

**ENGS021 - Spring 2025**  
Introduction to Engineering



**DARTMOUTH  
ENGINEERING  
THAYER SCHOOL**

## **UCL Protective Brace for Ski Gloves**

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## I. Executive Summary

Any skier can attest to the fact that falling is an occupational hazard, and many of these falls result in a tear of the ulnar collateral ligament (UCL) in the thumb. Our group has designed a brace implemented into an existing ski glove that maintains full dexterity while reducing the risk of this injury.

While the most common ski injuries happen at the knee, the second most common are thumb injuries, in particular the tearing of the UCL. However, even given the magnitude of this problem, these injuries tend to be overlooked. Over 200,000 skiers experience UCL injuries in the United States every year, most often occurring during a fall when a skier lands on their outstretched hand. Recreational and competitive skiers alike can experience UCL injuries, although the injury is much more prevalent among the latter group due to higher speeds and more time spent skiing. This seemingly small injury can result in early-onset arthritis, lessened grip strength, and in many cases, require surgery with a monthslong recovery. Among competitive skiers, this injury can easily derail an entire season, endangering the skiers' livelihood. As such, skiers need a non-invasive solution to prevent this common but serious injury to the thumb.

We propose a modification to existing ski gloves with a unique orthopedic brace to prevent injury to the thumb, designed to fit snugly between the layers of the glove to provide protection. This brace is hingable, allowing thumb flexion towards the palm, but limiting hyperextension and excess lateral flexion. The brace consists of sections formed by a 3D printed urethane photopolymer, and each piece is adhered to cross-stitched nylon and Kevlar for strength and flexibility. The brace is inserted in between the layers of the glove at the thumb and the glove is then resealed shut. An additional piece of the implementation includes a small strap of Kevlar connecting the base of the thumb with the forefinger, limiting the lateral angulation of the thumb known as *valgus flexion*. This solution will prevent the mechanism of UCL overextension in the thumb while still providing the dexterity for natural gripping and movement.

The user and purchaser of our product are the same since users will typically be buying the product to use themselves. Our early adopters will likely be ski racers who have previously injured their thumb, since they are already on the lookout for a solution. We anticipate expansion into the larger market of all recreational skiers as product recognition grows.

We researched many existing market solutions but found that the few solutions that exist are cumbersome to users, and most were out of production entirely. Notable existing patents include an orthopedic hand brace and an external thumb cover, both of which severely limit the range of motion of the user. While some of these braces transfer force effectively away from the UCL, our design seeks to keep this level of safety while still allowing normal thumb use.

Our team includes a current US Ski Team member, Kyle Negomir, who not only has many years of professional experience in the skiing world but also has unique connections with orthopedic surgeons and glove manufacturers. Additionally, Holden Langenhagen is a PSIA Level 1 certified ski instructor who previously worked as a ski instructor in Aspen, Colorado. Peyton Acker, Chase Hofmann, and Kabir Datta have extensive technical skills and knowledge, and all have limited skiing experience which provides an important perspective on the usability of our product to the average recreational skier.

Important milestones we achieved included successfully designing our 3D model to snugly fit over a thumb, adhering the model to Kevlar and nylon, performing extensive material strength and range of motion tests, and receiving much positive feedback from users.



## II. Problem Background, Magnitude, and Opportunity

Over the past 10 weeks, we developed a proactive solution to prevent Skier's Thumb injuries. Skier's Thumb, as it is colloquially known, refers to a tear of the ulnar collateral ligament (UCL) which spans across the MCP joint of the thumb (the base of the thumb, known technically as the metacarpophalangeal joint). The injury usually occurs when a skier falls onto an outstretched hand, and often a ski pole acts as a lever over which the thumb is pressed into valgus flexion or hyperextension. The UCL supports and limits this movement, but tears under excessive stress.

This is an incredibly common injury. In the United States alone, roughly 200,000 people injure this exact ligament annually (Mahajan & Rhemrev, 2013). It makes up 86% of all injuries sustained to the base of the thumb, and is second in frequency only to knee traumas (Physiopedia, n.d.) in the skiing world. Unfortunately, it is rarely discussed because much of the medical attention is currently focused on protecting the knee. This focus is warranted, as functioning lower extremities are extremely important, but we believe that the hand is not to be overlooked. The recovery for this injury is difficult, frequently requiring surgery and several months to rehabilitate (Mohseni, Sina, & Graham, 2024). In 64-67% of UCL injuries, a Stener lesion can occur, which is where the muscle between a person's thumb and forefinger, known as the adductor aponeurosis, gets trapped between the ligament and the bone it previously was attached to (Physiopedia, n.d.). This always requires surgery to correct, and although grip strength and mobility will be mostly normal after about 3 months, it will take 6-12 months until the hand regains its full function (The Center, n.d.).

There is also an increased risk of early-onset arthritis (Saint Luke's, n.d.) and long-lasting issues with thumb function as a person gets older. Thumb dexterity and strength are critical to almost every movement and activity we do as humans, and are even sometimes cited as one of the primary differences that allowed early humans to differentiate themselves from primates and gain an advantage (Kivell, 2021). When this ability is infringed on, it should always be regarded seriously.

Speaking to a veteran ski patroller who has spent his life helping injured skiers on the mountain, we learned that Skier's Thumb is the number one most common injury he sees on the hill, outpacing even knee injuries from his subjective experience. Another interview with an Olympic and World Cup podium skier revealed that over half of the women's USA World Cup team has scars from surgeries to correct this exact tear, highlighting its prevalence among frequent skiers. Additionally, out of our five team members, two of them have experienced this exact injury within the last twelve months. One has even had three different occasions of injuring the UCL and having to repair it over the last 9 years, averaging one UCL tear every 3 years. Obviously, this is a select demographic, but it does help to emphasize the commonness of this injury.

The problem is: there is not a single currently available product to help alleviate this risk. Level Gloves previously sold an external thumb protector, but it has been taken off the market, leaving people looking for a proactive solution feeling helpless in preventing injury. We spoke to a leading hand surgeon at the Steadman Clinic in Vail, CO, Dr. Randy Viola, about this specific thumb protector, and even when it was readily available, he remarked, "the problem with that brace is that people hate it. It's like having a cast on the thumb". This leads us to believe the primary problem with this protector, and why it was discontinued, stemmed from the lack of comfort and people's inability to retain their normal movements while wearing it. This lack of a proactive solution means the only current market alternative is a retroactive orthopedic brace

only available from professional occupational physical therapists. These are fully constraining and uncomfortable, and don't serve to address the risk before it happens. Thus we have our problem statement: *Skiers need a way to prevent Skier's Thumb injuries that does not inhibit their athletic abilities.*

In summary, we have a problem that is ubiquitous in the skiing world, and yet there is not a single solution out there to prevent it. This leaves a perfect opportunity for passionate groups such as our own to utilize our expert knowledge, access to resources, and motivation to build an effective product that is tailored to what the consumers want and need.

### III. Users and Purchasers

Our suggested product is primarily geared towards preventing UCL tears in all skiers, making both competitive and recreational skiers part of our targeted demographic. The user and purchaser groups are the same. Additionally, we predict that although the need for a protective brace is higher among competitive skiers, the injury is both serious and common enough that recreational skiers would also adopt the brace. Early adopters would be competitive skiers who have previously sustained hand injuries, as they would likely already be on the lookout for a way to prevent this from happening again. Subsequent adopters are recreational skiers seeking to use our protector as a preventative measure. The total addressable user base, including all recreational skiers, is estimated at 13 million skiers annually in the US alone (Statista, 2023). We would be involved in the ski gear and equipment market which represents approximately \$17.70 billion annually (Precedence Research, 2025). Additionally, although the proposed brace solution caters towards skiing, in the future, the project may also be used for its protective capabilities and inspiration in other sports where athletes are susceptible to UCL tears, such as mountain biking or ice hockey.

### IV. State of the Art

#### *Current Market Products*

There are several market products already in existence that aim to prevent Skier's thumb injuries, but these products lack one or many of the characteristics critical to their function and widespread adoption, and in some cases are no longer sold.

The most relevant product that has ever been on the market was the Level Gloves Thumb Protector. This product aimed to solve the issue of Skier's Thumb by developing a hard exterior brace that attaches to the outside of a glove. This design, which succeeded in obtaining support for the thumb during impact, failed to provide the user with an enjoyable experience during the use of this product, and is no longer sold. It inhibited proper movement, was bulky, and didn't allow much if any grip strength. This product was so restricting that, according to Dr. Randy Viola, "It's like having a cast on the thumb all the time". The product was discontinued, and with no current market options, the need for a product that protects the thumb is clear.

The second market product found was an orthopedic thumb brace. This product, rather than being designed for prevention, is aimed at





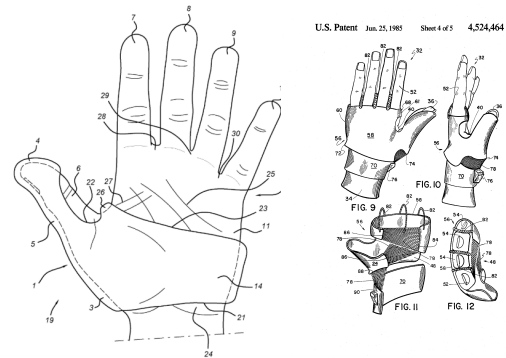
assisting in the recovery and restoration of the injury. It should be noted that, while it aims for recovery, it carries with it the structural integrity to provide preventative measures as well. This product consists of a hard plastic that is located at the joint of the thumb, but is braced with forearm supports. This product, which provides proper support, again fails to provide the user with any thumb mobility. It restricts the gripping ability of the thumb and is very bulky. It is also designed to directly contact the skin, adding a level of discomfort for the user. Additionally, because of its size, it requires the use of larger gloves in order to ski.

### Relevant Patents

There are a variety of patents that protect the hand, and by extension, the thumb, currently in existence, but none effectively prevent the Skier's Thumb Injury while being comfortable and allowing flexibility and grip strength.

Some of the patents that aim to provide ample protection to the thumb provide general hand support through the implementation of hard plastics and structured material to disperse the force of impact from the hand to the arm. This adds substantial weight and material to the product, adding to its discomfort.

Many patents, such as US 4524464 A (left) and EP 2975961 B1 (right), are constructed with gaps in the structure located on the inner thumb. This is meant to allow for mobility and a more effective grip, but in reality the spring-like nature of the material resists motion. Additionally, these designs are intended to contact directly with the skin, meaning they will be a significant source of discomfort.



Both designs consist of large panels of hard plastic and support on both sides of the hand. This creates the mechanism for the dispersion of the impact on the thumb, but it also adds to the bulk and limits other articulations of the hand. The implementation of a strap could provide similar support with much less material and limitation to movement.

### V. Specifications

As is especially the case with devices intended for medical use, this device will require testable specifications to ensure safety and effectiveness. The design and manufacturing process must be ethical, legal, and safe. An important consideration is controlling the range of motion of the thumb, as it is traditional hyperextension and lateral hyperextension (valgus flexion) at the MCP joint (base of the thumb) that causes the most damage to the UCL during a fall. At the same time, the hand must be able to properly grip a ski pole and other objects such as phones and water bottles. Ideally, this device will limit the ranges of motion that put the thumb in a vulnerable position (MCP valgus flexion, MCP extension, and CMC radial abduction), while preserving the ranges of motion that are essential for unhindered thumb flexion and functionality (MCP flexion, IP flexion, and Kapandji grade). Since the thumb is subject to extreme forces in the event of a fall, we must be able to limit the torque acting on the MCP joint, which is where the UCL is located. The device must be capable of raising the torque threshold for injury. Since this is a product designed for widespread use by recreational and professional users, it must be also comfortable enough to wear during a day of skiing with minimal hindrance to the user.



Minimizing weight and thickness is essential, and user feedback is necessary. This is important because no matter how safe we make a product, if it isn't comfortable and easy to use, people will not wear it so it doesn't matter. Please refer to Appendices A, B, and C for diagrams explaining the anatomy and articulations of the joints of the thumb.

| Specification              | Qualitative Justification   | Priority (1-5) | Target Metrics  |
|----------------------------|---|----------------|---|
| Ethical                    | Materials will be sourced from known ethical manufacturing companies.   | 5              | Binary (yes/no)   |
| Safe                       | This device is designed to prevent injuries. None of the materials used are hazardous.  | 5              | Binary (yes/no)   |
| Legal                      | This design does not infringe upon any patents. Assembly of this device will comply with local and federal laws.                      | 5              | Binary (yes/no)   |
| MCP Joint Range of Motion* | See Ritting et al. for valgus safe range. See Barakat et al. for flexion and extension. See Appendix A for the anatomy of the thumb.  | 4              | Valgus <6° in MCP Extension<br>Flexion >45°<br>Extension <8°  |
| IP Joint Range of Motion*  | From Barakat et al. See Appendix A for the anatomy of the thumb.  | 3              | Flexion >70°<br>Extension <12°  |
| CMC Joint Range of Motion* | From Barakat et al. See Appendix B for the articulations of the CMC joint and Appendix D for a visual of the Kapandji grading system. | 3              | Radial Abduction <60°<br>Kapandji Grade >6  |
| MCP Joint Torque           | Baseline torque to injure UCL is 10N*m from Chambers et. al. We wanted to raise this threshold by at least 50%.                       | 4              | 5 N*m increase in minimum torque threshold to injure the UCL. In practical terms, the brace must resist at least 50N of force directed towards MCP hyperextension applied to its end. |



|         |  |   |   |
|---------|--|---|---|
| Comfort | Estimated weight and thickness values for comfort, based on typical glove thickness. | 4 | Weight <100 g<br>Thickness <10 mm<br>User Experience (1-10) |
|---------|--|---|---|

\*It is important to note that these target metrics for range of motion refer to medically researched safe values for a hand with no glove or attachments. To establish accurate baselines with a glove on, we took consistent measurements across a regular, un-modified glove before measuring a glove modified with our implemented brace.

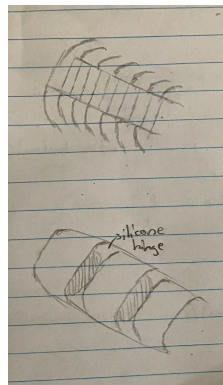
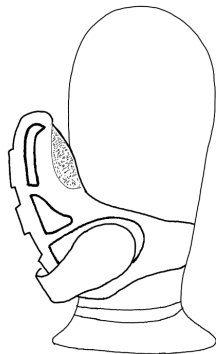
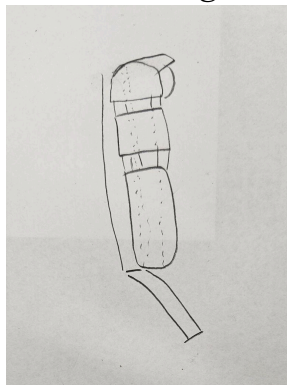
## VI. Problem-Solving Method

To go about choosing which brace design to implement for every iteration, for the first ~8 prototypes, we focused mainly on the range of motion, because this is the basis of what would determine the safety and thus the effectiveness of our design. We would build a prototype, test it to determine if 1), the flexion ranges of motion were preserved so the user would have normal function, and 2), the “dangerous” ranges of motion that put excess stress on the UCL tendon were reduced. We wanted to pay special attention to keeping the precise amount of extension in these ranges as was natural, but as soon as you passed the threshold of a natural range of motion, we wanted to limit mobility and transfer the load into our brace and ultimately disperse it over a larger area in the hand.

Once we had braces that passed these initial range of motion tests, we then subjected them to both qualitative user testing as well as quantitative force measurements using the INSTRON machine to see how much torque it took to force the brace past the allowable range of motion. Getting strict empirical data from the INSTRON allowed us to further refine materials and make the brace as strong as we possibly could. During user testing, we wanted to make sure the brace was as comfortable as possible so that our target demographic would wear it. Our final iteration feels nearly the same as a normal ski glove in terms of comfort, limits hypermobility in dangerous ranges of motion, preserves normal flexion and use of the thumb, and can withstand typical forces needed to tear the UCL without bending past the allowable range of motion.

## VII. Prototyping

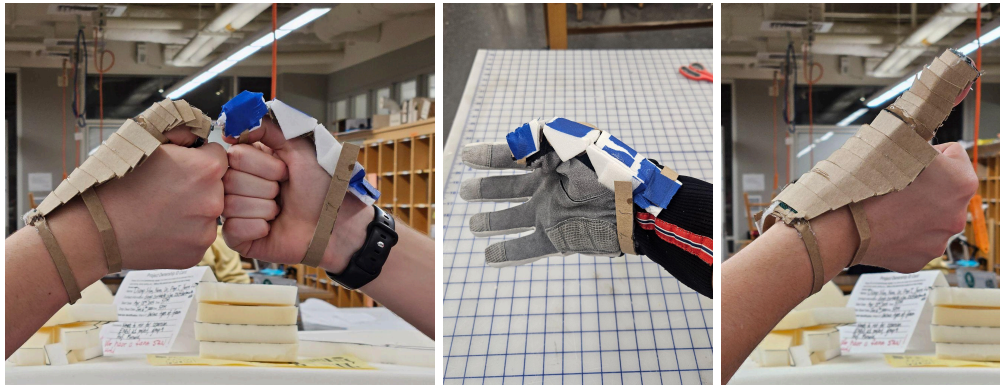
### *Brainstorming and Designing*





Throughout our design process, we iterated extensively to ensure that our device could meet the goals and specifications that we set. Some generations of prototypes involved multiple iterations because the size of our five-member group enabled us to simultaneously design, implement, and test new ideas. Our early sketches and brainstorming led us to consider a brace external to a traditional ski glove with a hinging mechanism to prevent hyperextension but allow safe ranges of motion like flexion towards the palm.

### *First Generation*



The first generation prototypes were made from cardboard, low-quality fabric, hot glue, styrofoam, and cyanoacrylate (super glue). These were very low fidelity, but they provided a good proof of concept of our idea and allowed us to test different mechanisms. We settled on solid scales connected by fabric. Our biggest takeaway from this generation was that the fabric connecting the scales was able to act as a hinge to allow flexion but not hyperextension, confirming our initial hypothesis.

### *Second Generation*



The second generation of prototypes used thermoplastic instead of styrofoam or cardboard for quick prototyping and ease of altering the designs. We quickly realized that thermoplastic would not be mass-producible and repeatable, and we needed a CAD-designed 3D printed part to achieve the accuracy we desired. We also started looking into fabrics with higher tensile strength, such as ballistic nylon or Kevlar, since we thought that would be the primary factor in determining how much force the brace could support.



### *Third Generation*



The third generation of prototypes included our first 3D-printed design, using PLA plastic. Although these were better than previous iterations, we realized that we needed a better CAD design to allow for bending of the brace since the sides would flex into each other due to the curved nature of the brace. Simultaneously, we considered how to address the problem of lateral flexion of the thumb and added a piece of paracord using leverage about a point near the base of the thumb to prevent this dangerous type of valgus flexion. Moving forward, we would use a braided Kevlar cord due to its high tensile strength. We also started experimenting with how to secure the brace to the glove during this time, since it was necessitated by this new valgus prevention piece. Our idea here was to have a wrist strap to help transfer force from the thumb to the wrist via the brace, and another strap just below the knuckles to secure the static end of the new valgus prevention piece.

### *Fourth Generation*



Our fourth generation of prototypes utilized a better CAD design with more tapered “wings” to allow for better flexion, and a small raised spine to give more surface area to prevent the scales from flexing into each other in hyperextension. We used ballistic nylon as the fabric to adhere the 3D printed parts; however, the nylon didn’t adhere properly to the plastic. This led us to search for better adhesives or a different fabric. As with previous prototypes, the CAD design also still needed tweaking for further robustness.



### *Fifth Generation*



During the fifth generation of prototypes, we started using Kevlar to secure the scales, which turned out to bond quite well with super glue. We also further refined our CAD design by making a wider, more raised spine to give more surface area to prevent any sort of backward flexion between scales. We also added holes on the inner sides of the wings of the terminal five scales to allow for this valgus prevention piece from the previous generation to be threaded through effectively. Both were a step in the right direction, but we realized we needed some interlocking mechanism to prevent the design from twisting into a helix during use. This led to male/female interlocking parts in the following generations.

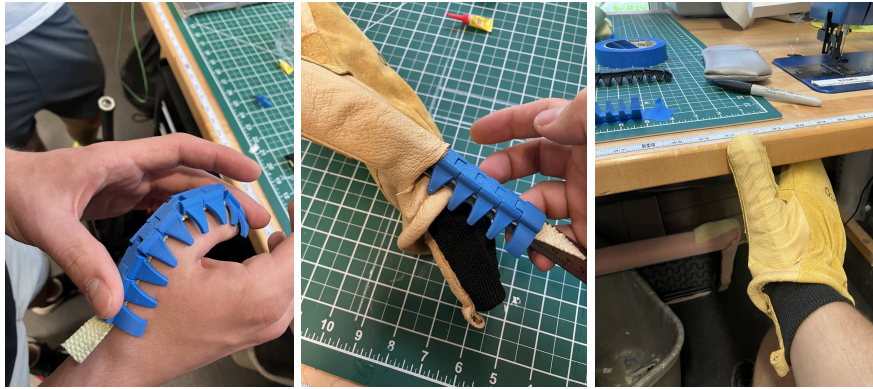
### *Implementation Shift*



Between the fifth and sixth prototypes, we shifted our intended implementation strategy for our mechanism, that is, to integrate it into the layers of the glove itself, as opposed to an external brace or a mechanism that directly contacts the hand inside the glove. This shift was motivated by preliminary observation and testing of the prototype external brace shown below. The external brace and strap were far too thick for the user to be comfortable. We knew comfort and ease of use would be paramount in a device if we wanted users to use it every day that they ski, so if we could somehow deliver a glove to the users that was already altered and ready to use, this would find much more success.

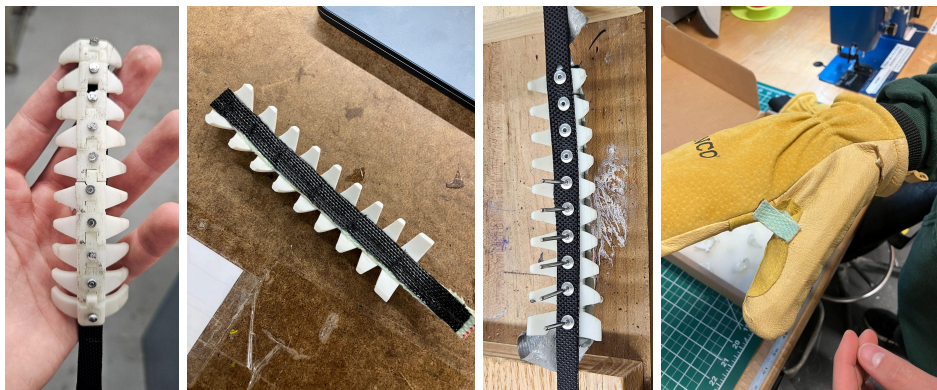


### *Sixth Generation*



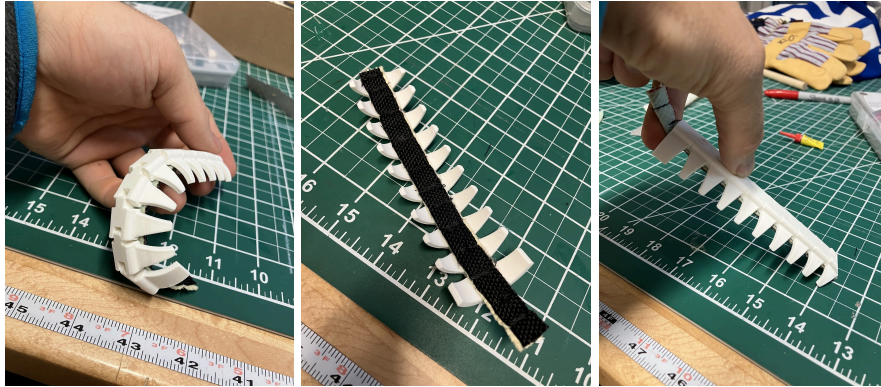
By the 6th generation, we had finalized the CAD design for the protector. The major improvement with this generation was the addition of male and female parts, which improved both the stability and the lateral stiffness of the brace, acting as a measure of internal protection against the valgus flexion without the need for Kevlar cord or extra straps. This device finally met the requirements of our range-of-motion testing (to be discussed in the next section), but when we force-tested it with the INSTRON machine, we found that the Kevlar tended to stretch under intense strain. Now that we had a workable CAD model, we also wanted to move ahead with better materials than the standard PLA we had used for prototyping, which would hopefully have a higher compression strength and would be able to sustain more force. During this generation, we also began moving forward with our new implementation strategy inside a Kinco mitten.

### *Seventh Generation*



This led us to the 7th generation, in which we tested a wide range of materials and adhesives. For the solid elements of our protector, we tested ABS, Urethane (a photopolymer), and rigid glass-reinforced resin. We attempted to use rivets instead of adhesives with our glass resin model, which led us to understand that both riveting and rigid resin were undesirable for our project due to difficulty in accurately spacing each piece during riveting and excessive brittleness of the resin, which tended to crack and snap under load. Additionally, to combat the stretching of the Kevlar, we cross-stitched Kevlar with ballistic nylon to preserve the superior adhesion and flexibility of the Kevlar while preventing excessive stretch with the superior tensile strength of the nylon. Additionally, to augment our implementation into the glove, we attached a small strap of Kevlar between the thumb and the index finger to provide extra support against valgus hyperflexion.

### *Eighth and Final Generation*



Our final brace (see above) utilizes the Urethane photopolymer with super glue as the adhesive, and cross-stitched ballistic nylon and Kevlar serving as our fabric hinge. For our final model, the brace is integrated between the layers of our ski glove, just under the outer leather, and sealed shut with superglue. In future models, this could be sealed shut by sewing instead for visual appeal. See below for pictures of the final integrated glove with protector. See Appendix D for drawings of our final 3D model from SolidWorks.



### **VIII. Testing And Analysis**

It should be noted that because of the nature of our brace, and really any preventative orthopedic brace, it is difficult to conduct real-life testing and analysis due to the ethical and



safety considerations of intentionally putting people in harm’s way. For this reason, all of our tests were conducted in the lab with appropriate safety measures to simulate skiing conditions and forces.

### *Range of Motion Testing*

The first major test we conducted was range of motion testing. This test was first because it allowed us to quickly determine the effectiveness of new prototypes and designs. It allowed us to adapt and change our designs efficiently and methodically. Once we settled on a specific design, we utilized a strict set of tests to measure the effectiveness of the brace in limiting the range of motion of the MCP joint (base of the thumb where the UCL is located) in hyperextension and valgus flexion (the two ranges that put the most stress on the ligament), and radial abduction of the CMC joint as well since that motion also adds load to the UCL. In addition to limiting the previously mentioned ranges, we also sought to maintain the range of motion of IP flexion, MCP Flexion, and Kapandji Grade, so users could flex their thumb as they normally would and have proper function. See Appendices A, B, and C for visuals corresponding to the anatomy of the hand and each range of motion. Each of these measurements was taken using a digital protractor first with a regular glove, and then again with a glove that had the brace implemented into it. Due to the nature of wearing gloves, there is often some wiggle room for the hand within each measurement. For this reason, the measurements for range of motion needed to be recorded with as little variation as possible. To accomplish this, all of the measurements for a given participant were conducted and recorded by the same person, meaning every measurement recorded followed the same procedure and reduced experimental error drastically.

Table 1: Range of Motion Raw Test Data

|           | Participant | IP Flexion (°) | MCP Flexion (°) | Kapandji Grade | MCP Extension (°) | MCP Valgus Flex (°) | CMC Radial Abduction (°) |
|-----------|-------------|----------------|-----------------|----------------|-------------------|---------------------|--------------------------|
| GLOVE     | Holden      | 52.70          | 58.80           | 8              | 17.50             | 27.90               | 37.90                    |
| GLOVE     | Peyton      | 50.60          | 57.70           | 9              | 18.70             | 42.50               | 26.30                    |
| GLOVE     | Kabir       | 53.70          | 37.30           | 9              | 14.70             | 48.90               | 35.40                    |
| GLOVE     | Kyle        | 52.40          | 68.00           | 8              | 9.80              | 18.80               | 27.00                    |
| GLOVE     | Chase       | 56.80          | 44.20           | 8              | 21.70             | 38.00               | 42.80                    |
| PROTECTOR | Holden      | 53.80          | 51.40           | 8              | 6.30              | 18.20               | 26.10                    |
| PROTECTOR | Peyton      | 54.60          | 62.80           | 9              | 9.40              | 35.70               | 20.70                    |
| PROTECTOR | Kabir       | 53.90          | 33.40           | 9              | 8.70              | 29.60               | 24.20                    |
| PROTECTOR | Kyle        | 51.00          | 66.00           | 8              | 4.70              | 11.70               | 22.00                    |
| PROTECTOR | Chase       | 54.20          | 45.30           | 8              | 11.10             | 30.30               | 29.60                    |



Table 2: Average Values Measured

|                 | IP Flexion (°) | MCP Flexion (°) | Kapandji Grade | MCP Extension (°) | MCP Valgus Flex (°) | CMC Radial Abduction (°) |
|-----------------|----------------|-----------------|----------------|-------------------|---------------------|--------------------------|
| Average (glove) | 53.24          | 53.20           | 8.4            | 16.48             | 35.22               | 33.88                    |
| Average (brace) | 53.50          | 51.78           | 8.4            | 8.04              | 25.10               | 24.52                    |

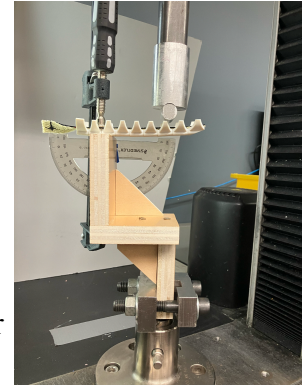
Table 3: Percent Change

|                         | Participant | IP Flexion (%) | MCP Flexion (%) | Kapandji Grade (%) | MCP Extension (%) | MCP Valgus Flex (%) | CMC Radial Abduction (%) |
|-------------------------|-------------|----------------|-----------------|--------------------|-------------------|---------------------|--------------------------|
| Change                  | Holden      | -2.09          | 12.59           | 0                  | 64.00             | 34.77               | 31.13                    |
| Change                  | Peyton      | -7.91          | -8.84           | 0                  | 49.73             | 16.00               | 21.29                    |
| Change                  | Kabir       | -0.37          | 10.46           | 0                  | 40.82             | 39.47               | 31.64                    |
| Change                  | Kyle        | 2.67           | 2.94            | 0                  | 52.04             | 37.77               | 18.52                    |
| Change                  | Chase       | 4.58           | -2.49           | 0                  | 48.85             | 20.26               | 30.84                    |
| <b>Average % Change</b> |             | <b>-0.62</b>   | <b>2.93</b>     | <b>0</b>           | <b>51.09</b>      | <b>29.65</b>        | <b>26.69</b>             |

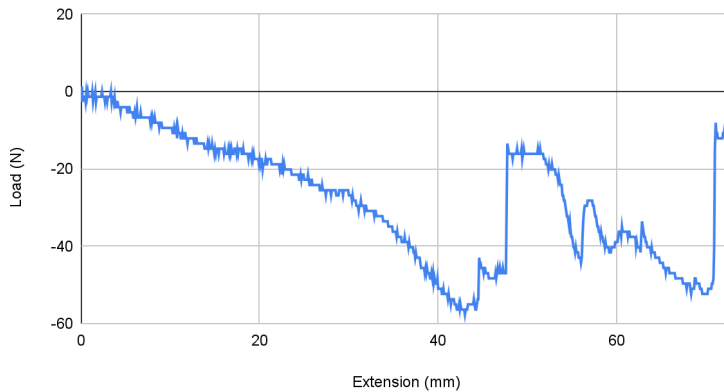
The main takeaway from Tables 1-3 is highlighted in yellow at the bottom of Table 3. Tables 1 and 2 show the data collected from the range of motion testing on each individual. Due to variation in individual flexibility, the most important findings are the percent change between gloves with and without the brace, rather than the individual measurements themselves. As seen in Table 3, it is clear that the three main ranges of motions that the brace is supposed to allow are almost completely uninhibited. The IP flexion, MCP Flexion, and Kapandji Grade all had percent changes of less than 5%. This, when considering experimental error, is roughly no change in range of motion. In addition to these metrics, the 3 ranges of motion that the brace was designed to prohibit were reduced by 50%, 30%, and 25% (MCP extension, MCP valgus flexion, and CMC radial abduction, respectively). An important note with this is that we wanted to preserve all natural motion of the thumb, so we were wary of taking away too much range of motion for these movements to where it would feel “off” for the user. So when testing with a normal glove, we pushed past a comfortable range into unnatural ranges of motion where the ligament was put under load. This is what we were aiming to take away, while keeping all function extension and valgus flexion. Through this testing, it was clear that our brace maintains flexibility in the required ranges, but limits the range of the dangerous movements for the UCL.

### Force Testing

The second major test conducted was the Force test. The purpose of this test was to determine how much force each brace could withstand while still being within a safe range of extension. To conduct this test, the INSTRON was utilized to provide and accurately record the force being put into each prototype. To mount each brace to the Instron, we constructed a wooden attachment to interface with the machine. This attachment allowed the brace to be positioned with a C-clamp such that the INSTRON would make contact with the end of the brace. A protractor was placed behind it to measure the degrees of extension, and the Instron pushed down on the end of the brace to provide a torque and simulate an impact. This process was repeated with three different prototypes to determine the most effective material combination for withstanding the most force while staying within the safe range of extension. The safe range of extension for this test was under 28 degrees, which was determined by taking the maximum safe extension across the two joints acting in this test, the MCP and IP. The safe range was calculated by adding the MCP measured normal ranges of extension from our testing and medically researched IP joint safe ranges of extension. If a thumb was in the brace, these would be the only joints involved between the C-clamp and the point of contact with the INSTRON.

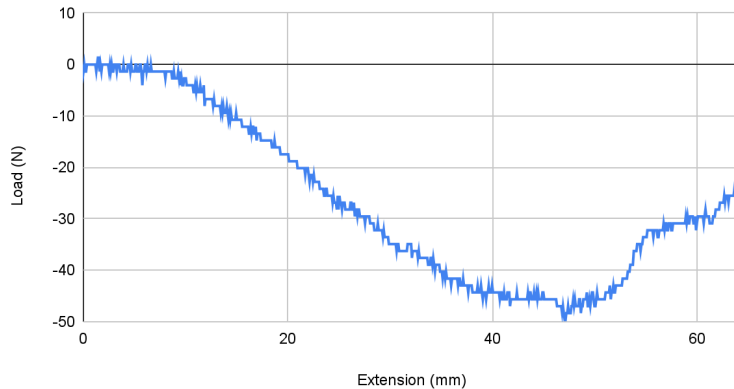


Load (N) vs. Extension (mm) PLA WITH KEVLAR



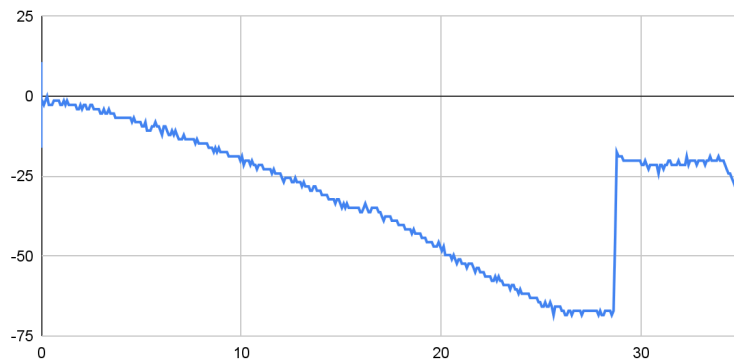
The first of the three tested prototypes was a 3D-printed PLA brace superglued to Kevlar. As seen in the graph above, it withstood about 55 Newtons of force at an angle of 45 degrees and continued to flex until 55 degrees. This model not only surpassed the safe range for extension, but the Kevlar itself stretched and was not as rigid after the test. This observation forced a re-evaluation of the fabric used in our brace.

Load (N) vs. Extension (mm) ABS WITH KEVLAR AND NYLON



The second prototype tested was a 3D printed ABS material superglued to Kevlar, cross-sewn into two sheets of ballistic nylon. As seen on the graph above, this brace withstood roughly 47 Newtons of force while allowing 35 degrees of extension before crushing and continuing to flex until 45 degrees of extension. Interestingly, the ABS crushed under less force than the PLA. This model again surpassed the safe range of extension, but in addition, the scales themselves were crushed by the force between the pieces. While this didn't provide us with a material to use for the brace, it did prove that the Kevlar and nylon cross-sewn worked well together to provide a higher tensile strength.

Load (N) vs. Extension (mm) PHOTOPOLYMER WITH KEVLAR AND NYLON



The third and final prototype, tested with the Instron, was a urethane photopolymer super-glued to the same Kevlar and ballistic nylon combination. As seen in the graph above, this prototype withstood 67 newtons of force while allowing an extension of 25 degrees. At 67 newtons of force, the superglue gave out and popped off. Since the photopolymer withstood the most force while remaining within the safe range of extension, this prototype was picked as the current material for our prototype. It should be noted that for future models, a stronger adhesive will be sought out (possible options include Gorilla Super Glue or UV-cure glue).

Using the data taken from the photopolymer prototype, we effectively redistributed 67 N of force more evenly along the thumb and hand. This protector reduces the torque acting on the



MCP joint where the UCL is attached by approximately 6 Nm, assuming a lever arm of 9 cm. For context, a typical UCL tear requires approximately 10 Nm of torque applied to the MCP joint.

This means that we have raised the threshold for tearing the UCL by **60%**, demonstrating that our brace is an effective preventative measure for UCL tears.

### *Comfort Testing*

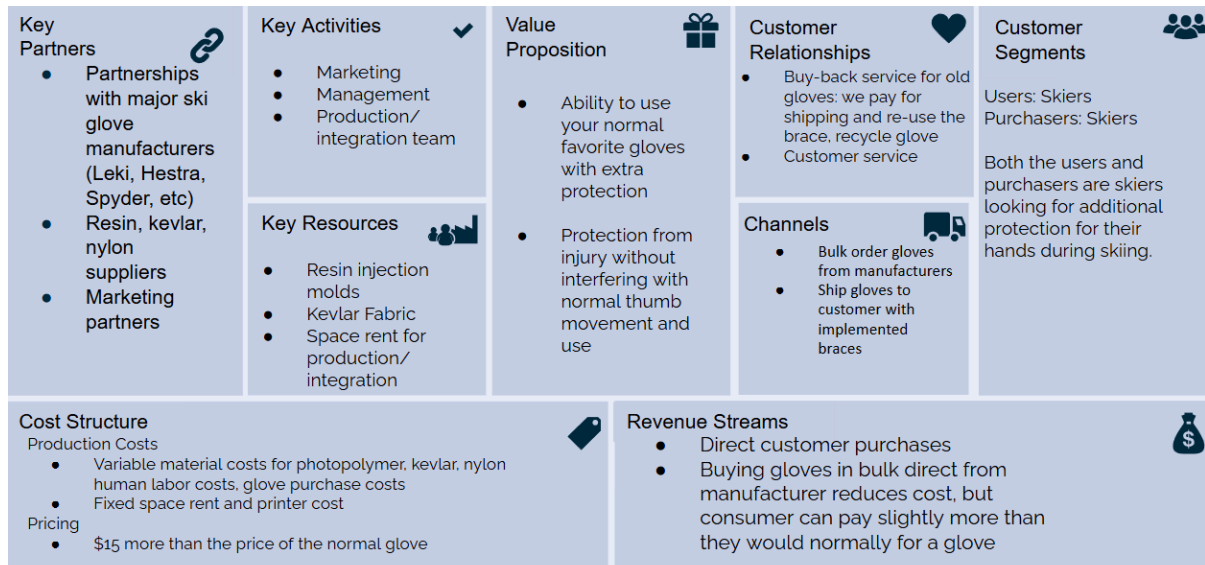
The final component of our testing involved measuring the weight and thickness of our brace and conducting a user survey. The weight was 20g and the thickness was 8mm on our final prototype, which is under both the max thresholds we set at 100g and 10mm for user comfort. The user survey involved comparing an unaltered glove to a glove with our brace implemented. We surveyed 18 potential consumers with the group, including ski racers, recreational skiers, and non-skiers. Participants were asked to rate the braced glove on a scale from 1-10 in resting comfortability and comfort while gripping something to emulate a ski pole. Setting the unbraced glove as having a comfortability of 10, users rated their resting comfortability with the brace to be 9.9/10, and gripping comfort to be 9/10. We also asked users to say how much extra they would be willing to pay to have a braced glove. Users said on average they would pay an additional ~ \$19.64 beyond the standard glove price to have our brace.

## **IX. Ethics and Sustainability**

As with any product, our device needs to be both ethical and sustainable. The biggest concern relating to ethics is that we must make clear that we cannot guarantee the user's safety when using our device. While we might be able to increase the threshold at which the user injures their thumb, in no way will this prevent all manner of thumb injuries, and should not be considered medically approved. Due to the inevitable environmental impact of producing materials rigid enough to form the scales on our brace, we must also take care to only source our materials from companies that hold their manufacturing processes to high ethical standards relating to the environment and their employees. Moving forward, there will be more research needed to find more environmentally-friendly alternatives to both the Kevlar/Nylon combination and the Urethane photopolymer which can provide the same tensile and compression strength, respectively. To address the sustainability and impact of our product, we will develop a send-back program to recycle braces into new gloves once the glove material wears out, since the gloves will wear out much faster than the brace inside them will. Our design is also modular, so we can replace single scales if one breaks instead of replacing the entire brace. While there are significant constraints concerning the strength of our materials, to the best of our ability we will continue searching for more sustainable and ethical processes for all of the materials and processes involved in this brace.

## X. Business Plan

Our business model revolves around buying in-bulk the ten most popular gloves on the market, modifying them by implementing our brace, and selling them directly to consumers. We will establish and utilize relationships with major glove manufacturers so that we can offer our customers the possibility of continuing to use their favorite gloves, but with added protection and peace of mind. Expanding our design to multiple styles will take some time, but it is made possible because of the similar design features in every major glove: an inner layer, layers of insulation, and a durable waterproof exterior. Key aspects of our business model are outlined in further detail in the figure below.



Our cost structure consists of both variable and fixed costs. Variable costs include the cost of the urethane photopolymer, nylon, and Kevlar used in each unit, as well as the estimated cost of transportation. We estimate that our brace will cost \$0.54 per unit (2 braces). Fixed costs include the initial cost of an injection mold, as well as the annual costs of an executive salary, rent for the workspace, and advertising. We estimate that our startup costs will be \$50,000, with an additional \$90,000 annually.

| <u>Variable Costs (per unit)</u> | <u>Fixed Costs</u>        |
|----------------------------------|---------------------------|
| Photopolymer - \$0.10            | <u>Startup</u>            |
| Nylon - \$0.06                   | Injection Mold - \$50,000 |
| Kevlar - \$0.18                  |                           |
| Transportation - \$0.20          | <u>Annual</u>             |
| <hr/>                            | Executive - \$50,000      |
| Total - \$0.54                   | Rent - \$20,000           |
|                                  | Advertising - \$20,000    |
|                                  | <hr/>                     |
|                                  | Total Annual - \$90,000   |



Based on our user survey of the brace, customers are willing to pay around \$20 per unit, agreeing that this is a reasonable price to pay once for a long-lasting solution that potentially saves thousands in medical bills. To gain traction, and considering that people are always more willing to spend hypothetical money, we will begin by selling this device at \$15. Considering the relationships that we will have with ski glove companies, we can potentially obtain a certain glove for \$10 cheaper than the listed price to customers. Then, selling to a customer at \$15 above the listed price, we can take a revenue of \$25 per unit. By subtracting the cost from the revenue per unit, we can profit \$24.46 per unit sold. Given the estimated startup and annual costs, we will need to sell 2044 units to recoup our startup costs, and an additional 3679 units to break even annually. If we sell to just 1% of the US market in a given year (130,000 skiers out of 13 million annually), then we can profit over \$3 million.

#### **Profit Analysis**

Annual Costs / Profit per unit = Annual breakeven  
 $\$90,000 / \$24.46 = 3679$

Startup Costs / Profit per unit = Initial breakeven  
 $\$50,000 / \$24.46 = 2044$

Profit per unit \* (units sold - annual breakeven units) = Total Profit  
 $\$24.46 * (130,000 - 3679) = \$3,089,811$

## **XI. Reflection**

### *Improvements and Future Steps*

One major improvement we would like to make is the optimization of materials. While we did test with a wide variety of materials, we acknowledge that there is still major scope for improvement. For example, we would like to source a higher grade of Kevlar, ideally military grade, with a higher tensile strength to reduce stretching. More importantly, we'd like to find the most effective adhesive for our mechanism, as the failure of the superglue we utilized was the reason why our final prototype gave out during testing. We will also research the process of injection molding, which is comparatively much more scalable and industry-friendly than 3D printing.

As discussed in the business plan, we will compile a list of the top 10 most popular ski gloves on the market, and work with an expert seamstress/seamster to find the most effective way to integrate our mechanism in each. This will provide the highest amount of protection as well as maintain maximal aesthetic value. Another future consideration would be sewing nylon onto the underside of the leather of the glove itself, which could protect the glove from wear from the inside due to the raised spine of the mechanism during flexion. Overall though, the biggest improvement to make this scalable moving forward would be to invest in an injection mold and learn more about that process so we could overcome the production limitations we would quickly hit with 3D printing.



### *Lessons Learned*

During this process, we learned much about the importance of iteration. Each prototype revealed new design constraints and opportunities that were not necessarily obvious before we could hold a physical device in our hands. Ideation is great, but we only truly realized the issues and benefits of a certain design once we built and tested it. We also learned that materials are often the make-or-break difference in taking a design from a concept to a physical device. Frequent testing with a variety of materials is necessary to make sure the best material is found for a given application. In our case, material shifts made a surprising difference when we started looking at objective data during our testing, even when using the exact same designs. We had a lot of work to do with so many generations of prototypes and so much testing, and quickly realized this would only be possible if we relied on each other's strengths as a group. Our productivity was exponentially increased once we stopped trying to do every piece of the project as a group and delegated different tasks based on where talents and passions appeared. Of course, this necessitates good communication and commitment from everyone for the group to realize the full potential of our productivity. An additional reflection from this project was that sustainability and medical devices do not often go hand-in-hand due to the huge number of constraints that medical devices have, including strength and safety for the user. However, given the impact on sustainability on our world today, product designers must do their utmost to implement sustainable design into their processes and protect our world for generations to come.



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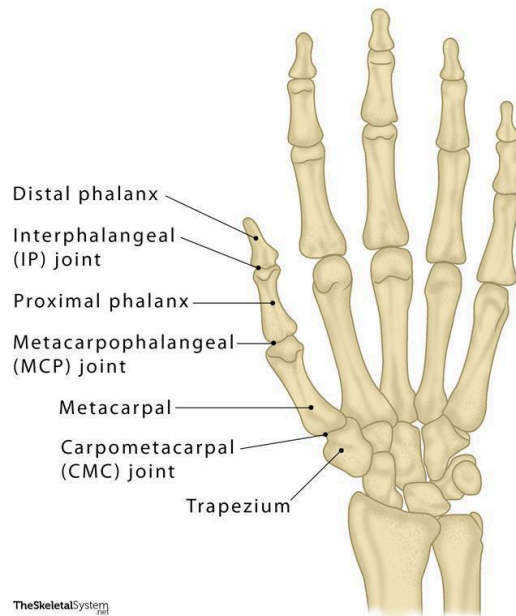


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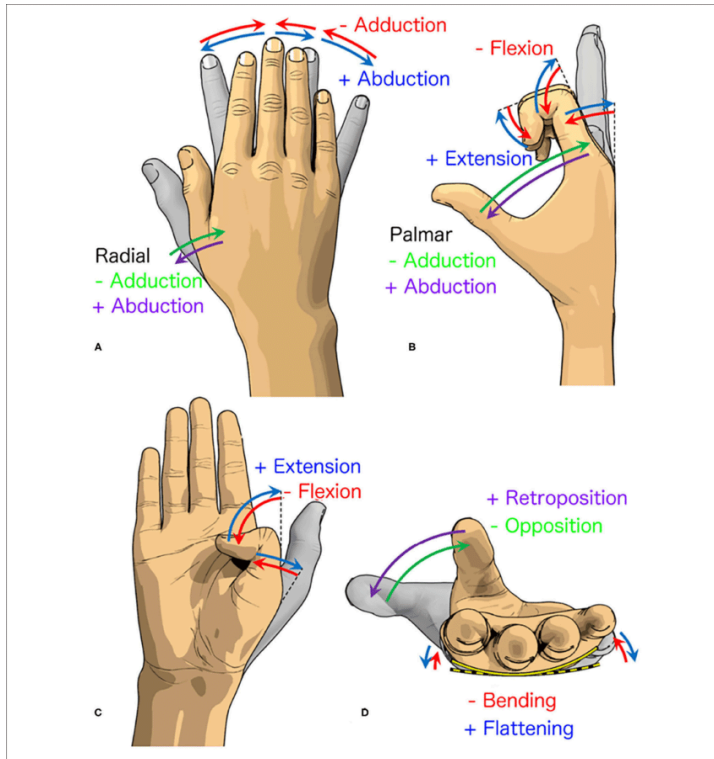
## Appendix A

### Bones in the Thumb



Note: Bones in the thumb. This image is from <https://www.theskeletalsystem.net/hand-bones>.

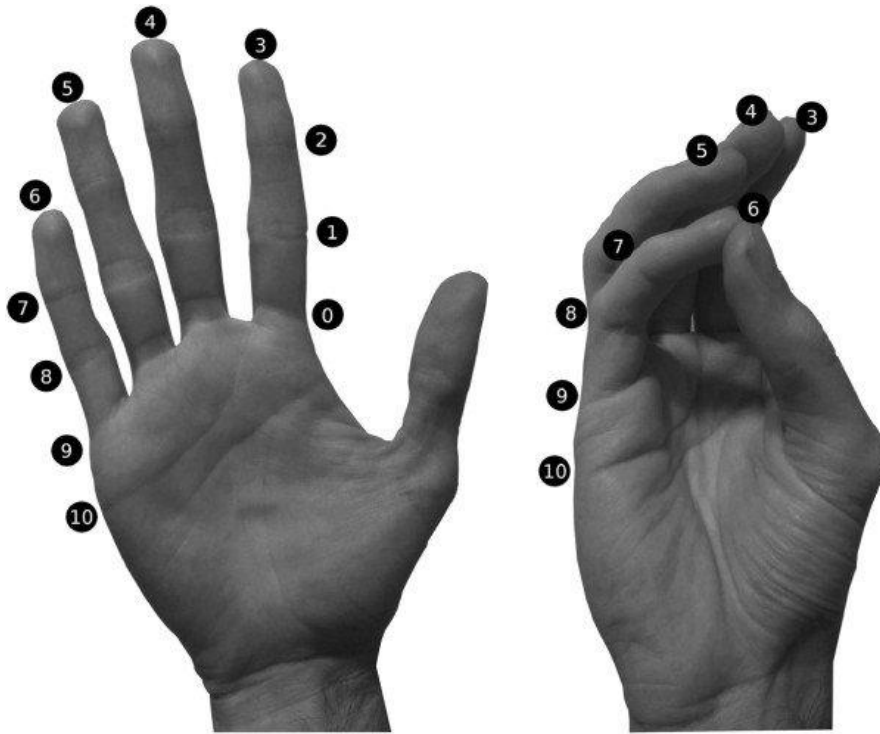
## Appendix B



Note: Articulations of the CMC joint of the thumb. This image is from [https://www.researchgate.net/figure/Various-movements-of-the-fingers-A-The-radial-abduction-adduction-of-the-thumb-and\\_fig5\\_348437896](https://www.researchgate.net/figure/Various-movements-of-the-fingers-A-The-radial-abduction-adduction-of-the-thumb-and_fig5_348437896).



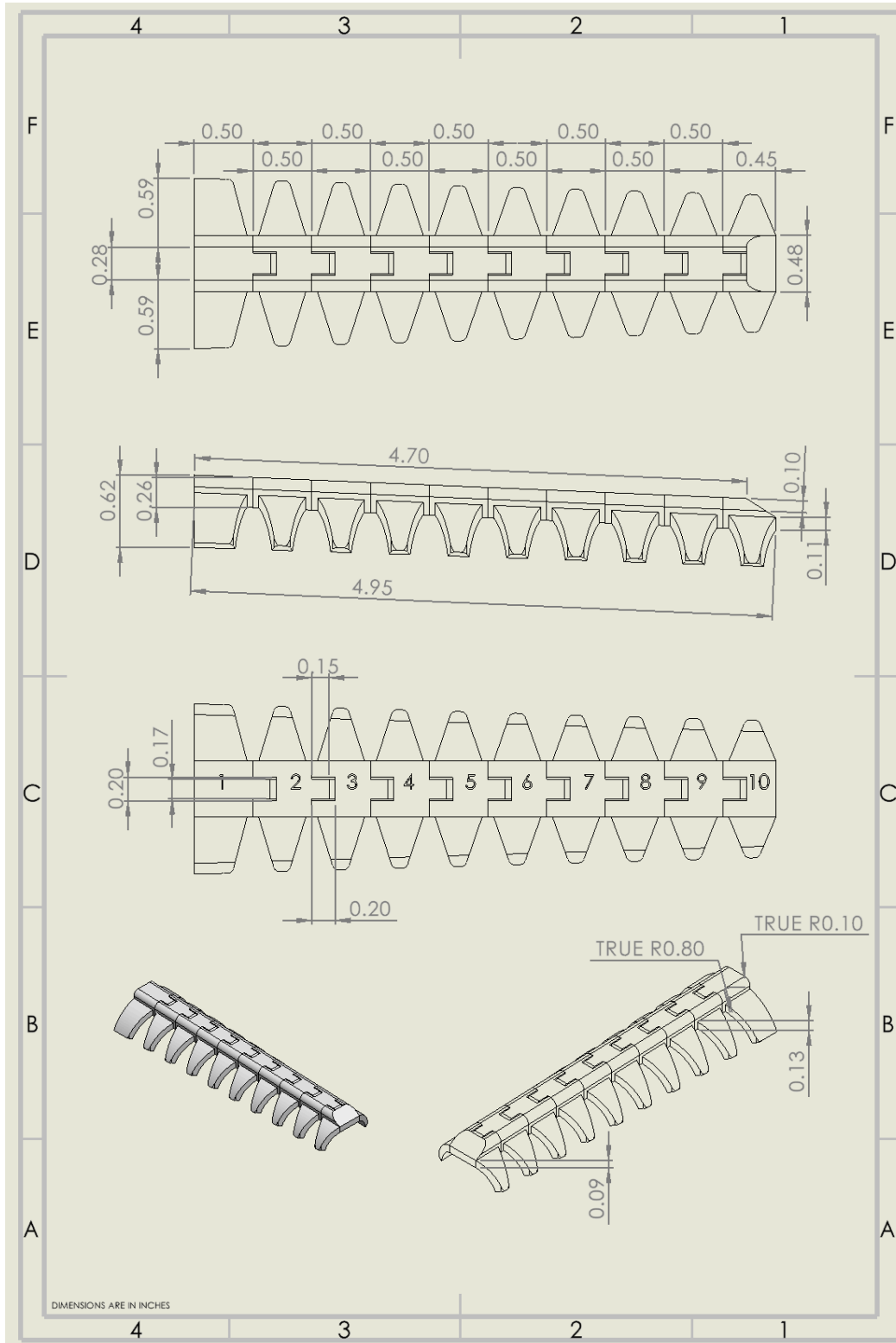
### Appendix C



Note: Visual of the Kapandji Index. This image is from [https://www.researchgate.net/figure/Kapandji-thumb-opposition-scores-A-score-of-0-indicates-no-opposition-a-score-of-10\\_fig1\\_259955074](https://www.researchgate.net/figure/Kapandji-thumb-opposition-scores-A-score-of-0-indicates-no-opposition-a-score-of-10_fig1_259955074).



### Appendix D



Note: Drawings of the final 3D model used in our brace.