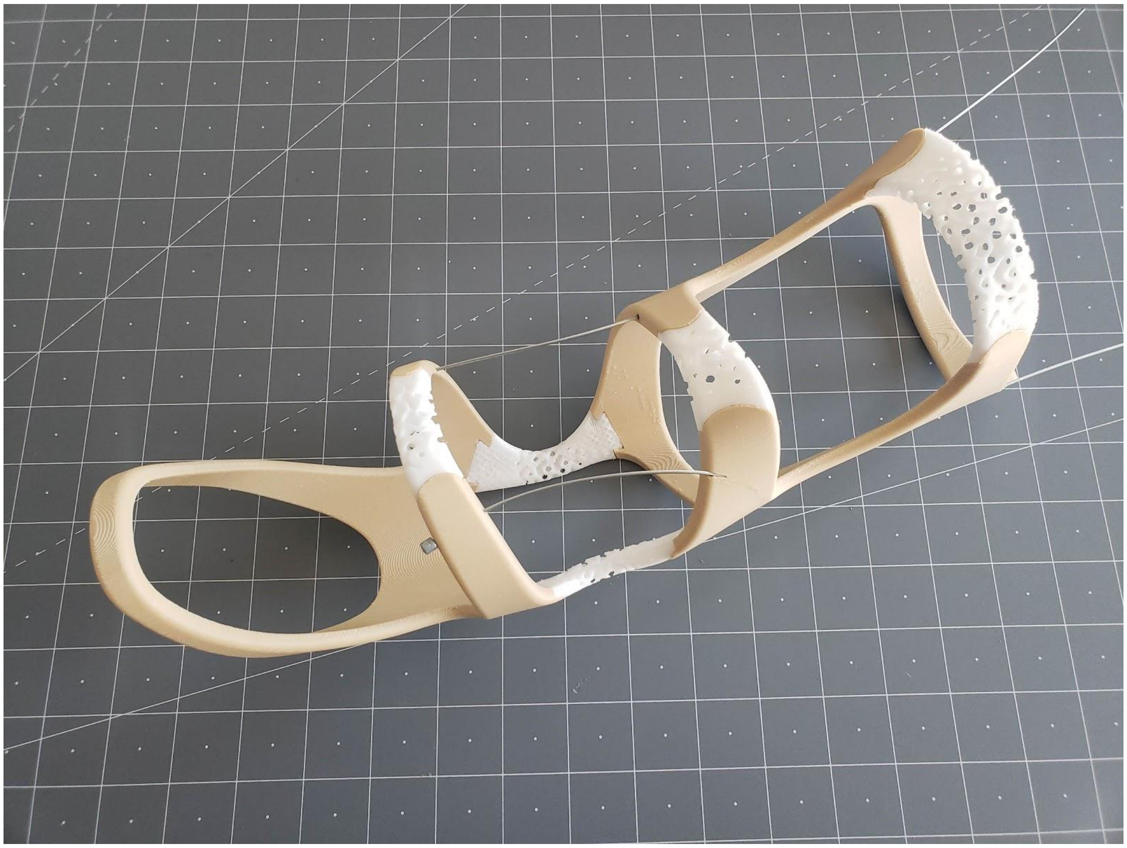


Figure 4. 13 Final Prototype physical model

The assembled physical model of the final product is shown above. The TPU parts fit in tightly and are further secured using super glue. The cables are inserted into the embedded channels. The left cable experiences more friction than the right one because of the smaller radius of the curve of the channel. When pulling the cables together, the elbow joints bend smoothly. Unlike the previous model's kerf cut joints, the TPU TPMS joints do not bend outside and stay close to the plane of the frame during the entire bending process. Also, compared to kerf cut joints, the force of going back to the original position is greater. The TPU straps provide better structural stability than the rubber straps used previously, but they are less comfortable and the added thickness prevents the joint from fully bending because the middle two straps will collide. Due to this, it is a good idea to keep using rubber fabric for the middle two straps. Overall, the final prototype meets the goal of this thesis: an arm exoskeleton that can provide support and is lightweight and compact, at the same time, comfortable to wear, and aesthetically pleasing.

One concern for the cable-driven system from the exosuit paper [9] is the friction generated by the Bowden cable. To find out the cable friction of the prototype, an extension test pulling the two cables is conducted. By fixing the upper arm frame to the bottom clamp of the Instron machine and pulling the cable using the top clamp, the following data is collected.

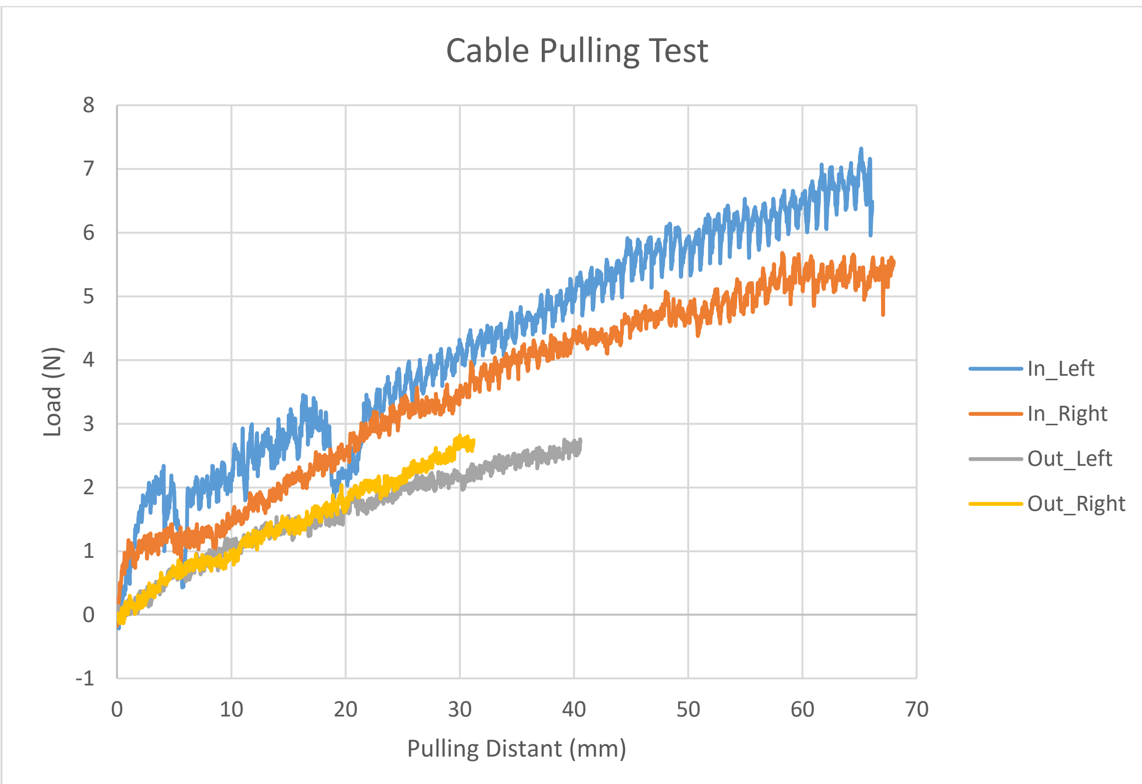


Figure 4. 14 Final Prototype cable pulling test

In_Left and In_Right represent the pulling forces when the cables are inserted into the upper arm frame. Out_Left and Out_Right are when the cables are taken out of the frame, meaning there was no friction. Comparing the left and right forces, the left force is larger because the two turns of the channel within the frame create more friction. Compare to the second data set, the added force is around 2 N for the left and 1 N for the right. The friction also causes more noise which can complicate the design of the control system.

It is worth noting that many of the properties of the prototypes depend on 3D printers. The machine used in this project is a low-end FDM printer using 0.75 mm filaments. The surface finish and accuracy can be greatly improved by using better printers. The final design separates the frames and joints, this is not necessary if a 3D printer can print the whole exoskeleton using TPU 95A. The TPU should be able to provide enough support and act as the frame when printed using 100% infill. Unfortunately, no such machine is accessible for this project. Future research should study this single material approach based on the NTop model of prototype 3.0.

4.3 Summary and Discussion

In this chapter, the most important concept is "design for additive manufacturing". It is critical to understand the basic principles behind additive methods like material extrusion and material jetting. A good AM designer should take advantage of the design freedom AM provide and try to minimize the disadvantages. Three design approaches are proposed: Separate compliant joints, varying lattice structure, and multi-material jetting. The final prototype combines these ideas by using lattice on soft material (TPU) to act as the compliant joints. To find the best lattice structure for the exoskeleton, nTop is used to generate the lattice and a test using TPU TPMS is conducted. The final product is generally functional and aesthetically pleasing. Due to the limitation of AM machines used in this thesis, the quality of the final prototype is compromised. For future studies, it will be interesting to see a more robust combination of generative design and 3D lattice. Both method's goal is to reduce weight and optimize the strength of the structure. Generative design "adds" parts connecting key points, while 3D latticing "reduces" parts to create lattices. With the power of more advanced additive manufacturing, this combination can be a breakthrough in the field of structural optimization.

5. Conclusion

5.1 Reflection on Design

The field of exoskeletons is expanding quickly nowadays, with the development of virtual reality and artificial intelligence. Engineers often focus on how to build a stronger frame or how to fine-tune the control system. Many projects are built upon tried and tested methods like high DOF external robotic arms, while excellent in a laboratory environment, such designs do not transition well into commercial products. The ultimate goal of the exoskeleton and robotics is to aid people and coexist with them in harmony. The machines should be friendly and inviting, like how service robots often have a smiling face and round body. Exoskeleton and prosthesis should care about user-friendliness the most because they become part of the user's body. This thesis project is designing an arm exoskeleton, but most of the methods can be translated to other applications like prosthesis and robotics. Using 3D scanning and generative design to achieve an organic shape can ensure fit and comfort, but more importantly, lessen the intimidation factors of a foreign object. It is easier to accept something that comes from one's own body and looks like things people see often in nature. The soft-compliant joint designs fit the polycentric human joints well and are less threatening to the user. The first thought of using any machine is often: "Will I get hurt?" For wearable devices, it is critical to eliminate this fear of injuring. Apple products are great examples, they use round corners and bright colors. For the Apple Watch, very soft rubber straps are used. As a result, people are more attracted to such designs. For the final prototype, the frame is processed to look and feel like wood, the TPU joints are covered by fabrics, because wood and cloth are not very threatening, since people are used to sitting on wooden furniture and wearing clothes. With the development of additive manufacturing technology, the "design for AM" term becomes popular. Many difficult designs can now be achieved using AM, like the embedded cable and 3D latticing. Learning different AM processing and AM CAD tools like nTop can open up design freedom for both engineers and designers. In the end, hopefully, this thesis can bring the gap between engineering and design a bit closer.

5.2 Future Work

This thesis project should act as a starting point for many future studies. By going through the process of designing an arm exoskeleton, with the focus set on form factor and joint design, the project explored many nontraditional methods. It is recommended to use generative design for inspirations now, but as the technology matures, future studies can validate the generated models and use them directly. For the joints, more compliant joint designs should be studied for soft robotics, like the arthropod and 3D kerf cut joint design. The arthropod joints have great potential but need substantial modification for applications like an exoskeleton. As for additive manufacturing, more AM processing and material should be tested other than material extrusion and TPU, like material jetting and soft resin. It will require much testing to find the best combination for different applications so simulation and optimization software will be helpful. Finally, future studies should focus on more specific topics and do in-depth research to enrich each field and accelerate the development of exoskeleton and robotics.

Bibliography

[1] N. G. a. G. A. G. Florian, "Closed-loop task difficulty adaptation during virtual reality reach-to-grasp training assisted with an exoskeleton for stroke rehabilitation," *Frontiers in Neuroscience,* vol. 10, pp. 1-13, 2016.

[2] M. J. S. S. Michele Folgheraiter, "Measuring the Improvement of the Interaction Comfort of a Wearable Exoskeleton," *Springer Science & Business Media*, 2012.

[3] M. Nick S. Ward and M. Leonardo G. Cohen, "Mechanisms Underlying Recovery of Motor Function After Stroke," *Arch Neurol,* p. 61(12), 2004.

[4] J. M. W. Michelle H. Cameron, "Gait Abnormalities in Multiple Sclerosis: Pathogenesis, Evaluation, and Advances in Treatment," *Current Neurology and Neuroscience Reports,* vol. 507, 2011.

[5] S. d. O. Barata, "THE ALTERNATIVE LIMB PROJECT," [Online]. Available: https://thealternativelimbproject.com/about/. [Accessed 2021].

[6] Y. G. Y. W. Y. Z. J. Z. Feiyun Xiao, "Design and evaluation of a 7-DOF cable-driven upper limb exoskeleton," *Journal of Mechanical Science and Technology,* vol. 32, p. 855~864, 2018.

[7] Z. Q. W. W. P. Z. F. H. Wei Wei, "Design on the Bowden Cable-Driven Upper Limb Soft Exoskeleton," *Applied Bionics and Biomechanics,* no. 1925694, p. 9, 2018.

[8] M. F. T. N. F. B. K. B. Christina M. Harbauer, "Too Close to Comfort? A New Approach of Designing a Soft Cable-Driven," in *2020 the 3rd International Conference on Intelligent Robotics and Control Engineering*, 2020.

[9] D. K. B. S.-C. Y. a. L. M. Leonardo Cappello, "Design and Preliminary Characterization of a Soft Wearable Exoskeleton for Upper Limb," in *6th IEEE RAS/EMBS*, Singapore, 2016.

[10] M. A. M. J. F. A. Monica Rojas-Martínez, "High-density surface EMG maps from upper-arm," *JOURNAL OF NEUROENGINEERING AND REHABILITATION,* vol. 9, p. 85, 2012 .

[11] S. Krish, "A practical generative design method," *Computer-Aided Design,* vol. 43, no. 1, pp. 88-100, 2011.

[12] T. B. M. d. L. e. Kirsten Huysamen, "Evaluation of a passive exoskeleton for static upper limb activities," *Applied Ergonomics,* vol. 70, pp. 148-155, 2018.

[13] G. X. e. RENGHAO LIANG, "A General Arthropod Joint Model and Its Applications in Modeling Human Robotic Joints," *Digital Object Identifier,* no. 10.1109, 2021.

[14] H. M. S. P. D. Cassandra Gribbins, "EXPERIMENTAL ANALYSIS ON AN ADDITIVELY MANUFACTURED ABS LIVING HINGE," 2014.

[15] C. T. M. J. e. Renzhe Chen, "Mechanics of kerf patterns for creating freeform structures," *Acta Mech,* vol. 231, p. 3499–3524, 2020.

[16] J. S. C. G. A. A. Lauren Safai, "A review of the fatigue behavior of 3D printed polymers," *Additive Manufacturing,* vol. 28, pp. 87-97, 2019.

[17] W. S. X. L. Y. M. X. Tao Xu, "Mechanical Properties of Additively Manufactured Thermoplastic Polyurethane (TPU) Material Affected by Various Processing Parameters," *Polymers,* 2020.

[18] N. A. M. C. B. W. Lindsey Bass, "Exploring variability of orientation and aging effects in material properties of multi-material jetting parts," *Rapid Prototyping Journal,* vol. 22, no. 5, 2016.

[19] A. S. J. L. Hyeunwoo Choi, "Mallet Finger Lattice Casts Using 3D Printing," *Journal of Healthcare Engineering,* vol. 2019, no. Special Issue, 2019.

[20] J. M. K. S. Thomas S.Lumpe, "Tensile properties of multi-material interfaces in 3D printed parts," *Materials & Design,* vol. 162, pp. 1-9, 2019.

[21] T. L. e. Fan Liu, "The effect of material mixing on interfacial stiffness and strength of multi-material additive manufacturing," *Additive Manufacturing,* vol. 36, no. 101502, 2020.

[22] R. K. e. Rupinder Singh, "Multi-Material Additive Manufacturing of Sustainable Innovative Materials and Structures," *Ployners,* vol. 11(1), no. Special Issue, p. 62, 2019.

[23] Q. T. e. Shuai Ma, "Manufacturability, Mechanical Properties, Mass-Transport Properties and Biocompatibility of Triply Periodic Minimal Surface (TPMS) Porous Scaffolds Fabricated by Selective Laser Melting," *Materials & Design,* vol. 195, no. 109034, 2020.

[24] L. Z. S. Z. J. Y. H. F. a. W. F. L. Sanjairaj Vijayavenkataraman, "Triply Periodic Minimal Surfaces Sheet Scaffolds for Tissue Engineering Applications: An Optimization Approach toward Biomimetic Scaffold Design," *ACS Applied Bio Materials*, p. 259–269, 2018.