Bistable Orthosis Process Deliverable

June 28 - July 31, 2024

3D Printable Paralysis Orthotics with Bistable Microstructures

Paralysis can stem from a variety of causes, each leading to dysfunctional joints or muscles and significantly hindering individuals' ability to carry out everyday activities. For instance, weakened quadriceps following a stroke can hinder one's ability to walk on uneven ground due to difficulty in lifting the knees, which impacts the patient's quality of life severely. The design of commonly used ankle-foot orthotics (AFOs), with their distinctive "L" shape, aims to provide necessary support and stabilization for the lower leg. However, due to their rigidity, they increase the fall risk when walking on uneven or sloped surfaces [1-3] as they don't accommodate changes in gait patterns effectively. While robotic orthoses mitigate this issue, the simpler passive orthotics are more widely used due to their significantly lower cost, lower maintenance, and smaller size which lets users wear them inconspicuously under clothing.

In this project, we plan to design a novel, **passive orthotic** based on **bistable mechanisms**, which are engineered to maintain two stable states without the need for continuous power, making them well-suited for precise positioning and adaptation without actuation. We plan to tune the structures' shape parameters to adapt the force required to switch the state from a stiff configuration offering support to a soft configuration allowing movement. During movement, if the user applies a small amount of force, it can trigger the shape change, allowing for detection. This can then trigger the stronger bistable structures to provide support. As a result, the transition between these states can be triggered by the user's motion, changes in muscle activity detected by the system, or can be manually controlled based on the user's preference. Additionally, the ease of being 3D-printed and customized is crucial for adjusting this mesh when there is a change in muscle strength.

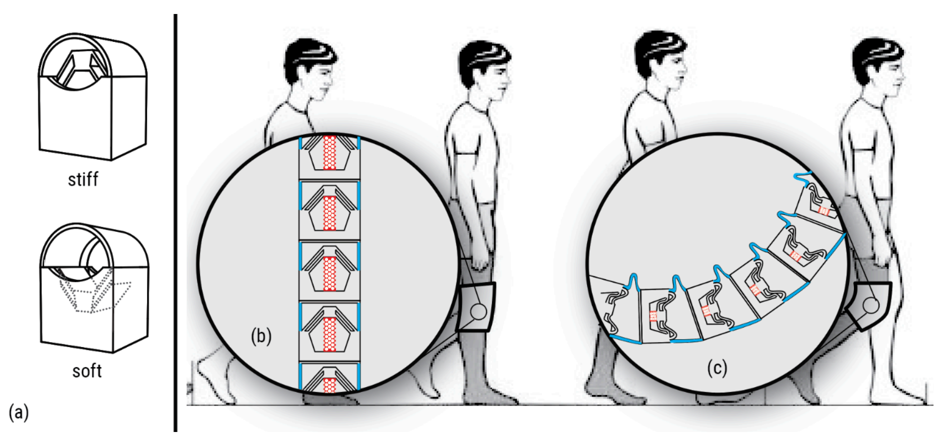


Fig. 1: Overview of our proposed knee orthotic composed of microstructures: (a) Our bistable cell can have both stiff and soft states. (b) When there is a load on the paralyzed leg during a gait cycle, the cell is in a stiff state to provide support. (c) When there is no load on the paralyzed leg during a gait cycle, the cell switches to a soft state to allow free movement.

Physical Iterations

Initial Sketch:

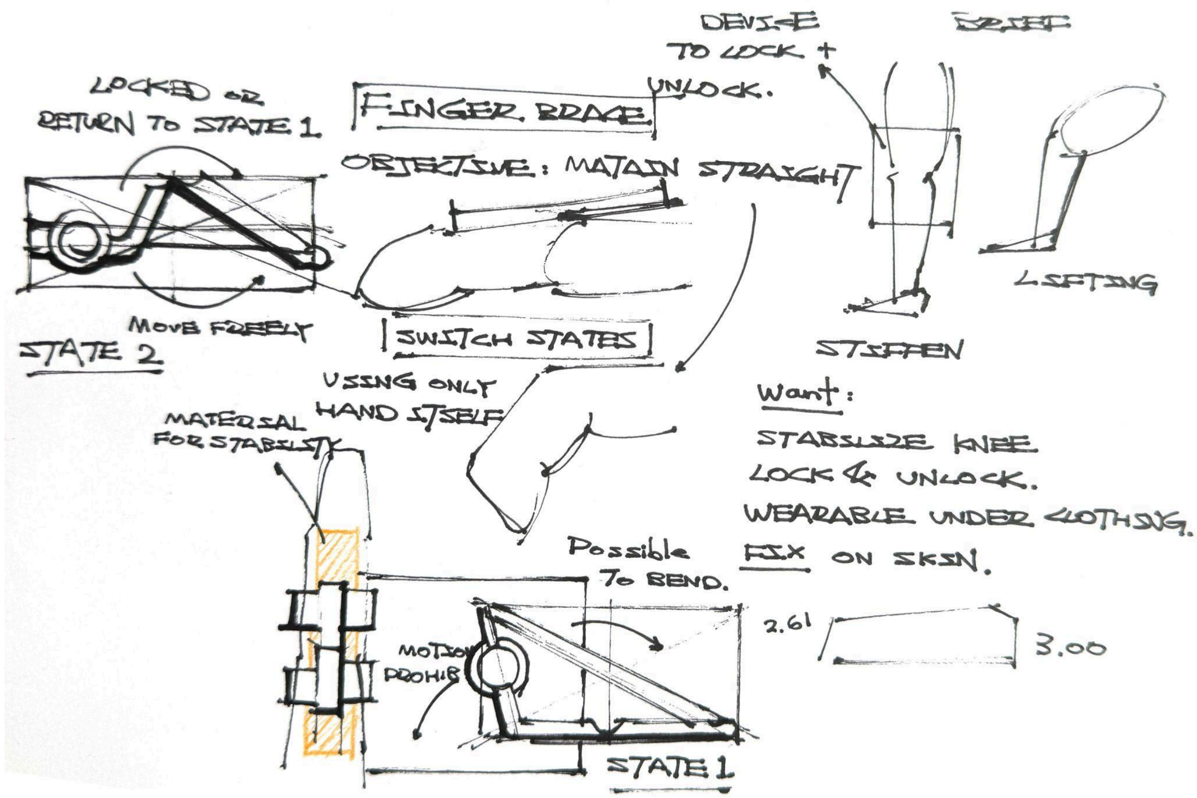


Figure 1.0 Exploring the purpose of the device and clarifying the two bistable states.

Initial Prototype:

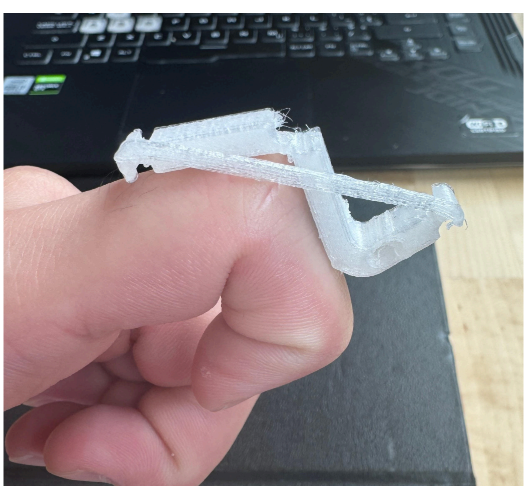


Figure 1.1 Unstable and band interferes with finger.

Instability Solution:

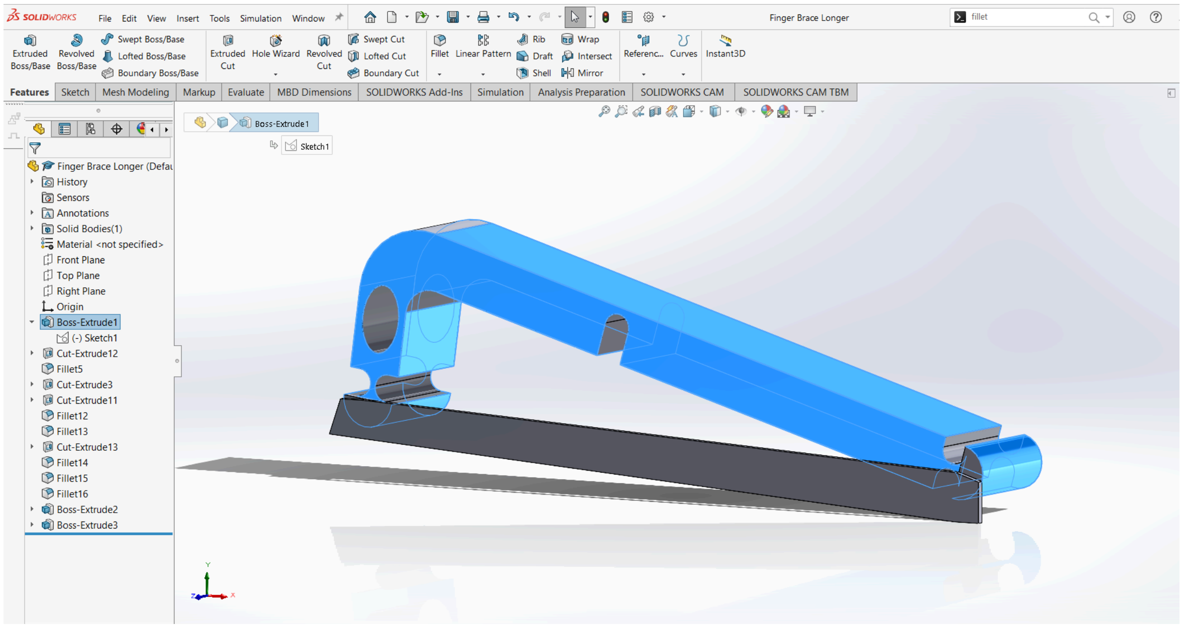


Figure 1.2 Increased the total length of the brace from 45mm to 52 mm.

Figure 1.3 Failed Prototype. Removing the bottom hinge caused the brace to lose bistability – snapping back up immediately once bent.

Solution for band interference with finger movement:

We attempted to move the band up in parallel to its original position, keeping the geometry constant.

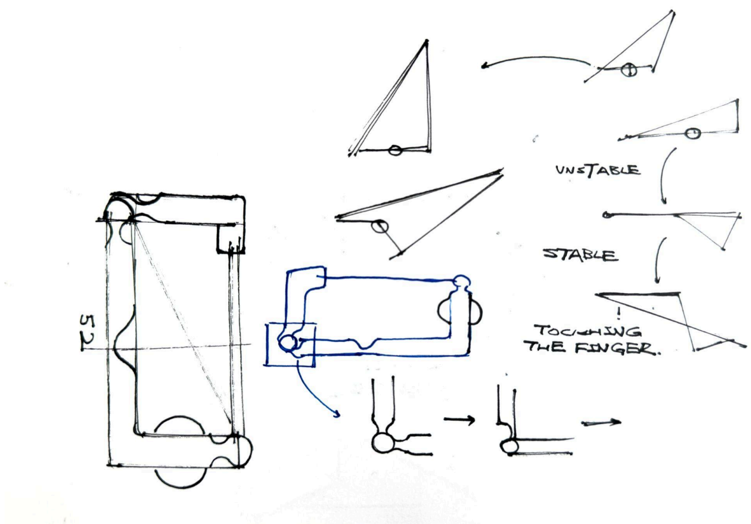


Figure 1.4 Idea Proposition

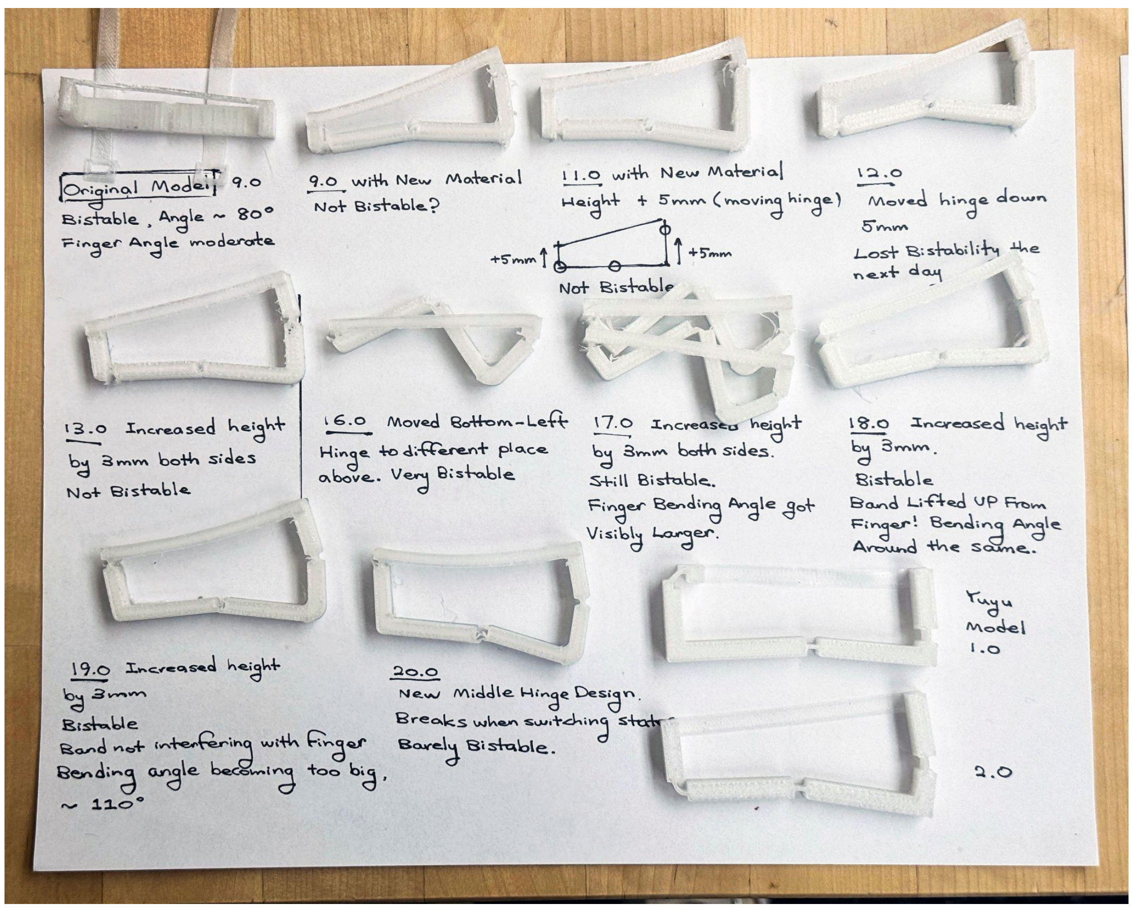


Figure 1.5 Iteration Map of Process

Through iterations 9.0 to 13.0, we incrementally increased the height of both vertical sides. However, the prototypes were unable to maintain their bistable state, resulting in them snapping back once bent.

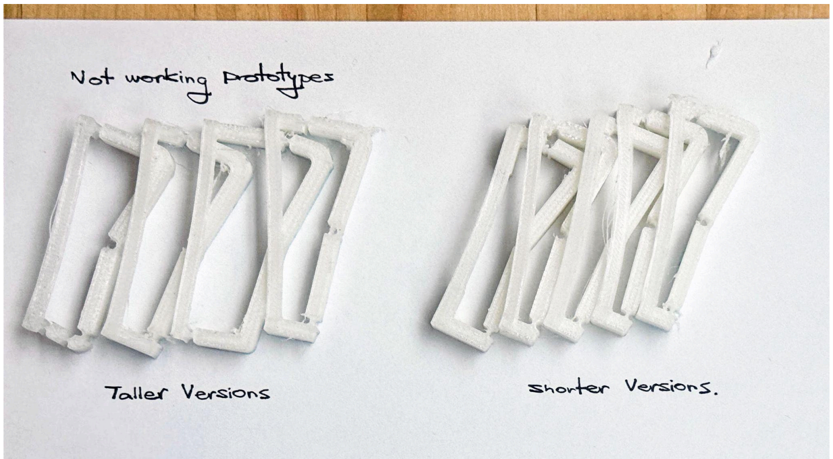


Figure 1.6 Not working braces.

Then, we tried different hinge designs and brace heights, and most of them were not bistable.

At version 16.0, we raised the hinge to a different elevation, which worked to keep the design bistable.


Figure 1.7 Pre 16.0. The hinge position is at the lower left and the prototype is not bistable.

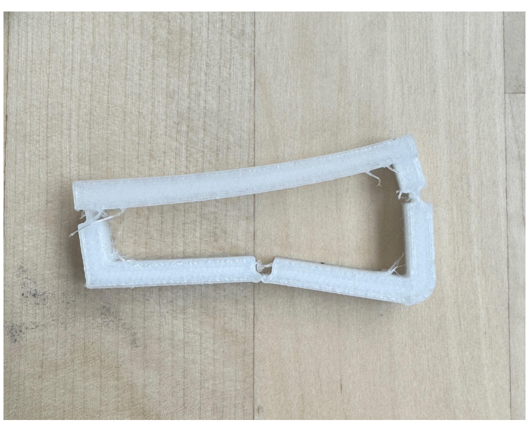


Figure 1.8 Version 16.0. Moved the hinge position to the upper left and fixed the lower left angle – everything else is kept the same. The prototype is now able to be stable at the bent state.

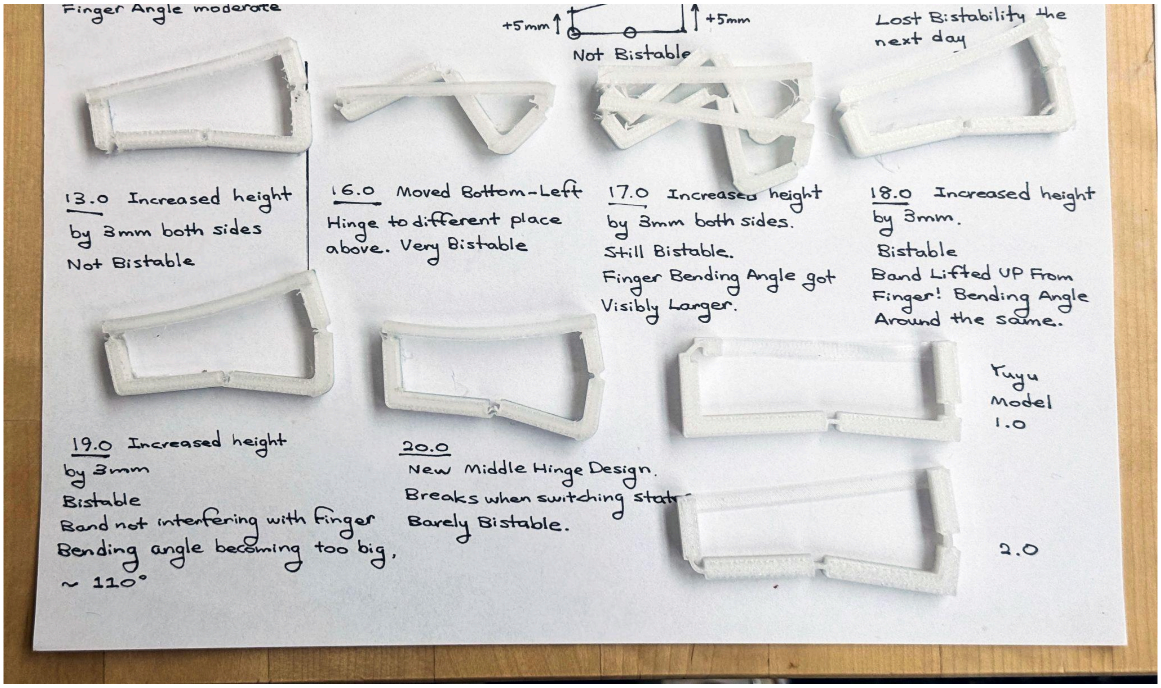


Figure 1.8 We further iterated upon the 16.0 model, increasing the height to keep the band from interfering with finger movement.

At Version 19.0, by increasing height by 9mm compared to Version 16.0, we were able to create a design in which the band is not in contact with the finger.

Figure 1.9 The Band is separate from the finger in the bent state. However, the brace's height is quite tall and the bending angle is large.

New Hinge Explorations

We noticed that the hinge often deforms after long-term use. So we redesigned the hinge to be thinner for more flexibility.

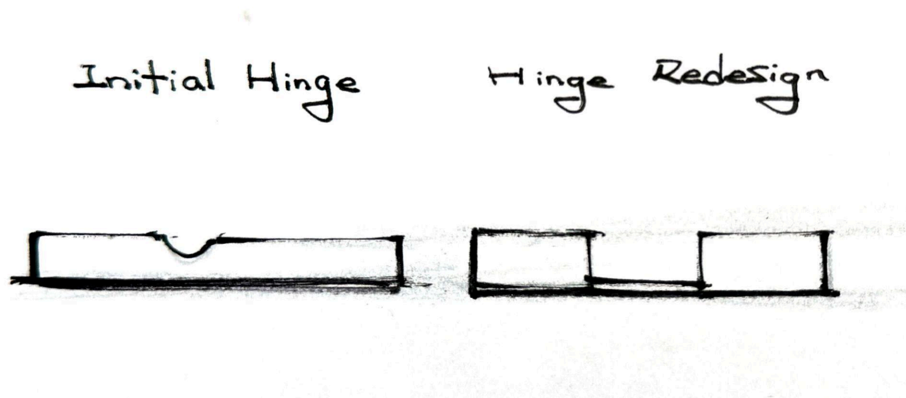


Figure 2.0

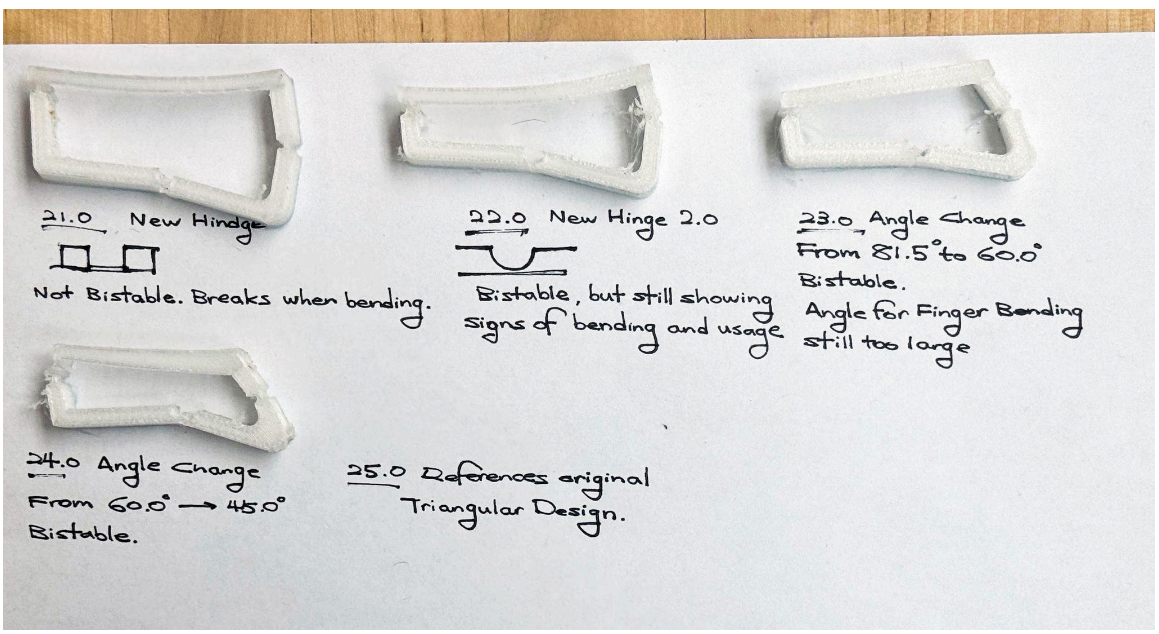


Figure 2.1 Iterations with new hinge.

We noticed that the new hinge proposed in Figure 2.0 is extremely prone to breaking due to its thinness. In addition, since the band is only on one side, the brace often twists when it transitions between states. This causes the thin hinge to rotate and break.

We realized that the hinge needed to be strong enough to withstand constant use without breaking; it also needed to be flexible enough to not deform. As such, we designed a new hinge that combines the **flexibility** and **sturdiness** of the two versions.

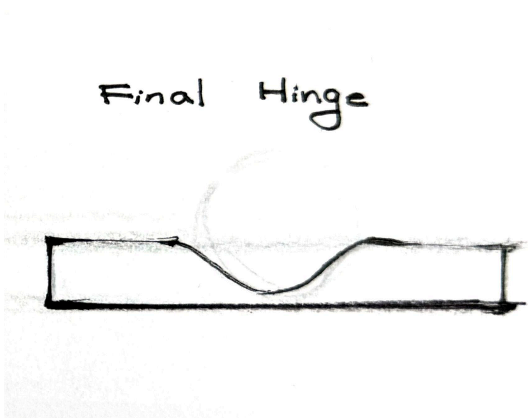
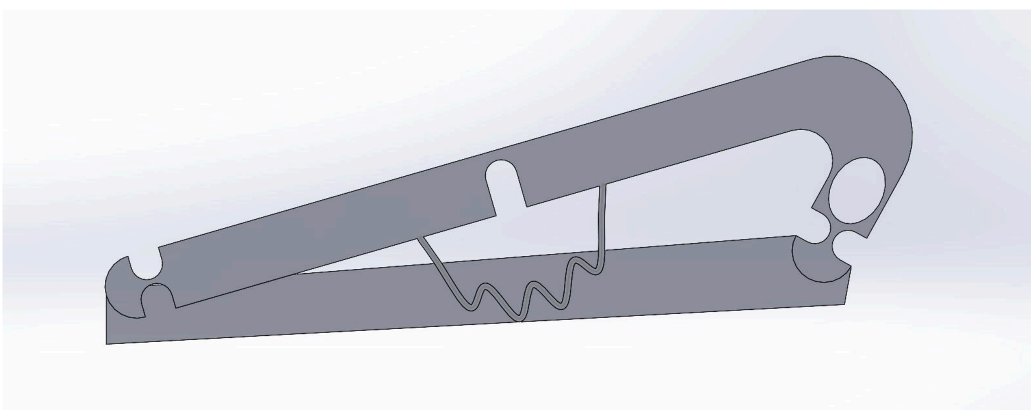


Figure 2.2 Final Hinge

Spring Designs



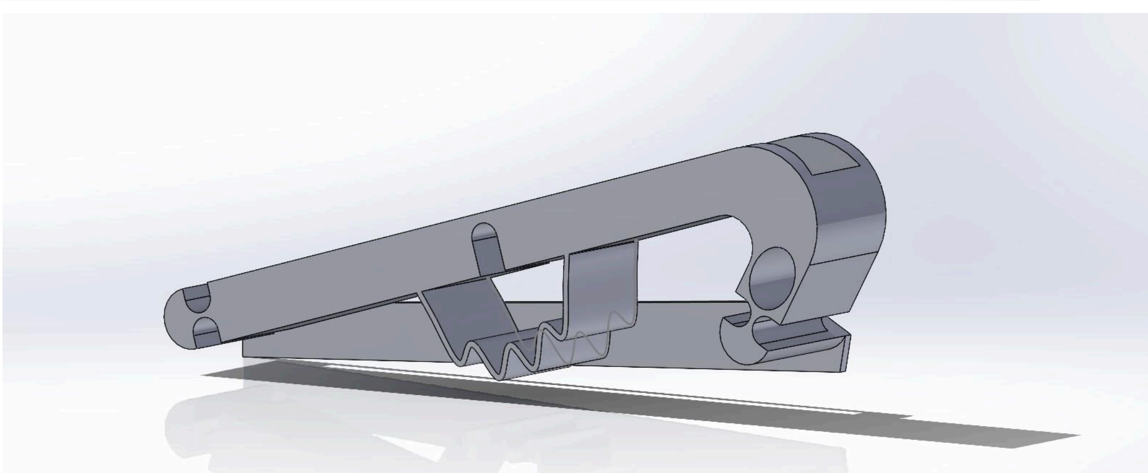


Figure 3.0 and 3.1 Original Model with Spring added.

We added a spring variable to tune the bending and returning force needed.

The graph is modeled with function f(x) = -1*((6.1^2 -(x - 10)^2)^0.5 + 10 + cos(2.2*x)) with x bounded between 4 and 16. By using a function for the physical spring, we can customize the force needed to switch states by simply increasing or decreasing the frequency of the cosine graph.

Figure 3.2 Spring Version Ortho View

Figure 3.3 Perspective View

While the spring serves its purpose in resisting the bending motion, the force is slightly too strong. As a result, the brace would always be pulled back.

In addition, due to the printer nozzle in use being 0.4mm, it may be difficult to print a thinner or smaller spring.

As such, we proposed a different spring design using spirals to be printed in later experiments.

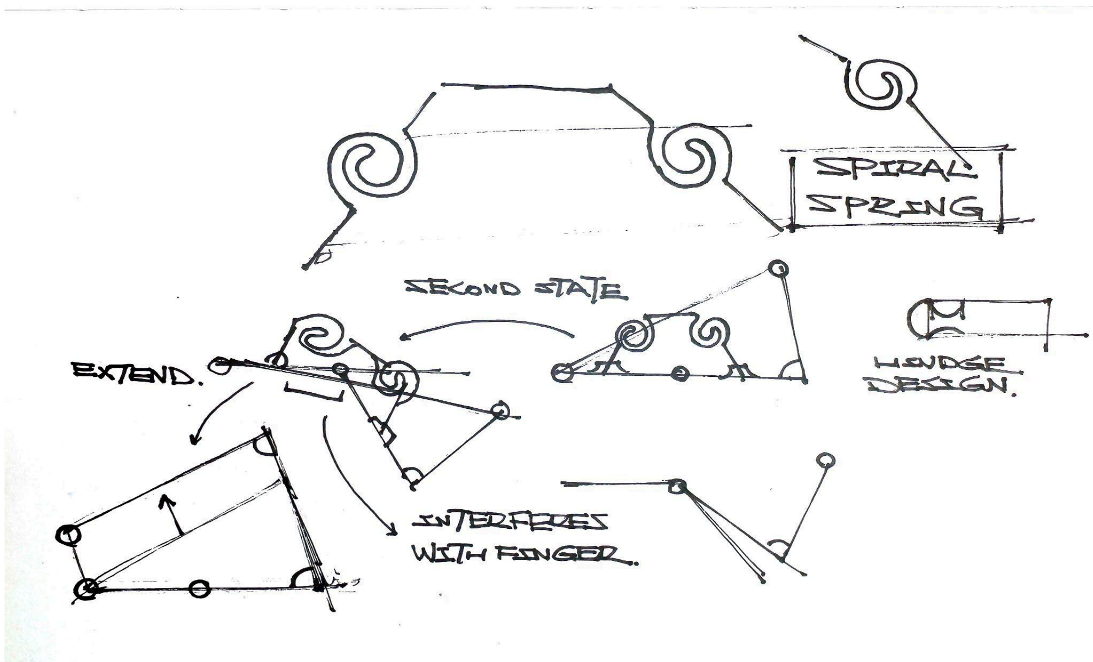


Figure 3.4

Attaching Mechanism on User

Sliding Mechanism:

The human skin stretches as the finger bends, meaning that the finger surface area increases. However, the brace uses a rigid material that has a fixed surface area. This causes the patient to feel large resistance when bending their finger.

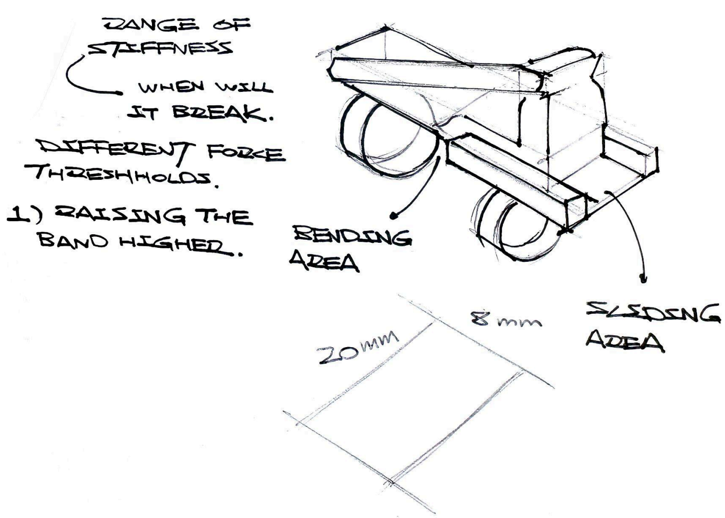


Figure 4.0 Sketch Proposal

We designed a sliding mechanism that allows the brace to adapt to the finger's changing surface area. As the user bends their finger, the sliding part will change position, which minimizes the resistance.

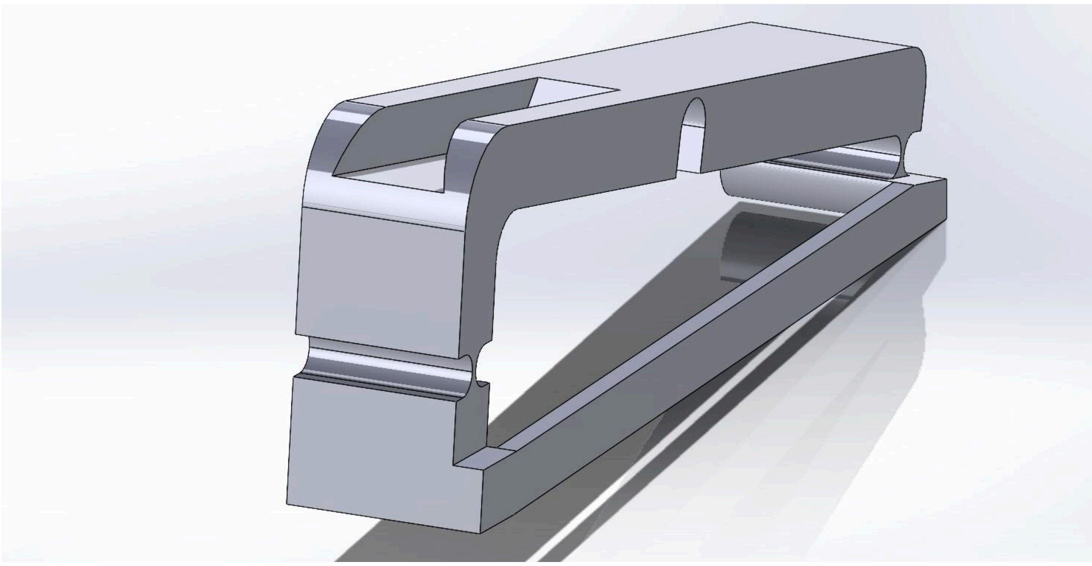


Figure 4.1

We created a trapezoidal cut-out in the brace.

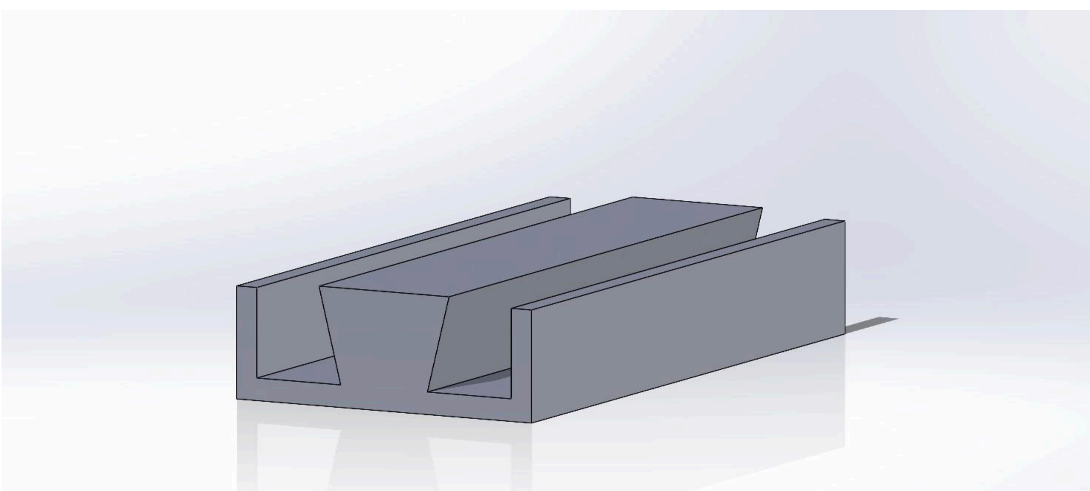


Figure 4.2

Then, we created a sliding part with a trapezoidal extrusion corresponding to the cut-out in the previous figure.

The trapezoid shape allows the sliding mechanism to lock vertically and only slide horizontally.

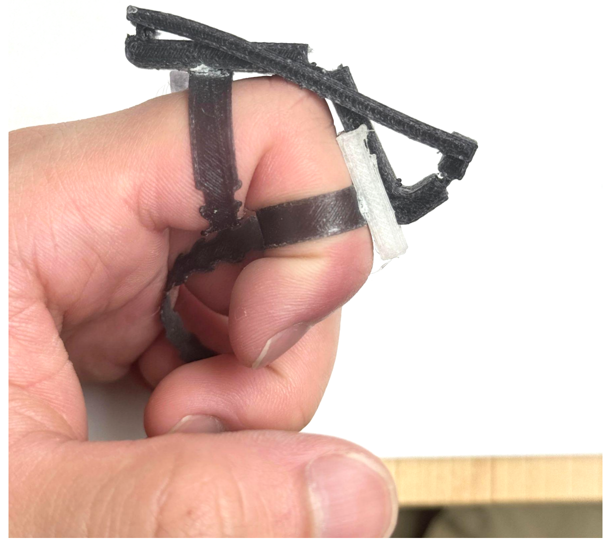


Figure 4.3

Finger rests in a straight position.

Figure 4.4

Finger bends; white sliding part moves down.

The sliding mechanism successfully addresses the bending resistance issue. However, it is not immediately functional after print: due to its small size, it requires sanding to slide smoothly. The additional work and product assembly might make the mechanism hard to replicate in other scenarios.

In the future, our goal is to work towards a more ergonomic version that requires minimal assembly and post-processing after printing.

Band:

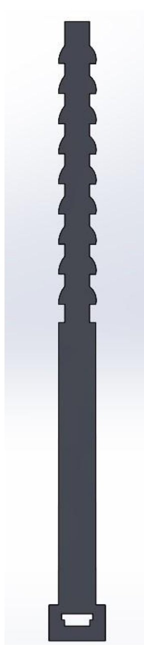


Figure 4.5 We designed a new band for an attachment to the finger.

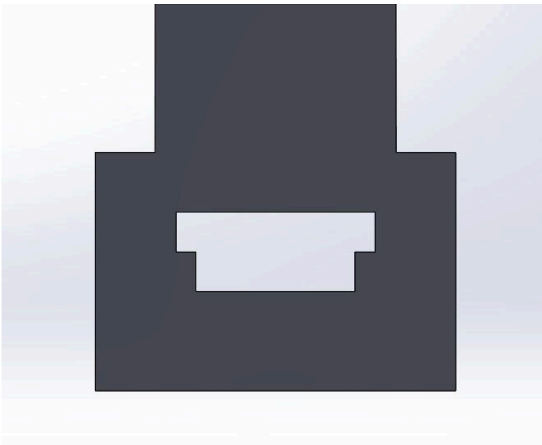


Figure 4.6 We designed a T-shaped slot to stabilize the band. The teeth can slide in through the larger slot, and they would be locked in place by the smaller slot.

Kinematic Simulation

The Angle

In our previous prototypes, while the braces are bistable, the angles in the bent state are often too large.

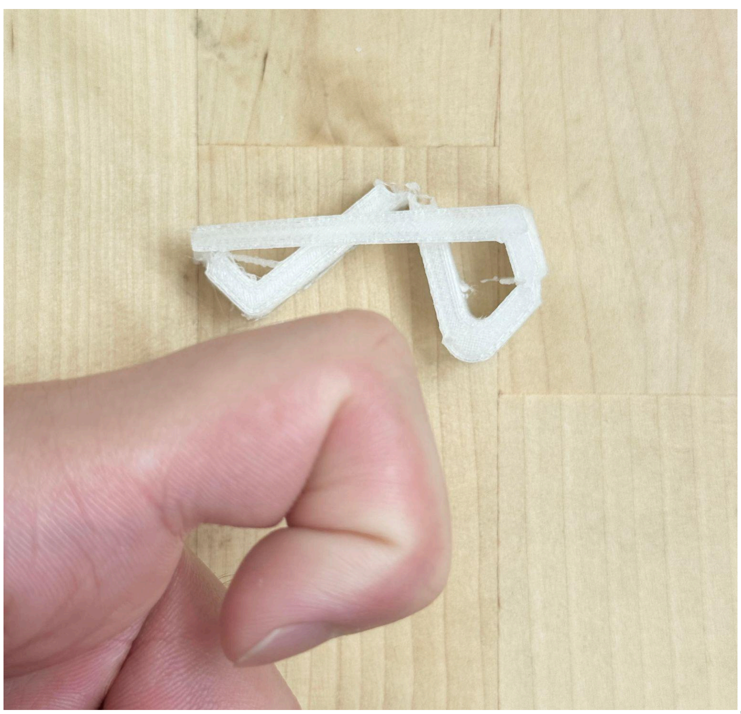


Figure 5.0 The Bending angle on prototype 20.0 exceeds 90 degrees, which is around the natural bending angle.

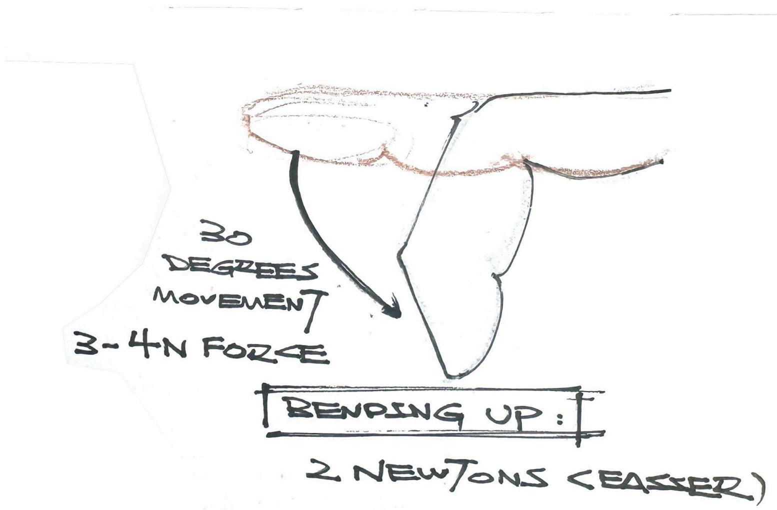


Figure 5.1 We plan to tune the finger brace to be bistable at Yue's natural bending angle, which is 30 degrees. We also kept in mind that the force needed to bend the finger should be between 3N and 4N, and returning should take 2N.

Digital Simulation

Simplifying the geometry, we created variables and adjusted them individually to find the relationship between them and the resulting bending angle.

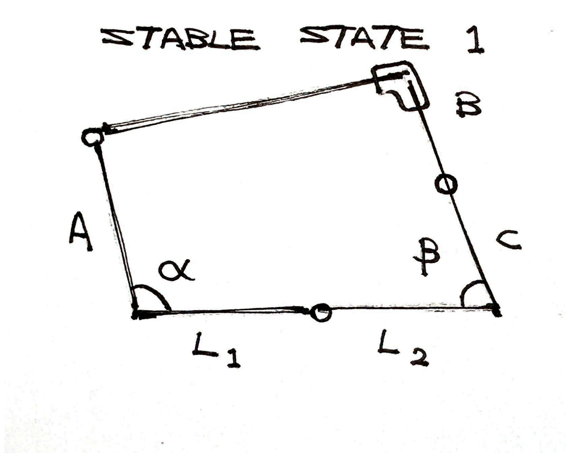


Figure 5.2 Labelled variables will change incrementally in the simulation. Circles represent hinge, and the top-right angle is fixed.

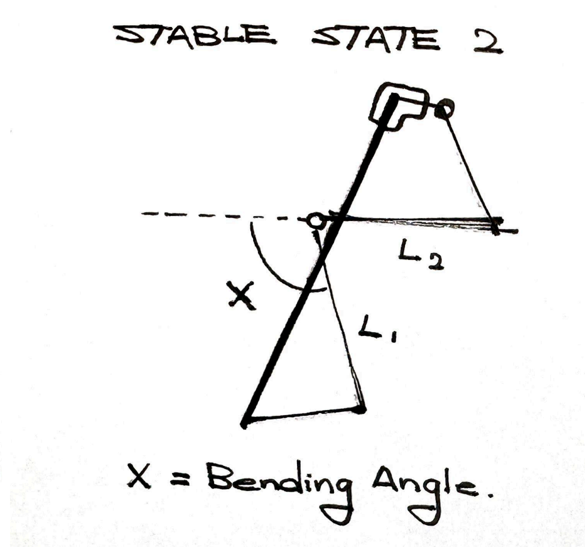


Figure 5.3 We will measure the resulting bending angle and find its relationship to the other variables.

Digital Setup

Initial State

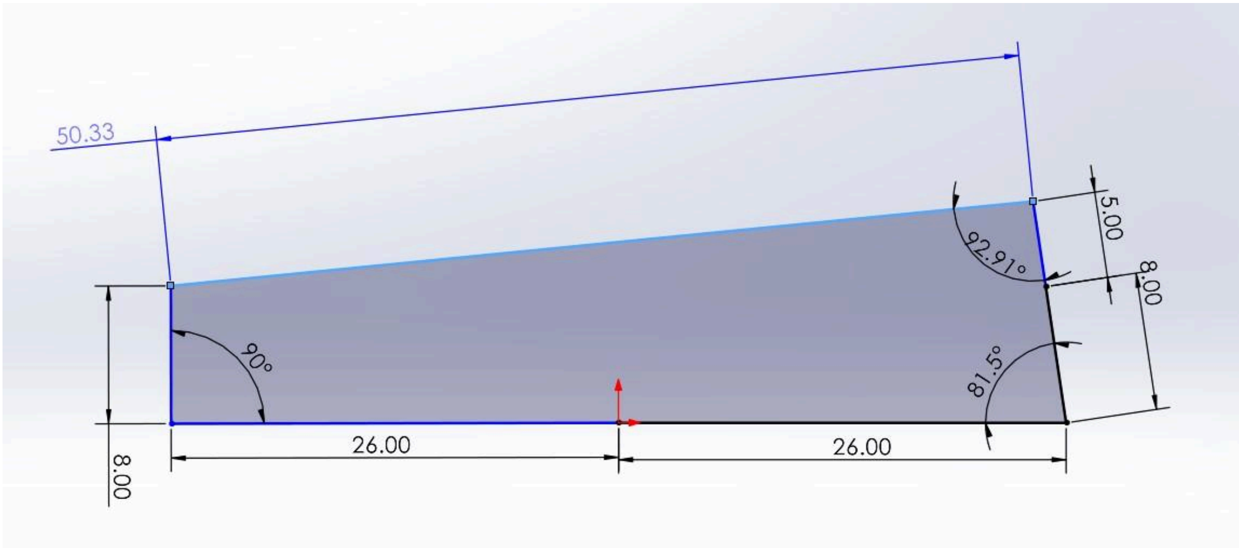


Figure 5.4 We establish the geometry in a sketch with testing variables and record the length of the top band.

Unstable State

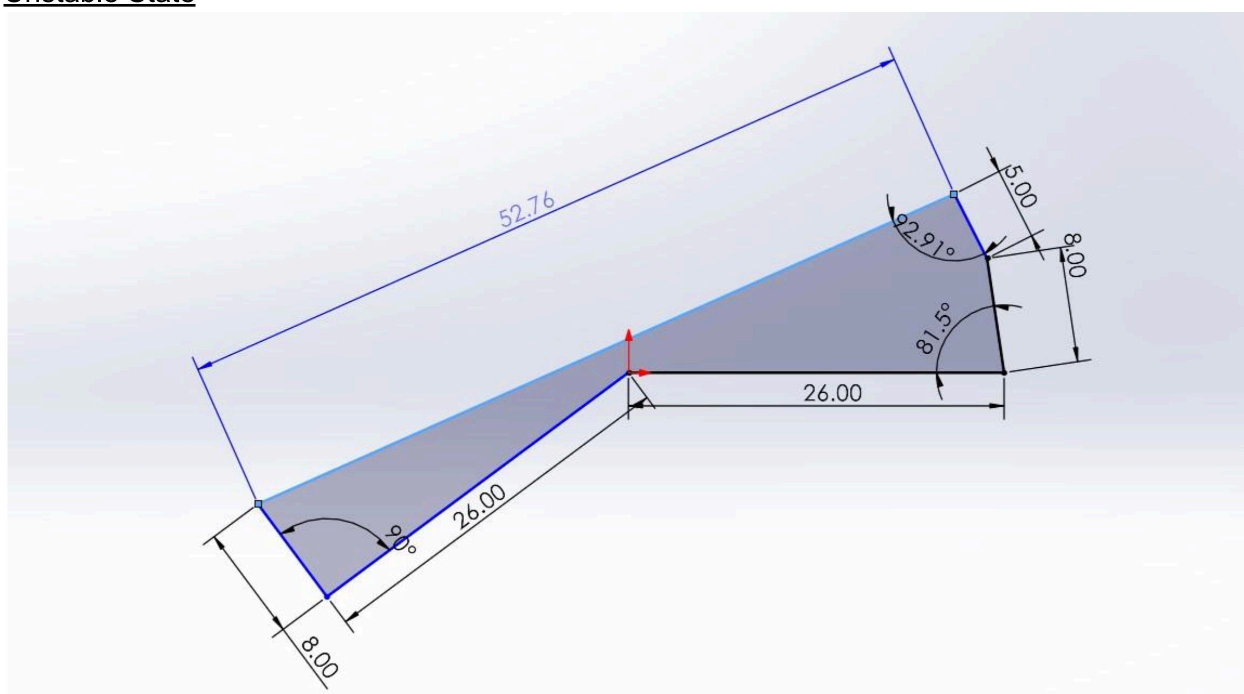


Figure 5.5 Then, we rotate the bottom platforms until the top band reaches its maximum length. This is the furthest point away from equilibrium. We record the maximum band length.

Second Stable State

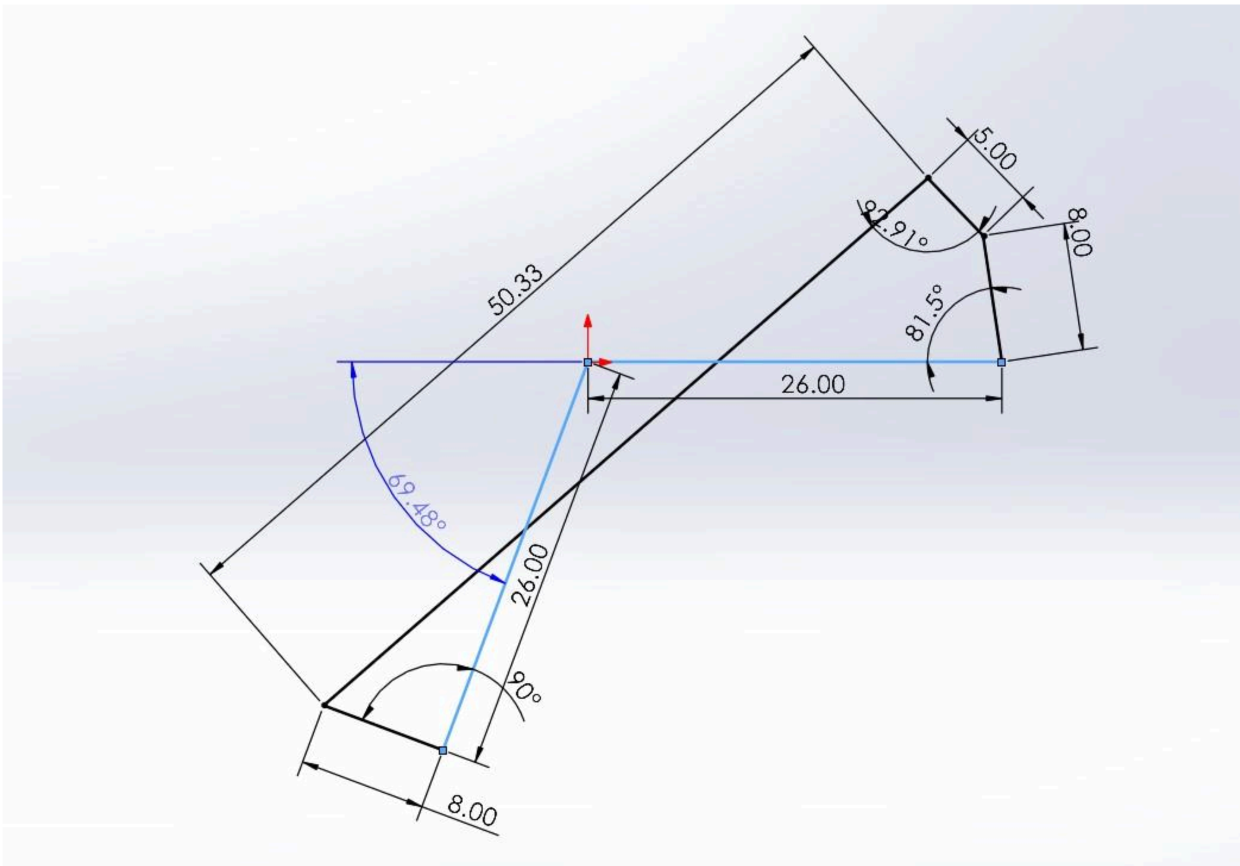


Figure 5.6 Lastly, the geometry reaches the bistable state, where the band is equal to its original length. We record the bending angle, which is how much the first platform has rotated.

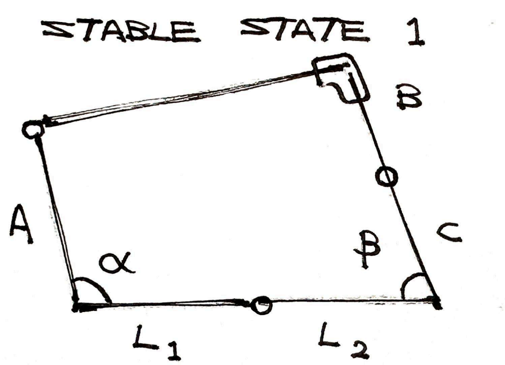


Figure 5.7 Using the method below, we incrementally adjust the variables A, Alpha, L1, L2, Beta, B, and C. We record dependent variables Bending Angle, Resting Band Length, Maximum Band Length, and distance between L1 and the band at the bistable state.

Graphs and Results

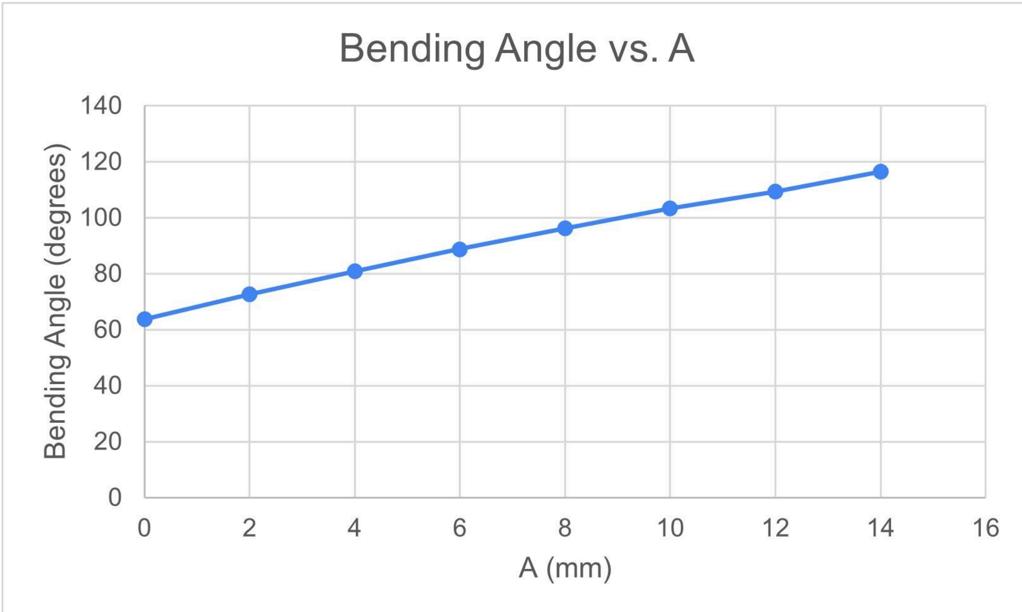


Figure 6.0 Changing the length A yields a linear relationship with the Bending Angle.

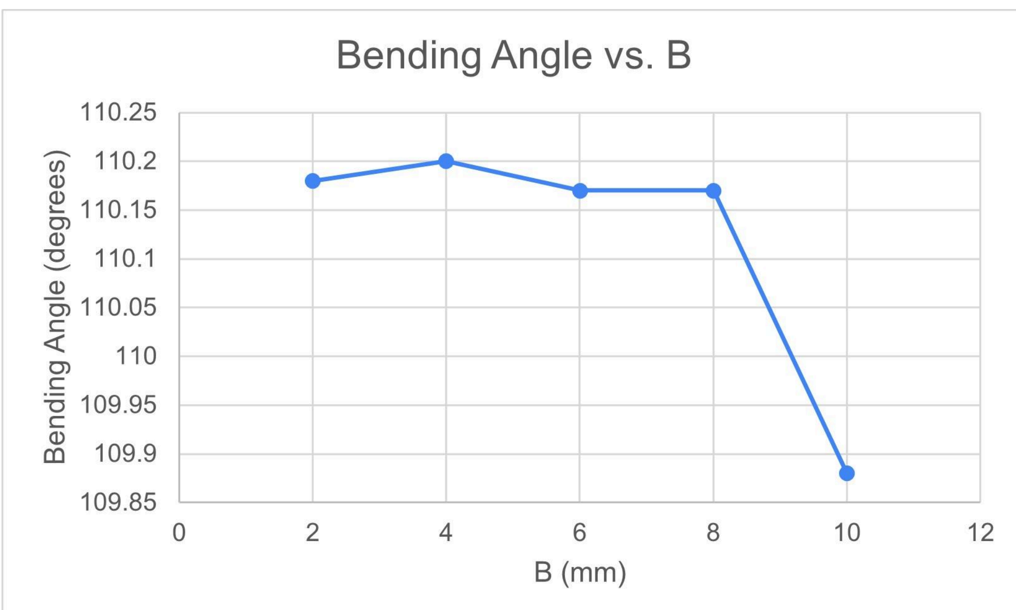
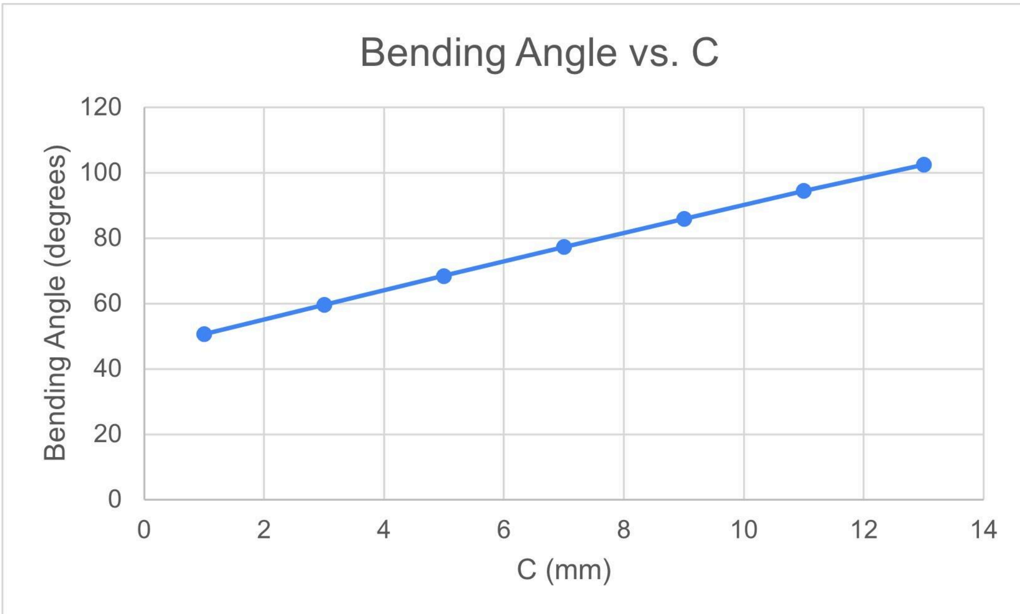


Figure 6.1 Changing B does not seem to affect the Bending Angle. This means that we can decrease B to lower the overall height without affecting the final angle.



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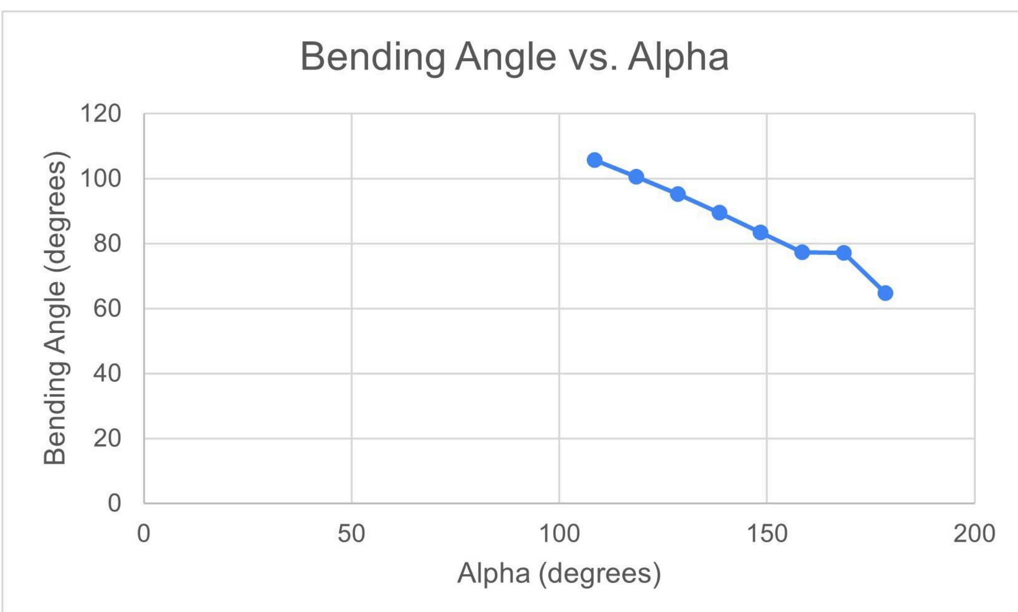


Figure 6.3 Increasing Alpha allows the bending angle to decrease, which is our desired goal.

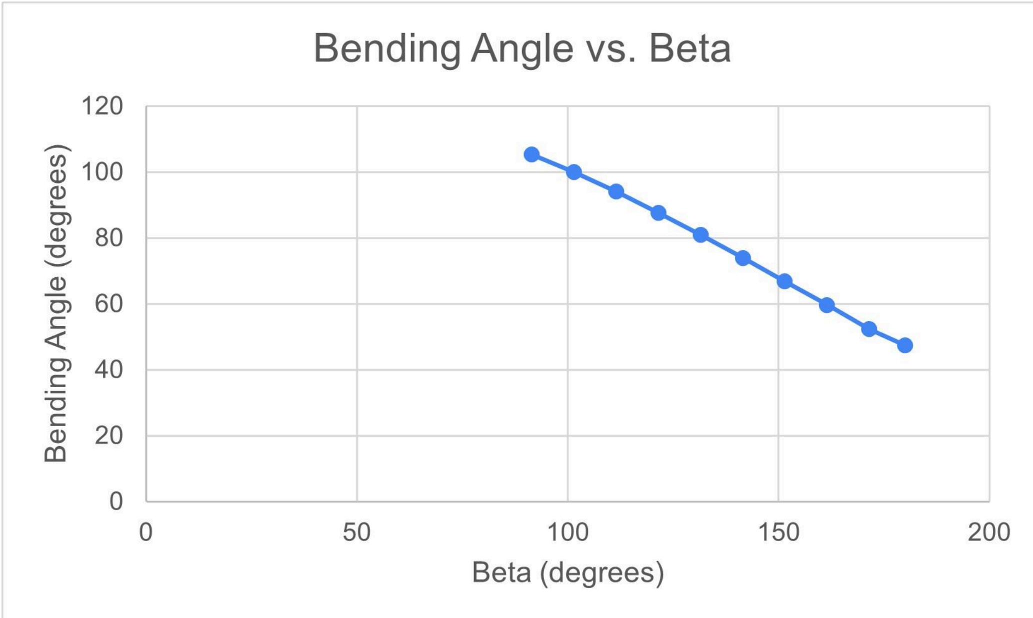


Figure 6.4 Similarly, Increasing Beta also lowers the Bending Angle linearly. We were able to theoretically lower the Bending Angle to about 50 degrees.

PS: We also experimented with adjusting the ratio between L1 and L2. The ratio L1:L2 = 11:15 yielded the least angle with other variables kept constant; the angle decreased by 7.25 degrees. Other than that, changing the ratio only increased the bending angle.

Comparing Theory and Reality

From the simulation data, we created a new version with greater angles and smaller side lengths. However, this model is unable to stay in the bistable state.

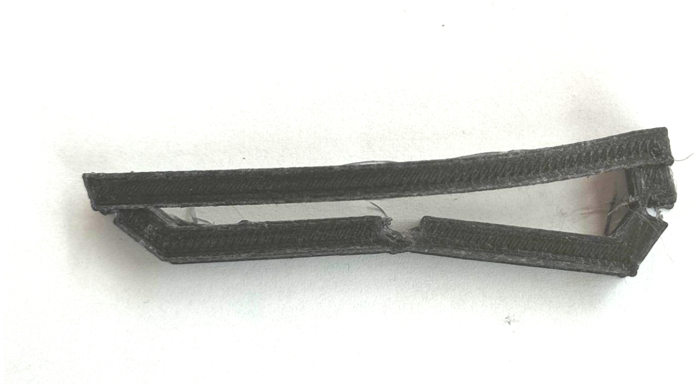


Figure 6.5 New model printed with black flexible nylon. The length is the same as in previous working models but the height drastically decreased.

Bending Angle and Band Stretch Length

We concluded that the strongness of bistability is dependent on how much the band stretches throughout the transition. When the band stretches more, the force for transitioning will be greater and the brace will be more stable in the bistable state.

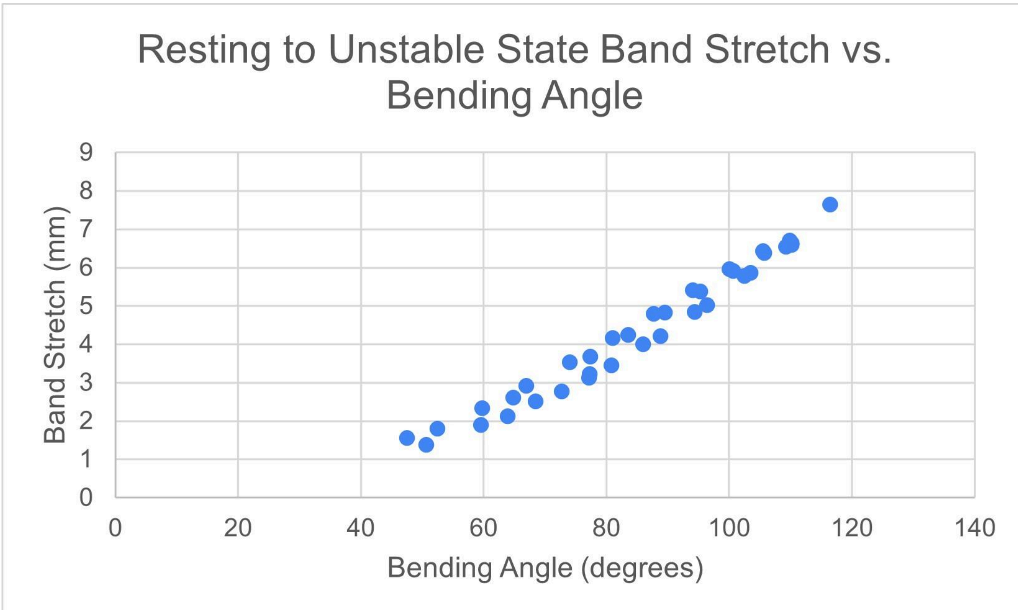


Figure 6.6 Using our Kinematic Simulation data, we graphed Band Stretch Length, which is the difference between resting band length and max band length, versus the bending angle.

From our physical prototypes, we learned that the minimum Band Stretch is 1.10 mm for the brace to display bistable characteristics. In the Graph, we can see that when the Band Stretch is near 1.16mm, the bending angle is approximately 47 degrees. Drawing a best-fit line through the graph, we can see that if the bending angle decreases further, the band stretch length would be below 1.16, causing the brace to lose bistability.

The Resulting Model

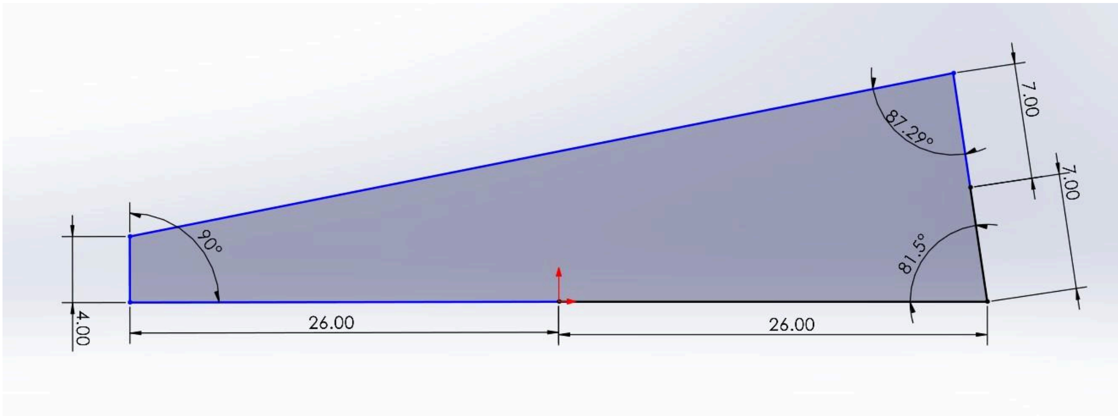


Figure 7.0 We developed the brace geometry with a theoretical bending angle of 48.45 degrees. The Stretch Length is 1.16mm which allows the structure to be bistable.

Physical Model

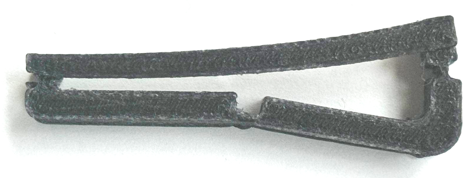


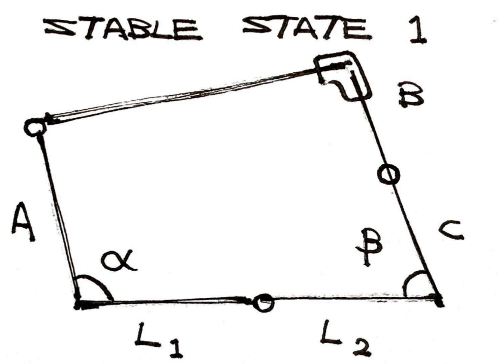
Figure 7.1 Resting State. The height is kept low and angles are acute to increase bistability.

Figure 7.2 Bistable State with 55 degrees bending angle.

The physical model showed a discrepancy between the estimated bending angle (48.25 degrees) and the actual bending angle (55.00 degrees) due to the thickness of the brace.

In this final physical model, we successfully solved the problem of the band interfering with the finger: the band no longer restricts finger movement, resting above the finger in the bistable state. In addition, from our experimental data, we were able to significantly decrease the bending angle from 110 degrees to 55 degrees by tuning different variables.

Design Guidelines



I gathered theoretical data for the Design Guidelines Section mapping the bending angle to corresponding variable values. Constructing the brace in Stable State 1 using the parameters will yield the bending angle with an error of +- 4 degrees. In addition, in all versions, the band would not interfere with the finger in the bistable state.

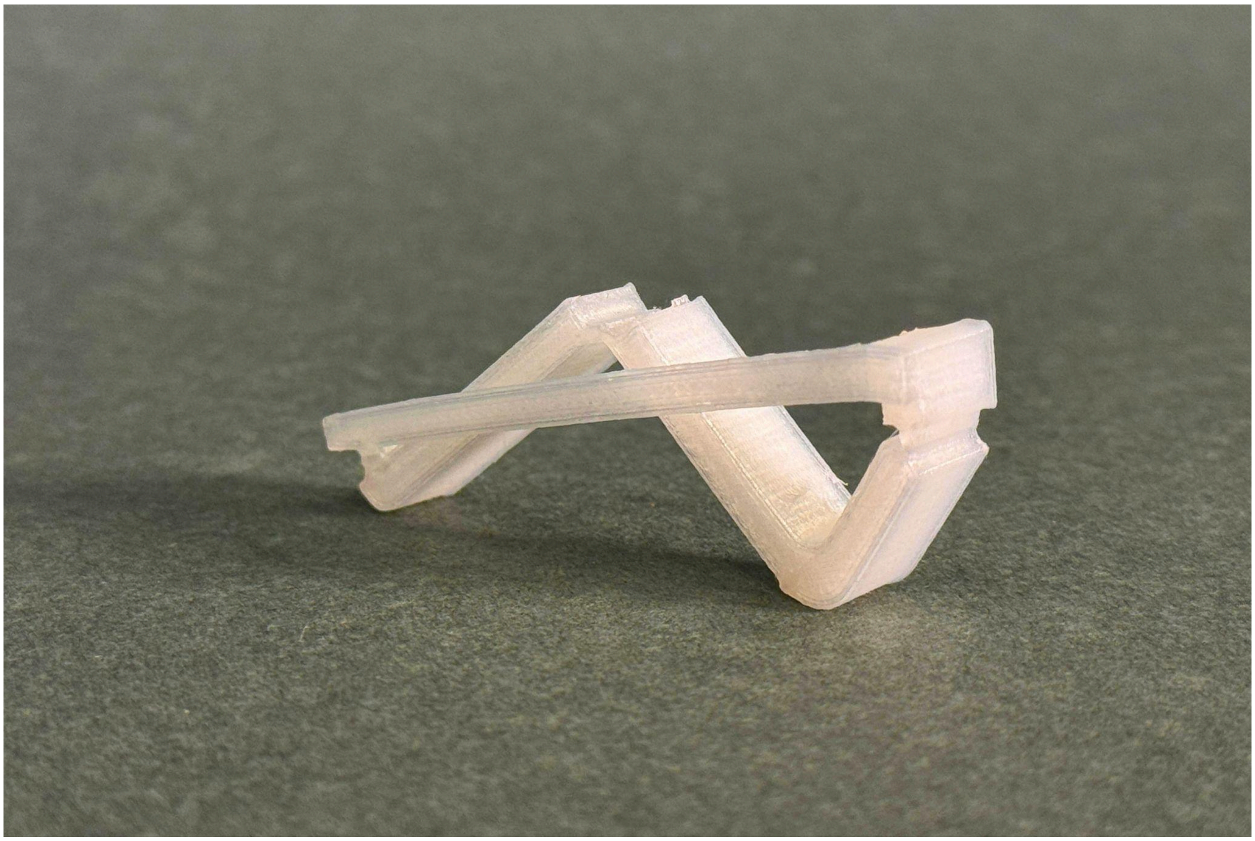
Bending Angle	L1 (mm)	L2 (mm)	A (mm)	Alpha (degrees)	Beta (degrees)	B (mm)	C (mm)	Band Stretch (mm)	Bistable Band Height (mm)*
50	26	26	4	90	81.5	7	7	1.16	1.88
60	26	26	6	81.5	81.5	10	7	1.64	1.31
70	26	26	6	70	70	12	10	2.51	1.84
80	26	26	7	70	70	12	10	2.70	1.71
90	26	26	10	60	60	13	10	3.56	1.89

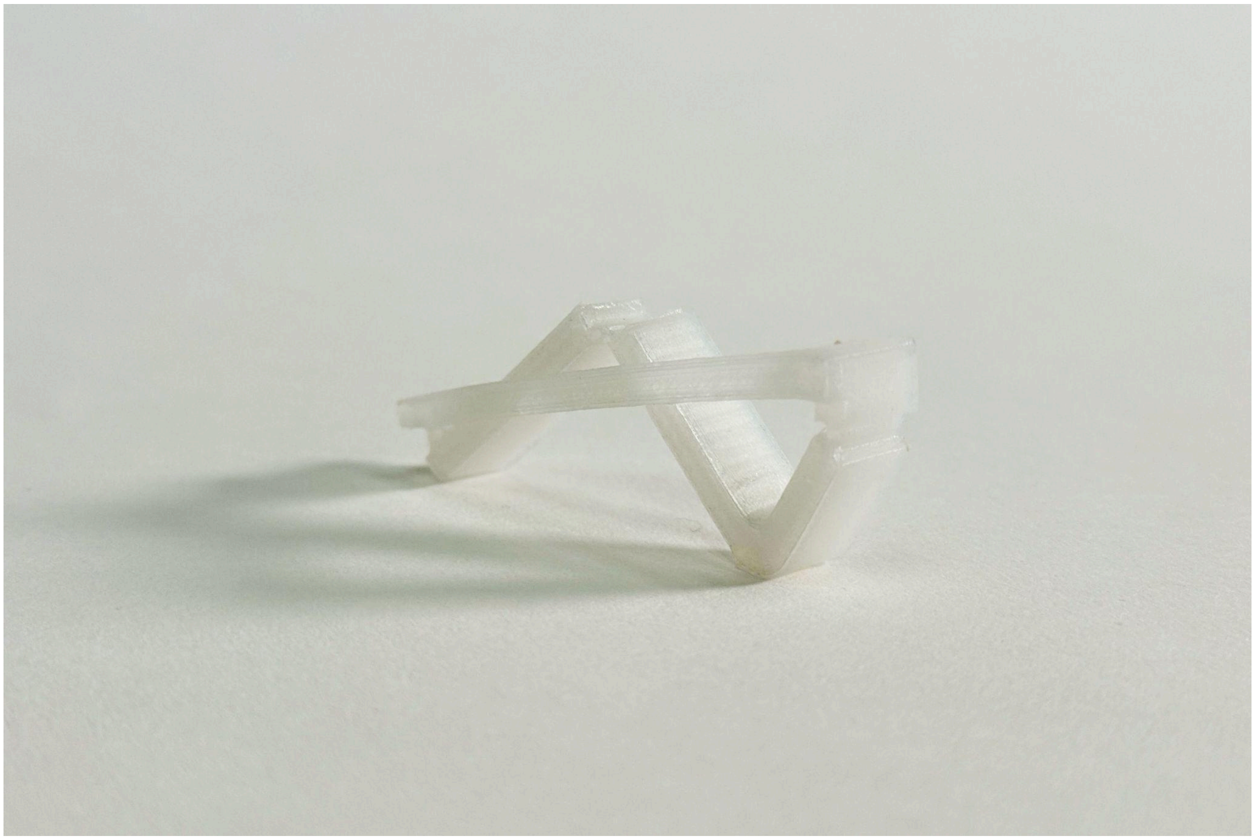
* The Bistable Band height is measured by how much the band drops below the brace in the bistable state. From physical testing, when the absolute distance is below 1.90mm, the band would not interfere with the finger in the bistable state.

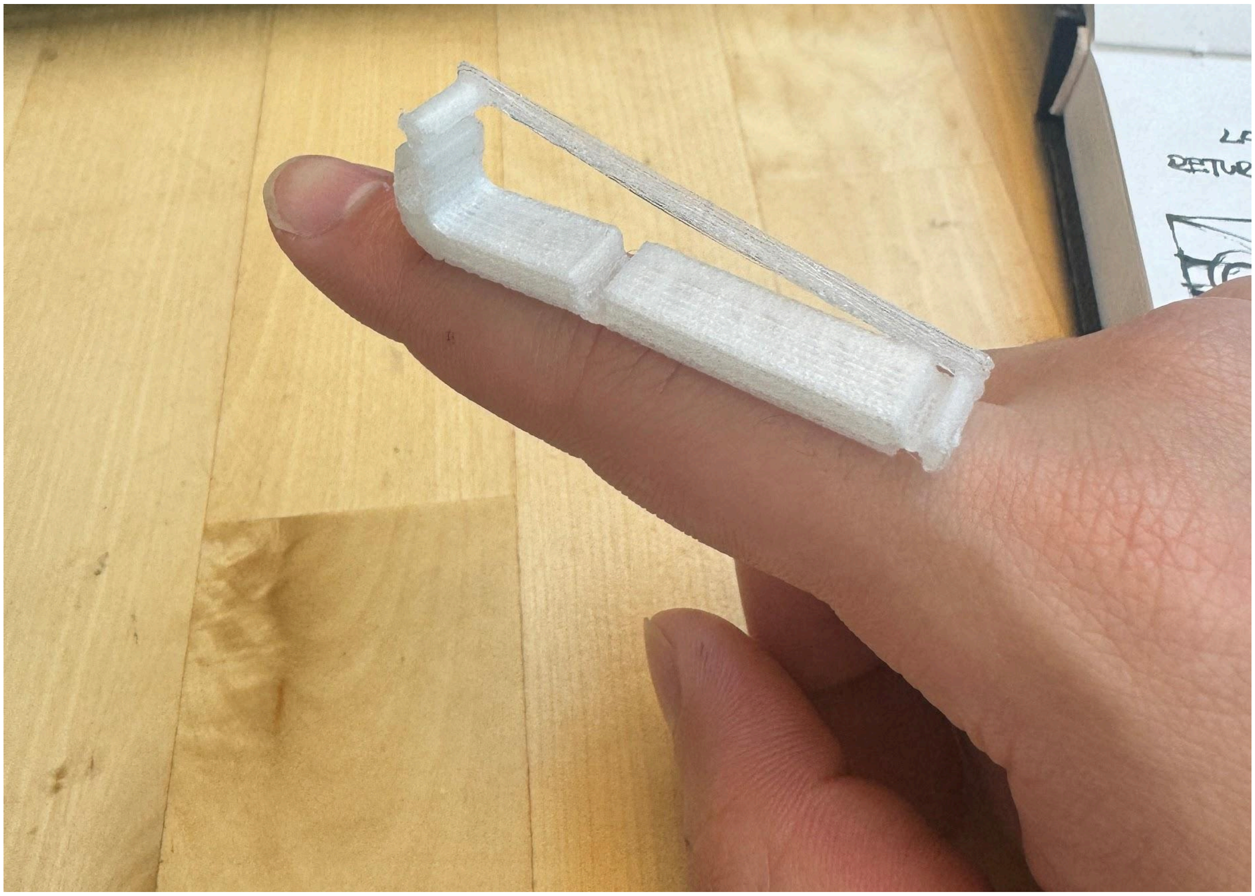
A thing to note is that while increasing the bending angle requires us to increase the length of the sides, we can decrease the angle to ensure that the overall height of the brace does not exceed the expected levels.

Photography & Miscellaneous Process Photos

(Dion put more videos and photos in the drive)





Original Prototype Testing Video Link:

https://drive.google.com/file/d/1v7DdVmCHYI1k_pN8iK5kD3ELm3HyG7F3/view?usp=sharing