Fall 2018

Tendon Rehabilitator

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The development and construction of the elbow tendon rehabilitator is meant for those who suffer from long-term damage to their arm tendons. The main two design types for this purpose is an arm-mounted device and a box table-placed device. Damaged tendons need small-magnitude forces for therapy to work, unlike the muscle-bulging weight-lifting scene in gyms. In order to not agitate the injury or make the user feel too much pain when using it, the device is restricted to making the arm resist a force, rather than the arm exerting a force to lift or move a weight. Hence, the latter box-design fits the restrictions, as the arm has freedom to move about without any arm mount to weigh it down and needs far less precision and materials dedicated towards keeping the mount from injuring the arm or keeping components inside a small space.

The box serves as storage for all the inner components, serves as an easy mean of transporting the entire device, and has a top rest for the arm, rather than resting and weighing the arm. A hand grip is connected to cords and springs, which are attached to an internal servo. Resistance on the hand is done by first having the hand remain in its position. The internal servo activates from a button press, and pulls the spring, which pulls on the hand. The longer the stretch, the more force is exerted. The hand resists this increasing force, and after reaching a user decision on how much force should be exerted is slowly allowed to be pulled by the spring. To reset, the button is pressed, causing the servo to return to its original position. No force is exerted on the hand, because of spring slack, letting the hand go free back to resting position.

MEMS 411: Mechanical Engineering Design Project
Fall 2018

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1 INTRODUCTION

Sports injuries has become an increasingly common occurrence. Finding ways to rehabilitate injuries, especially those pertaining to tendons, without the need of a gym or bulky weights is key to ensuring a consistent, convenient healing regimen. The focus of this device is performing therapy on tendinosis of the medial epicondyle caused by rock climbing. This injury, usually referred to as climber's or golfer's elbow, must be healed by focused and isolated exercises of the tendon through light resistances of forces. This device aims to recreate those exercises in a portable, lightweight, and fully adjustable manner. Care must be taken to ensure that the device has a wide range of adjustability as well as the ability to adjust in very small increments, allowing adaptation to each user's specific injury needs. The goal of this device is to eliminate the need of heavy, inconvenient, and bulky weights or dumbbells when performing tendon rehabilitation exercises, making rehabilitation accessible to more athletes. The key component of these exercises is that the tendons must only endure resistance forces when subjected to eccentric exercises, where the muscles and tendons resist a force, and not concentric exercises, where the muscles exert a force on the tendons in order to move and lift a mass. This motion ensures that only the tendon is being worked and not the muscles of the forearm. Therefore, this product must also be able to release the tension during the eccentric portion of the exercise and remove the need for the user to provide energy for the concentric component of the exercise.

2 PROBLEM UNDERSTANDING

2.1 BACKGROUND INFORMATION STUDY

Competing products

Flex Bar Exerciser

Figure 1. Torsion bar bending position

Figure 2. Torsion bar twisting position

The first device has multiple modes of usage. It is basically a long foam bar that can undergo torqueing twist motions and bending motions. However, it does not isolate and stretch the wrist tendons only; instead, in the twist torqueing motion of exercise, it engages fingers, wrist, and forearm muscles. We only wish to affect the tendons, and with eccentric exercises only. This device has concentric requirements for the initial twisting, and then eccentric from slowly letting it return to its original shape from the device torqueing back to its original shape. A load needs to be put on the bar in order to provide resistance for eccentric motion to occur; our design must remove the need for people to supply the muscle power for the concentric loading. It does have portability and ease of use but requires multiple bars to be purchased in order to access a large range of resistance.

Spring Forearm Strengthener

Figure 3. Spring device stationary position

Figure 4. Spring device bent position

The device is made of a ladder-like device whose sides are springs and rungs are bar-like pieces meant to stabilize the device from slipping, and to provide a grip for the hand to use. Strengthening exercises is done by bending the wrists forward or backwards and bending the spring out of its straight shape and into a curved shape. This device uses concentric exercise to bend the spring, then eccentric to return back to its original orientation, and develops the strength of the lower arm region. It targets and develops muscle groups, alongside tendons, which is less useful for our purposes. In rock climbers, who are part of the target audience, the fingers are assumed to suffer from tendonitis as well; this device may exacerbate such conditions.

Cord Forearm Strengthener

Figure 5. Cord device positions

Figure 6. Cord device positions 2

This device is most similar to the device illustrated in the patents. A cord attached to a resistance piece is connected to the hand grip. The hand flexes and bends forward, pulling the cord and tensing the muscle and tendon groups required for such an exercise. A plastic extension braces the device against the forearm, though as some reviewers state the device may need a second hand to brace it even further, and may be too large or small, depending on arm proportions. This device uses concentric exercise to target muscles and is not quite fit for dealing with tendonitis. How exactly a second hand braces the device may complicate issues, as this includes the other arm into the exercise.

The first patent we found is number US5454769A, a wrist and forearm exercise apparatus with improved resistance adjustment device. This device is close to what we were envisioning: a forearm mounted, portable and adjustable device that provides resistance to a handle with some key differences such as the inability to only provide eccentric resistance, so it is more suitable for exercise than tendinosis therapy. The device uses a tube with a spring inside rather than elastic bands.

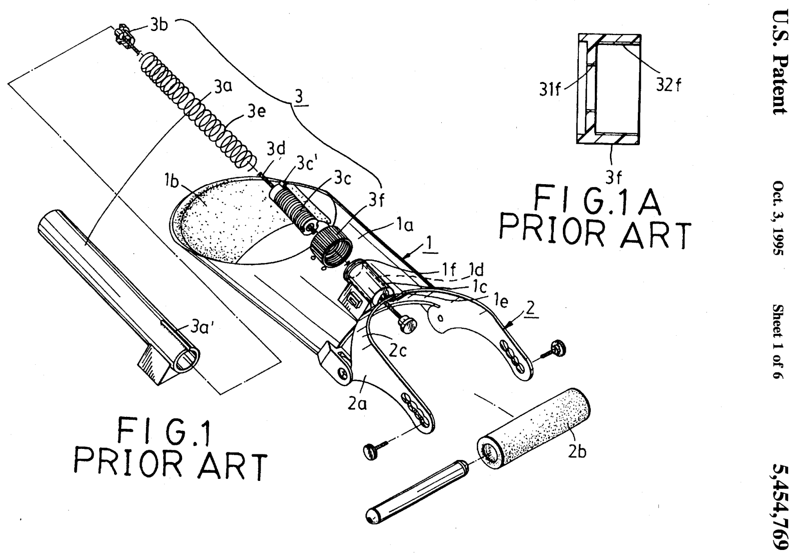


Figure 7. Patent US5454769A Image 1

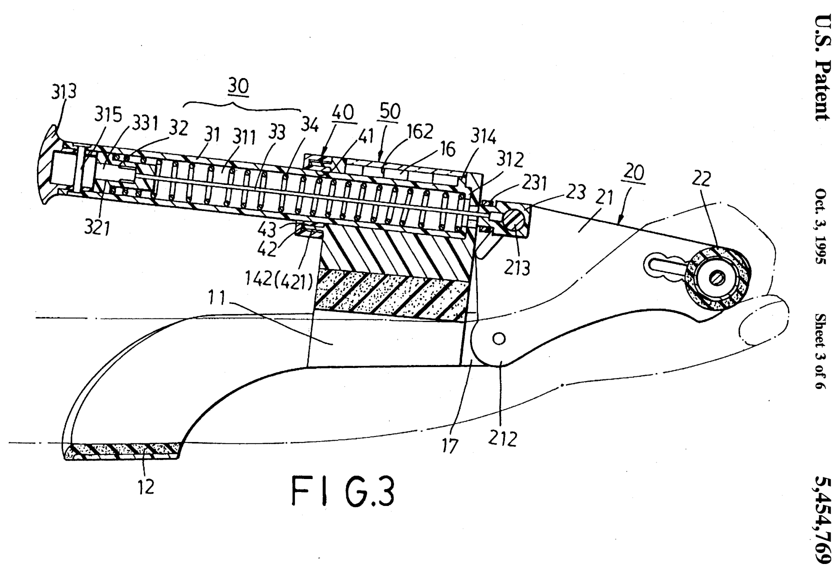


Figure 8. Patent US5454769A Image 2

The second patent, US4589655A, is also called a wrist and forearm apparatus. Like the previous patent, this device is for exercising the wrist and forearm and uses an adjustable spring-in-tube mechanism mounted on the forearm.

This patent is older than the previous example (1995 vs 1984) and looks more basic, with a couple of pads rather than a sleeve for attachment. Unlike the previous patent, however, this device is shown as being able to attach to either side of the forearm.

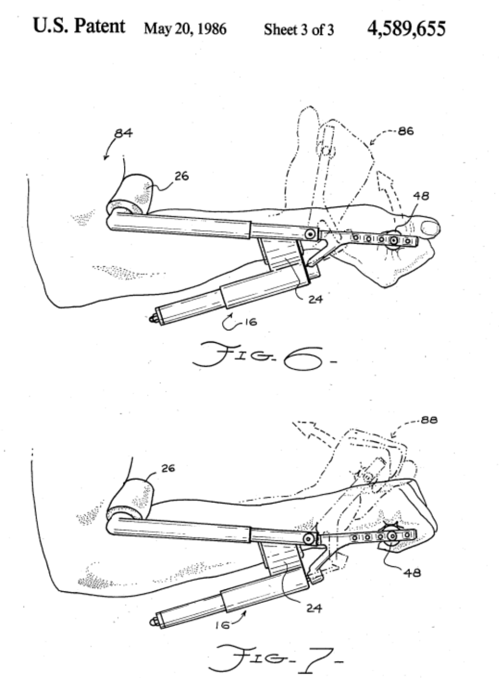


Figure 9. Patent US4589655A image 1

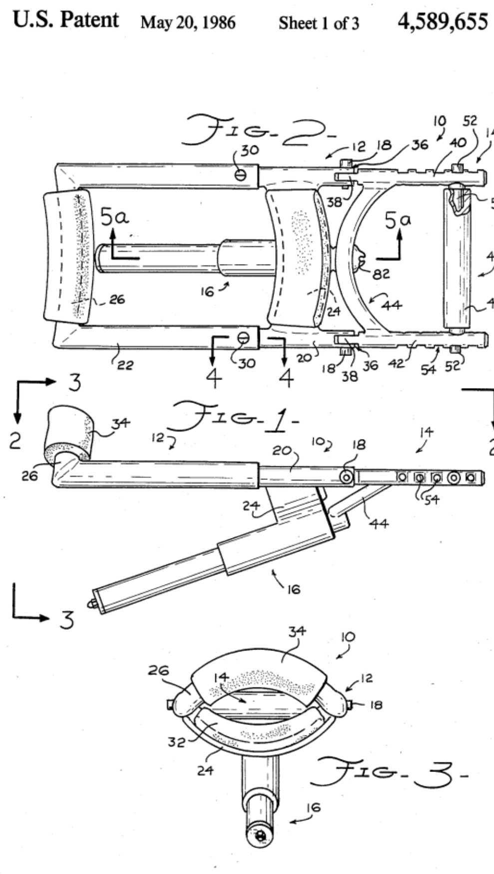


Figure 10. Patent US4589655A Image 2

ASTM F2276 Standard Specification for Fitness Equipment is our first standard. It describes design requirements for fitness equipment intended for users ages 12 and up or 13 and up (both ages are listed, possibly an error). The standard is split into four categories for construction: stability, support, edges, corners, and tube ends, and moving parts. Then it has five requirements for usability: Squeeze, shear, crushing points, adjustment and locking, handgrips, load development of transmitting components, and “intrinsic, extrinsic, and endurance loading.” Some of these would be relevant for our device, such as specifications for avoiding pinch points.

Our second standard is ASTM F2571 Standard Test Methods for Evaluating Design and Performance Characteristics of Fitness Equipment which relates to standard F2276 by providing test methods. It provides testing for many parameters from stability to electrical guarding to maximum surface temperature. The most relevant to our project are the edge and corner sharpness, adjustment/locking mechanisms, and various loading tests though various other testing could be useful.

2.2 USER NEEDS

Table 1: Customer Needs Interview

Product: Rehabilitation Device **Customer:** Nicki Oppenheim **Notes:** We described the rough idea of the product to the customer. The interview was conducted over the phone and took about 35 minutes.

Address: 6010A Kingsbury Ave, St Louis, Mo, 63112 **Date:** September 9, 2018			
Question	**Customer Statement**	**Interpreted Need**	**Imp.**
What is important when doing the typical exercises?	I had to try the exercise at different angles to find which was the most painful. As well, the elbow has to be as straight as possible. Elbow needs to be straight but should be rested upon a surface so you don't have to work to hold up your arm	Rehabilitation device needs to work at different angles Elbow has to be straight Elbow needs to be on a flat surface	5 5 5
What do you need when doing this exercise?	I need weights that you can take on and off the weight. You could use a hammer as long as it's the right weight.	The rehabilitation device has adjustable resistance.	5
How much weight do you use and how often do you vary it?	Last time I did them I was using a dumbbell with 3 lbs. for the twists and depending how much my elbow hurt I would adjust where my hand was on the weight. For the other one I can do more weight, like 5 lbs. on each side of the dumbbell. Varying the weight depends on whatever equipment I could find. I wouldn't have to hold the weight in awkward and weird places to adjust the resistance. I imagine as it gets healthier I can add more weight. My other elbow can handle more weight	Up to 10 lbs. resistance range Changing weights shouldn't be awkward	3 3
Would you do these exercises more often?	I think if it were easily transportable I would do these exercises more often	Rehabilitation device needs to be light. Rehabilitation device needs to be storable	4 4
What would you like to see adjustable in a device like this?	Resistance is really important. Especially with small increments. Small changes make a very big difference. The ability to use it on different surfaces. I have to be resting my elbow on something. It has to be on a weird table edge.	The resistance needs to be able to change in minor ways It needs to be comfortable on any surface It needs to work without a table edge	5 3 3

If you could would you do these exercises elsewhere?	It would be kind of nice. It would look a little weird but would be a good option on dates where you are busy and don't go home very much. I would when I'm travelling and don't have weight with me and even if I go to a gym I can't take the weights on and off so I can't find something that's appropriate	It needs to work anywhere It needs to be adjustable in resistance	4 5
What do you dislike about the current method?	Mostly that it's hard to keep it consistent cause I move around a lot. It becomes challenging if I don't have the equipment with me.	It has to be portable	4
What do you like about the current method?	I like the adjustability of the different weights to add on to each side. The bar is grippy and a comfortable size to hold not just a smooth piece of plastic or metal	It needs to have adjustable resistance It has to be comfortable It needs good texture for the handle	5 5 4
What would be some suggested improvements to the current design?	I don't want to have to just buy new weights all the time. It would be nice to have it offered in a gym so I don't have to buy my own equipment.	It needs to be cheap to change resistance	1

Table 2: Interpreted Needs Table

Need Number	Need	Importance
1	Adjustable Resistance	5
2	Follow exercise guidelines	5
3	Easy to change resistance	3
4	It needs to be portable	5
5	Comfortable	5
6	Works on any surface	4

2.3 DESIGN METRICS

Table 3: Target Specifications

Metric Number	Associated Needs	Metric	Units	Acceptable	Ideal
1	1	Total Weight	lbm	<5	2

2	2	Range of Motion	Degrees	180	>190
3	3	Applied Hand Grip Slippage (ASTM F2276 Standard Specification for Fitness Equipment)	lbf	20.2	>21
4	4	Belt/Rope Loads (ASTM F2276 Standard Specification for Fitness Equipment)	lbf	6 x maximum static tension	>7 x maximum static tension
5	5	Sharp Edge Test as specified by UL 1439	Binary	Pass	Pass
6	1	Stored Height	in	4	2

2.4 PROJECT MANAGEMENT

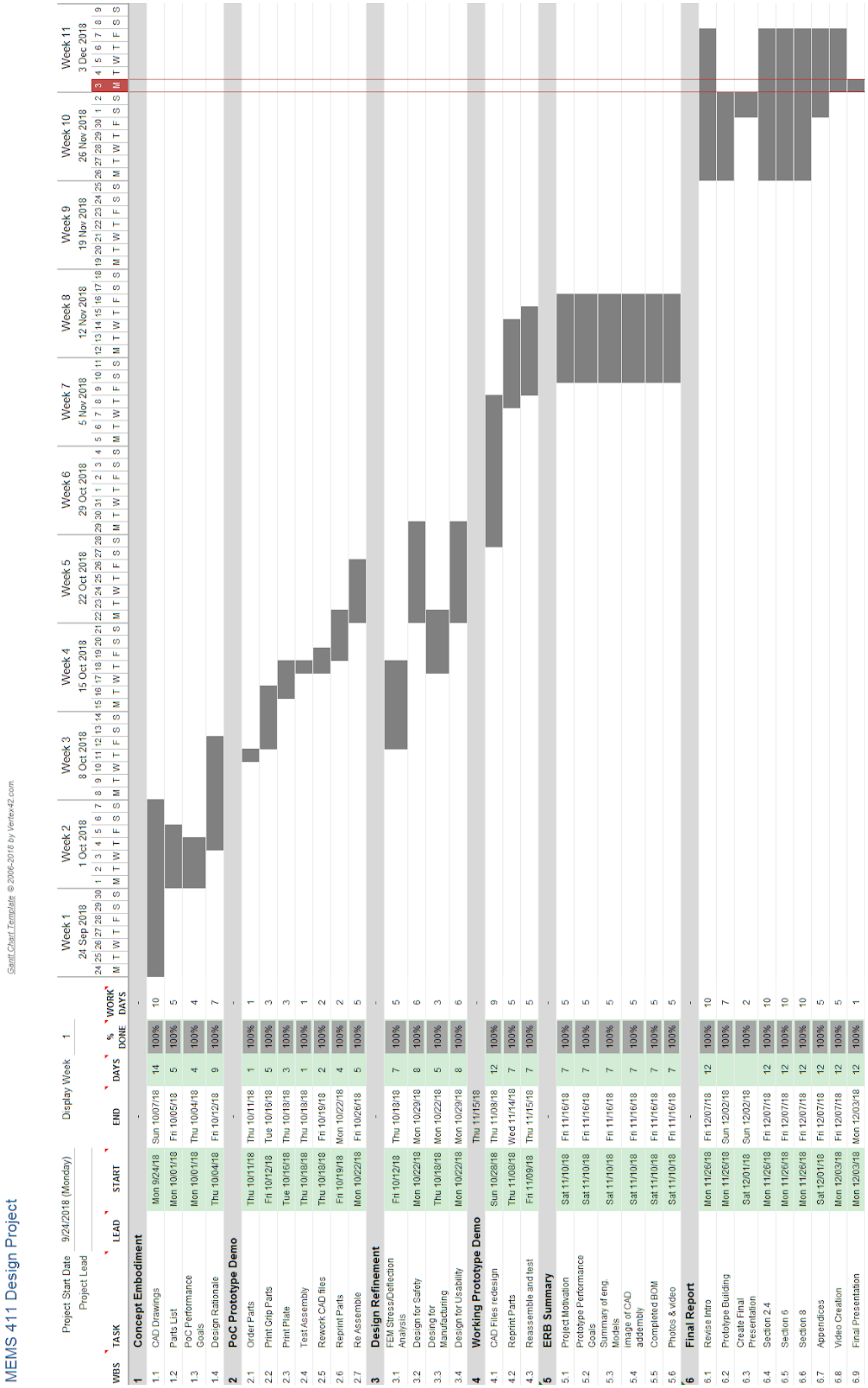


Figure 11. Gantt Chart

3 CONCEPT GENERATION

3.1 MOCKUP PROTOTYPE

While building the mockup for our tendon rehabilitation device, we came across several realizations. Putting the device on with only one hand was more difficult than we had anticipated. Therefore, we added being able to attach and detach the device easily to our list of functions. In addition, we realized that elastic bands could pose more of a danger than we had thought and that the device should prevent them from snapping into the user or another person. The user should be able to control the force mechanism with the push of a button. A device with a ratcheting mechanism in the handle could accomplish this. Finally, this mockup does not have the concentric exercise component removed, as removal requires much more complicated mechanisms to be added.

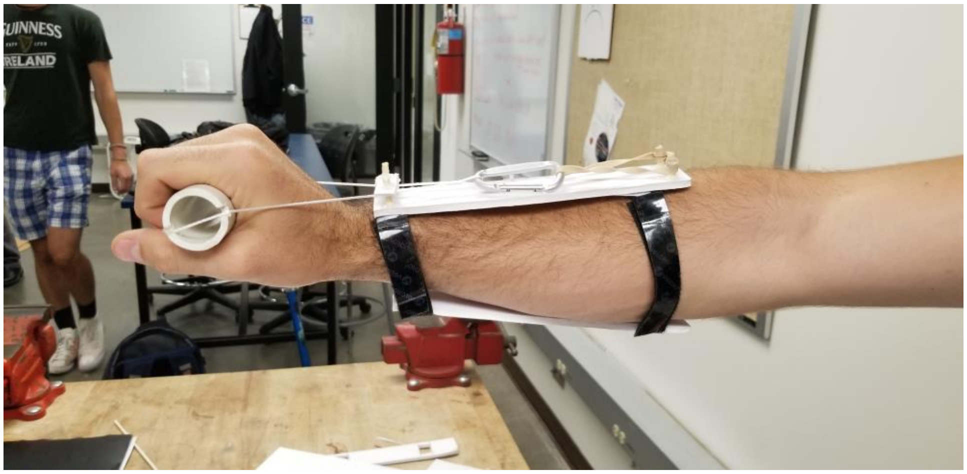


Figure 12. Mockup picture 1, side view showing mockup in rest position

Figure 13. Mockup picture 2, side view showing mockup in stretched position

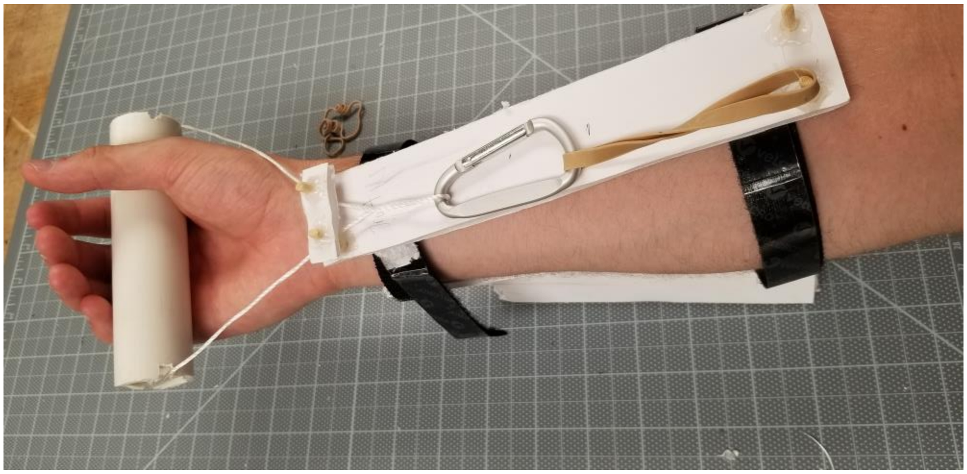


Figure 14. Mockup picture 3, palm-up view showing mockup in rest position

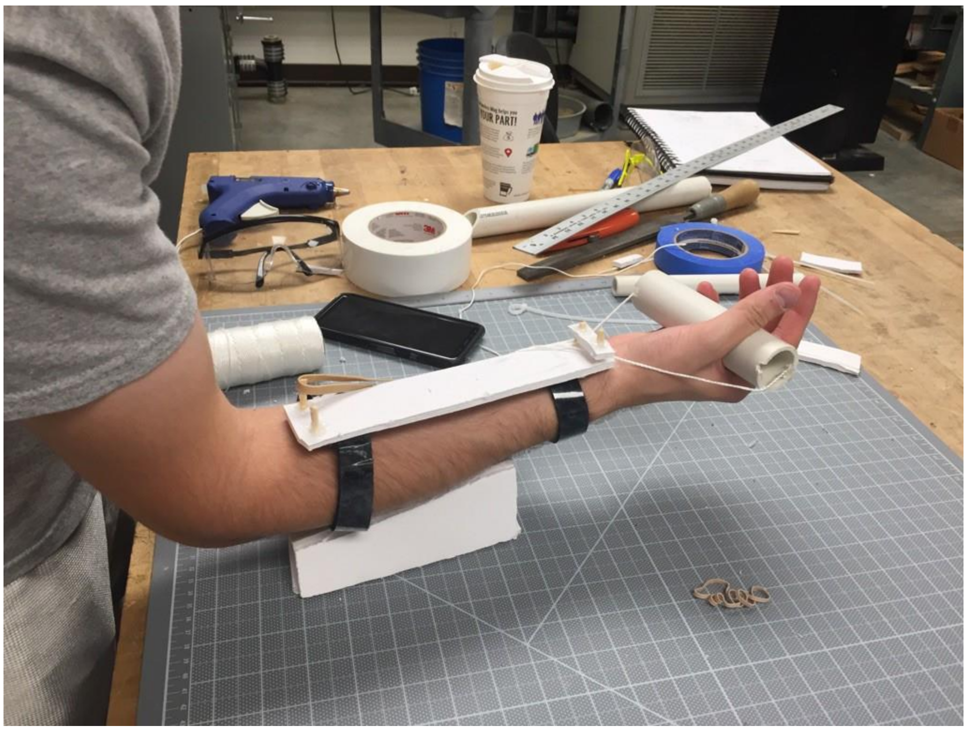


Figure 15. Mockup picture 4. Palm-up view, showing mockup with an arm support box

3.2 FUNCTIONAL DECOMPOSITION

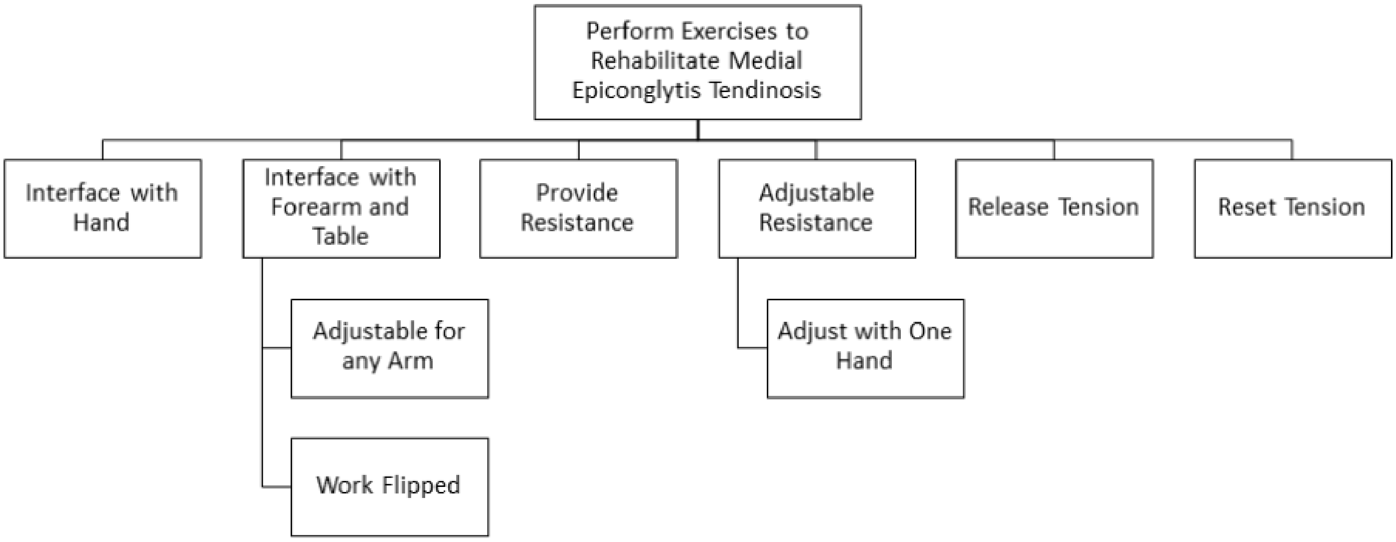


Figure 16. Function Tree

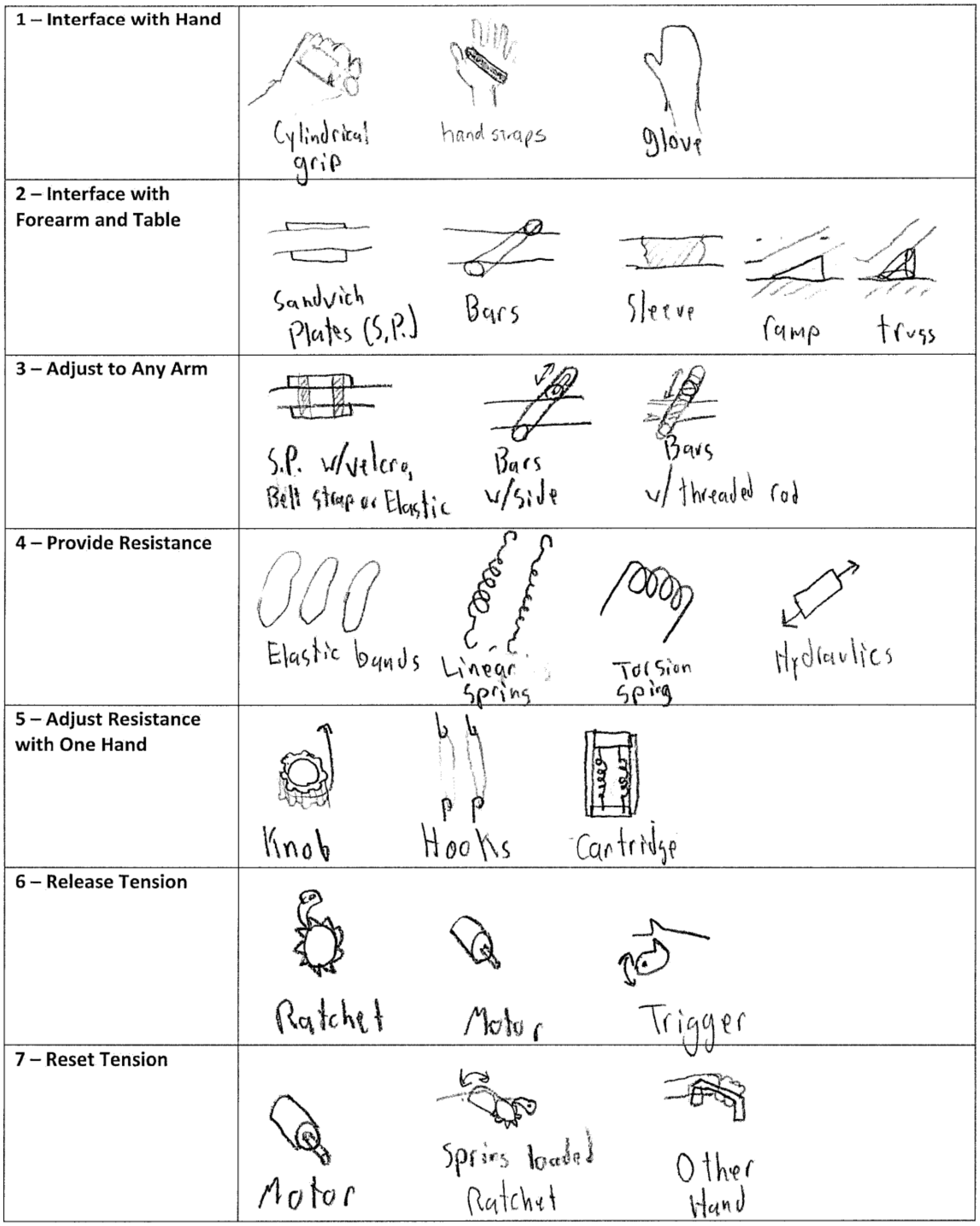


Figure 17. Morphological chart

3.3 ALTERNATIVE DESIGN CONCEPTS

Concept Name: "Ratchet Release"

Group Member: Lucas Parisot

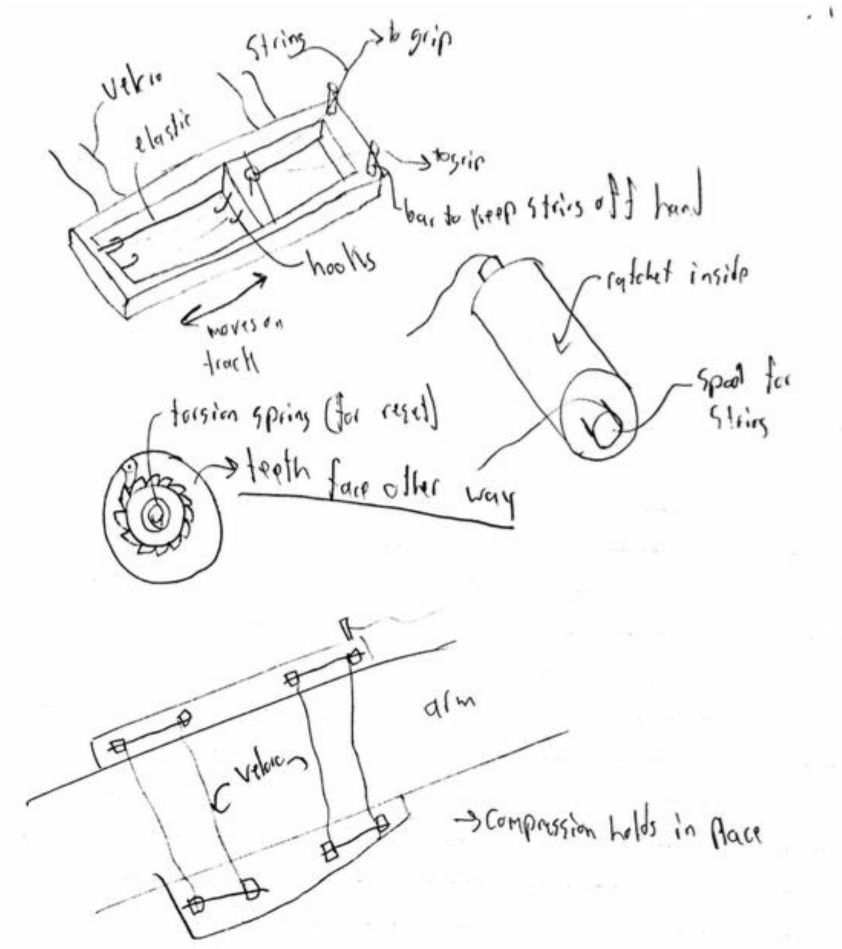


Figure 18. Lucas Parisot initial ratchet sketches 1

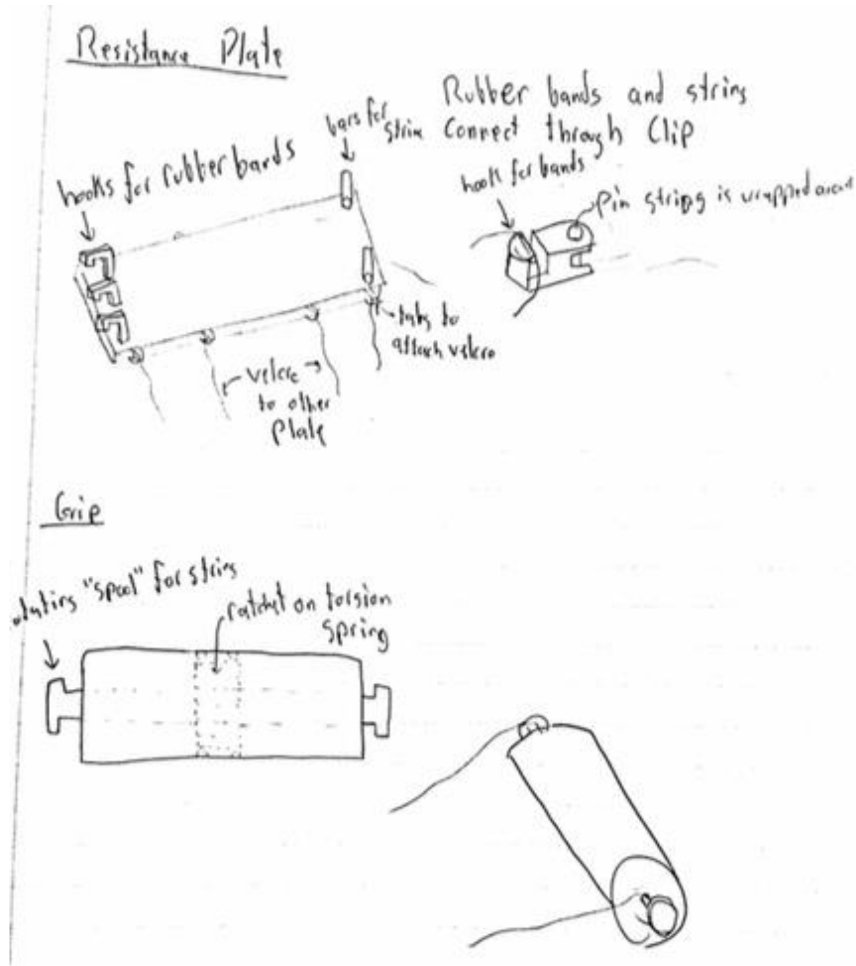


Figure 19. Lucas Parisot sketches 2

Description: Elastic bands provide resistance as they are stretched between the hooks, mounted on the rear of the top plate, and the clip. The clip has a pin through it which the string is fed around so that the system may be self-equalizing. The string then is fed to spools on the outside of the cylindrical grip. Inside this grip there is a ratchet system which keeps the spools from moving when a downward tension is applied, but when tension is released the torsion springs winds the spools back up, resetting the system.

Solution:

1. Cylindrical Grip
2. Sandwich Plates
3. Velcro Straps
4. Elastic Bands
5. Hooks
6. Ratchet
7. Spring Loaded Ratchet

Concept Name: “Ratcheting Torsion Spring Design”

Group Member: David Ricks

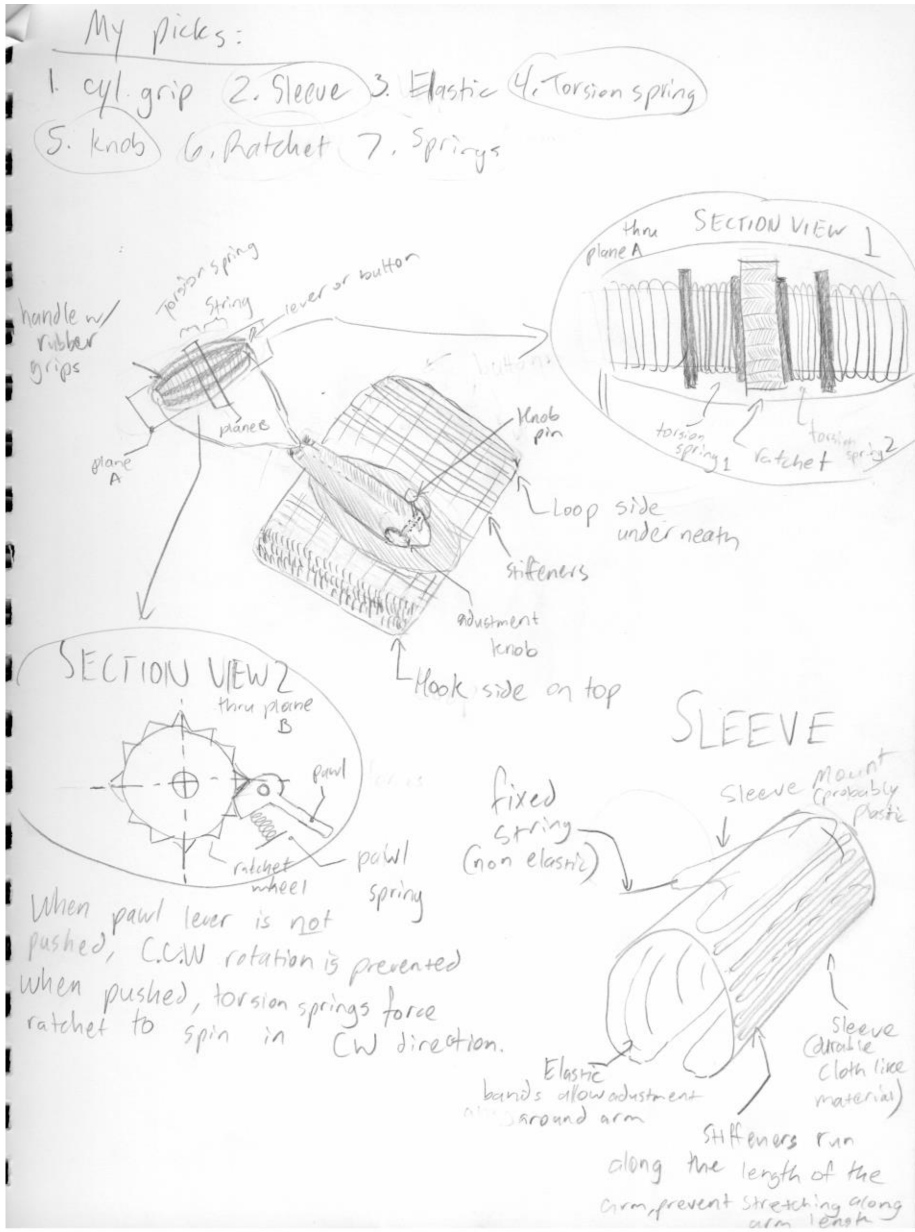


Figure 20. Final sketches by David Ricks

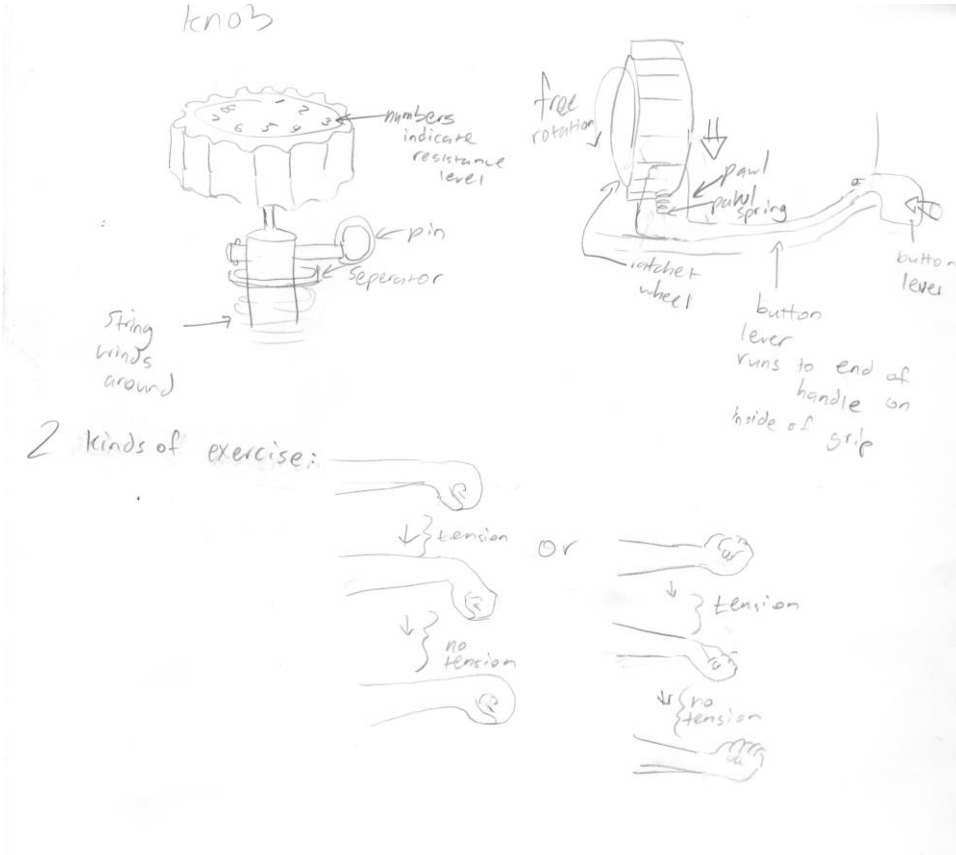


Figure 21. Unused sketches by David Ricks

Description: My design incorporates a thick cloth sleeve with hook and loops fasteners like those used to measure blood pressure. Since this would need to handle a fair amount of force without moving, I designed mine to have a crisscross pattern of semi-rigid stiffeners built into the sleeve along the arm, as well as elastic built into the sleeve perpendicular to the stiffeners. This way, the sleeve can be attached firmly with forces from the elastic holding it in place. The grip is a cylinder, tapered at both ends with a high friction material on the outside to make the handle as easy to grip as possible. There is a non-elastic spring attaching the handle the sleeve. The force for the tendon exercises comes from a torsion spring in the grip, which winds the string around an interior drum in the handle. This interior drum has a ratcheting mechanism, similar somewhat to that in a socket wrench. To release the tension from the torsion springs, a button is pressed on the outside of the grip that lifts a pawl, and the torsion springs force the device back to its “starting position.” When not pressed, a pawl spring forces the pawl to lock against turning back to this starting position. The non-elastic spring is spun around this interior drum as well, which is what provides the tension. A knob on the arm support can wind the string around another drum, which adjusts for tension. Numbers on the knob indicate the level of tension, and a pin holds it in place.

Solution:

1. Cylindrical grip
2. Sleeve
3. Elastic
4. Torsion Springs
5. Knob
6. Ratchet
7. Springs

Concept Name: “Motor-spring-driven handgrip”

Group Member: Benjamin Wang

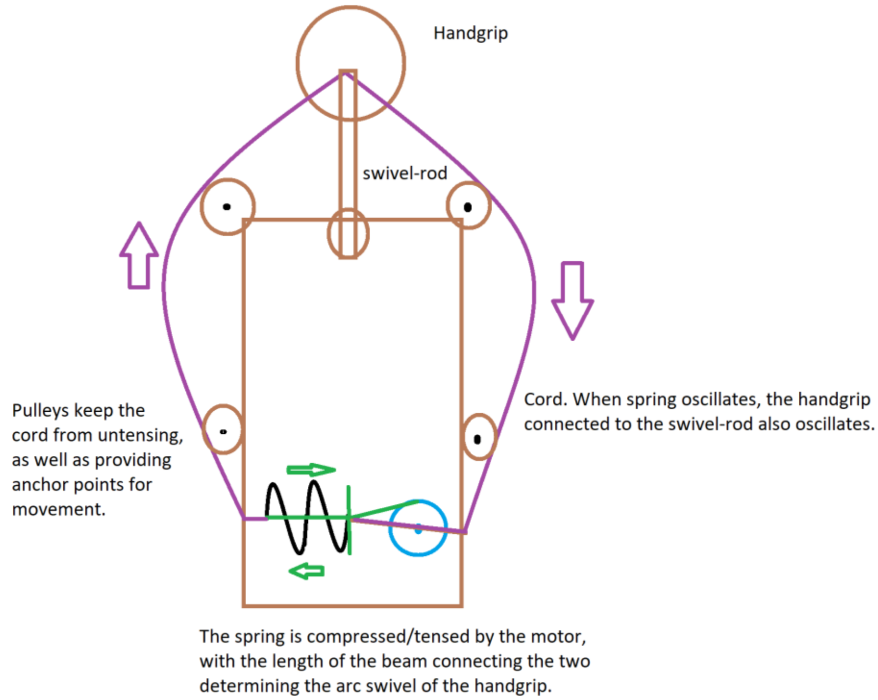


Figure 22. Benjamin Wang top-view initial sketches 1

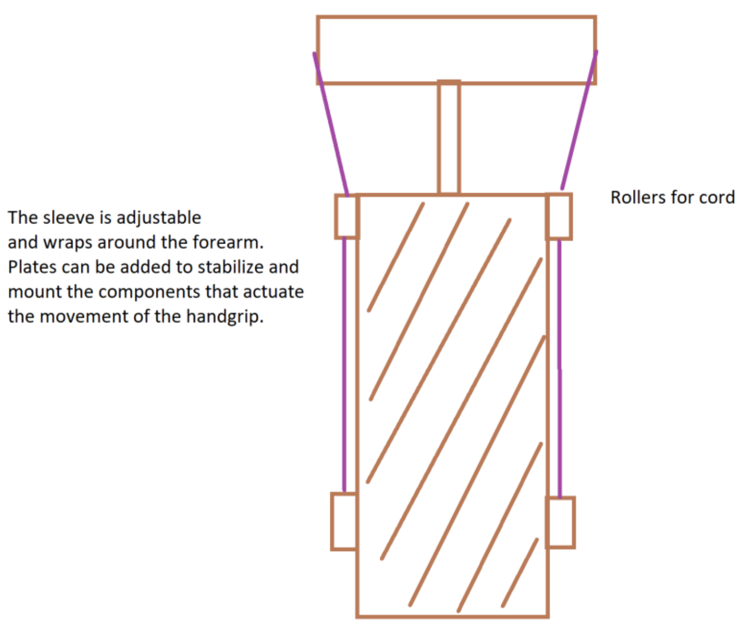


Figure 23. Benjamin Wang side-view initial sketches 2

Description: A motor drives a spring into compression and tension, which pulls the cord forwards and backwards. The entire cord forms a loop, with the spring at the bottom and the handgrip connected at the top. In order to keep slack from forming, the cords are connected to pulleys attached to the sleeve, with the swivel-rod connecting the handgrip to the sleeve allowing arcing movement of the hand. As the spring compresses or tenses, the loop is pulled forwards or backwards, moving the handgrip. Eccentric exercise is performed by resisting the movement of the handgrip, and the resisting impulse is fed back into the spring. The motor has a circular plate attached to the motor axis, with a rod connecting the circular plate to the spring. This transforms the angular torque and movement of the motor to linear motion of the spring.

Solution:

1. Adjustable full-wrap sleeve
2. Spring
3. Cord
4. Motor
5. Cylindrical handgrip
6. Pulleys

4 CONCEPT SELECTION

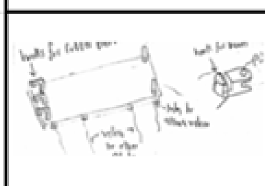
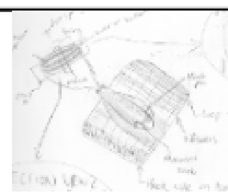
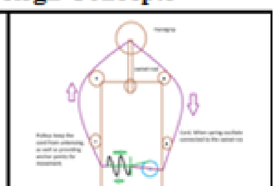
4.1 SELECTION CRITERIA

Table 4: Selection Criteria

	Adjustable Resistance	**Ease of Resistance Adjustment**	**Portability**	**Size Adjustability**	**Comfort**	**Affordability**	**Row Total**	**Weight Value**	**Weight (%)**
Resistance Adjustability	1.00	3.00	1.00	0.20	7.00	7.00	19.20	0.22	22.06%
Ease of Resistance Adjustment	0.33	1.00	0.33	0.14	5.00	7.00	13.81	0.16	15.87%
Portability	1.00	3.00	1.00	0.33	7.00	9.00	21.33	0.25	24.51%
Size Adjustability	5.00	7.00	3.00	1.00	3.00	7.00	26.00	0.30	29.87%
Comfort	0.14	0.20	0.14	0.33	1.00	3.00	4.82	0.06	5.54%
Affordability	0.14	0.14	0.11	0.14	0.33	1.00	1.87	0.02	2.15%
	Column Total:						87.03	1.00	100%

4.2 CONCEPT EVALUATION

Table 5: Concept Evaluation

		Alternative Deisgn Concepts					
							
Selection Criterion	**Weight (%)**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**
Resistance Adjustablilty	22.06	5	1.10	4	0.88	3	0.66
Ease of Resistance Adjustment	15.87	4	0.63	5	0.79	4	0.63
Portability	24.51	4	0.98	4	0.98	3	0.74
Size Adjustability	29.87	3	0.90	3	0.90	3	0.90
Comfort	5.54	2	0.11	4	0.22	4	0.22
Affordablity	2.15	3	0.06	2	0.04	1	0.02
	Total score	**3.790**		**3.817**		**3.171**	
	Rank	**2**		**1**		**3**	

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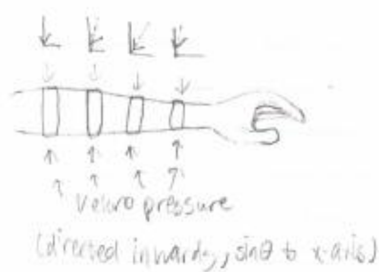
4.3 EVALUATION RESULTS

Based on our concept evaluation scoring matrix, the Ratcheting Torsion Spring Design won. It ranked highest in ease of resistance adjustment and never ranked last in a category, making it a well-rounded design. The resistance adjustability ranked high but not the highest since the torsion spring has limits whereas a band method would allow for a huge range of tension since you could continue to add resistance bands. The third design's resistance is based on the spring's tensing from the resistance provided by the wrist, but this meant the resistance will not be constant, and if wrist resistance were to exceed spring stretching strength, the spring would need to be replaced with another one of a greater spring constant to provide more tension. A potential problem with this design, though, could be finding a torsion spring with enough angle of twist range for the full range of motion. A possible alternative might be wrapping an elastic band around a spool. Adjusting the resistance would be easy since it would only require turning a knob on the base. Since it does not incorporate a motor, the device should be light and portable, compared to the third design, which would either need batteries or bulky cords connecting to a power source to power such a motor. The Velcro sleeve would be easily adjustable as well as comfortable, which would fit a variety of forearm sizes and shapes. Lastly, it would not require any high-cost components so it should be reasonably affordable, though the need for custom parts could drive the price up.

4.4 ENGINEERING MODELS/RELATIONSHIPS

Velcro Stress Analysis



$$F_{\mu static} = \sum_{1}^{4} P_{(pressure\ of\ velcro)} \cdot A_{(area\ of\ velcro)} \cdot \mu_{s(static\ friction)} \cdot \sin(\theta) + C \cdot W_{device} \cdot \mu_{static}$$

$$F_{\mu static} = F_{motor}$$

$$F_{\mu static} = \left(\sum P \cdot A \cdot \sin(\theta) + C \cdot W_{device} \right) \cdot \mu_{static}$$

C = constant of how much weight is supported by arm.

$$F_{\mu static} = \left[\sum \left[P \cdot C_e \cdot A \cdot \sin\theta \right) + \left(C_w \cdot W_{device} \right) \right] \cdot \mu_{static}$$

P = Pressure from velcro straps

C_e = factor from state of velcro. Damaged, deteriorated velcro does not stay stitched for too long.

A = Area of contact of velcro

$\sin\theta$ = angle made by velcro compression force on arm skin to x-axis along arm

C_w = factor of how much weight of the device the arm supports

W_{device} = weight of device

μ_{static} = coefficient of static friction.

Figure 24. Velcro stress analysis

The Velcro stress analysis model is an estimation model for determining the necessary amount of Velcro for our device. At a deteriorated state, Velcro barbs have a likelihood to slip depending on the shear force exerted between the two contacting Velcro straps. The shear force is proportional to the inwards pressure or force that the Velcro exerts on the arm. The analysis does not take into consideration sections of skin bunching up against the pulled movement of the velcro, which would keep the bands stable.

Cantilever Tube Stress Analysis

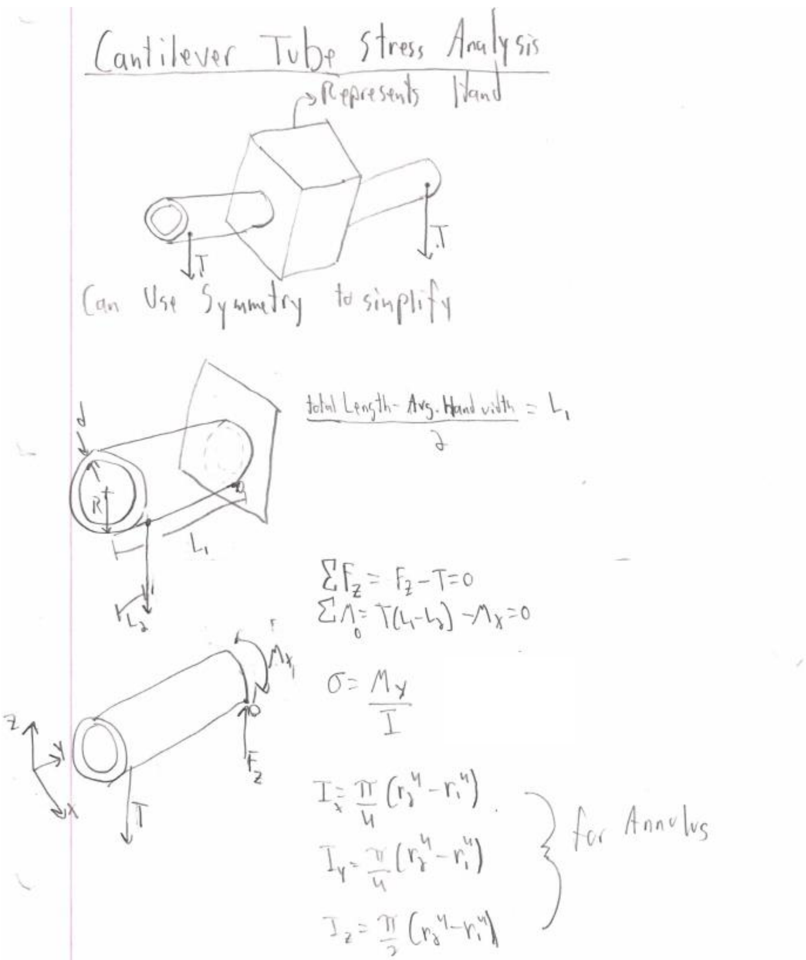


Figure 25. Cantilever tube stress analysis

This model helps us to understand how thick to make the tube used in the grip. This tube would contain the ratchet mechanism and spools which may add some structural rigidity, but this is being ignored. As well, the tube would have caps on each end, which are also being ignored. We are treating the hand as a solid block holding the tube, like a cantilever beam, and then using symmetry to only solve for one side of the tube. Knowing the average width of a hand, the tube length will be made slightly longer. We can optimize the thickness as compared to the weight of the material used. The symbols used are: tension T, cantilever length L_1, force exerted by hand onto grip in the z, y, and z directions F_x, F_y, F_z, inner and outer radius r_1 and r_2, stress σ, bending moment M, and moment of inertia about neutral axis I.

Hooke's Law

A torsion spring produces the force tensioning the rope between the grip and the sleeve. Hooke's law for torsion springs can help us choose a spring to produce a required tension quantity or range.

$$\tau = -\kappa\theta$$

Where τ is the torque in newton-meters, κ is the spring torsion coefficient in newton-meters per radian, and θ is the angle of twist in radians. Since there are two ropes wrapped around a spool with radius r_{spool} attached to this spring, finding the tension in each spring T is simple:

$$T = \frac{1}{2}\frac{\tau}{r_{spool}}$$

And the force exerted on the grip, F_{grip}, is therefore:

$$F_{grip} = 2T = \frac{\tau}{r_{spool}}$$

5 CONCEPT EMBODIMENT

5.1 INITIAL EMBODIMENT

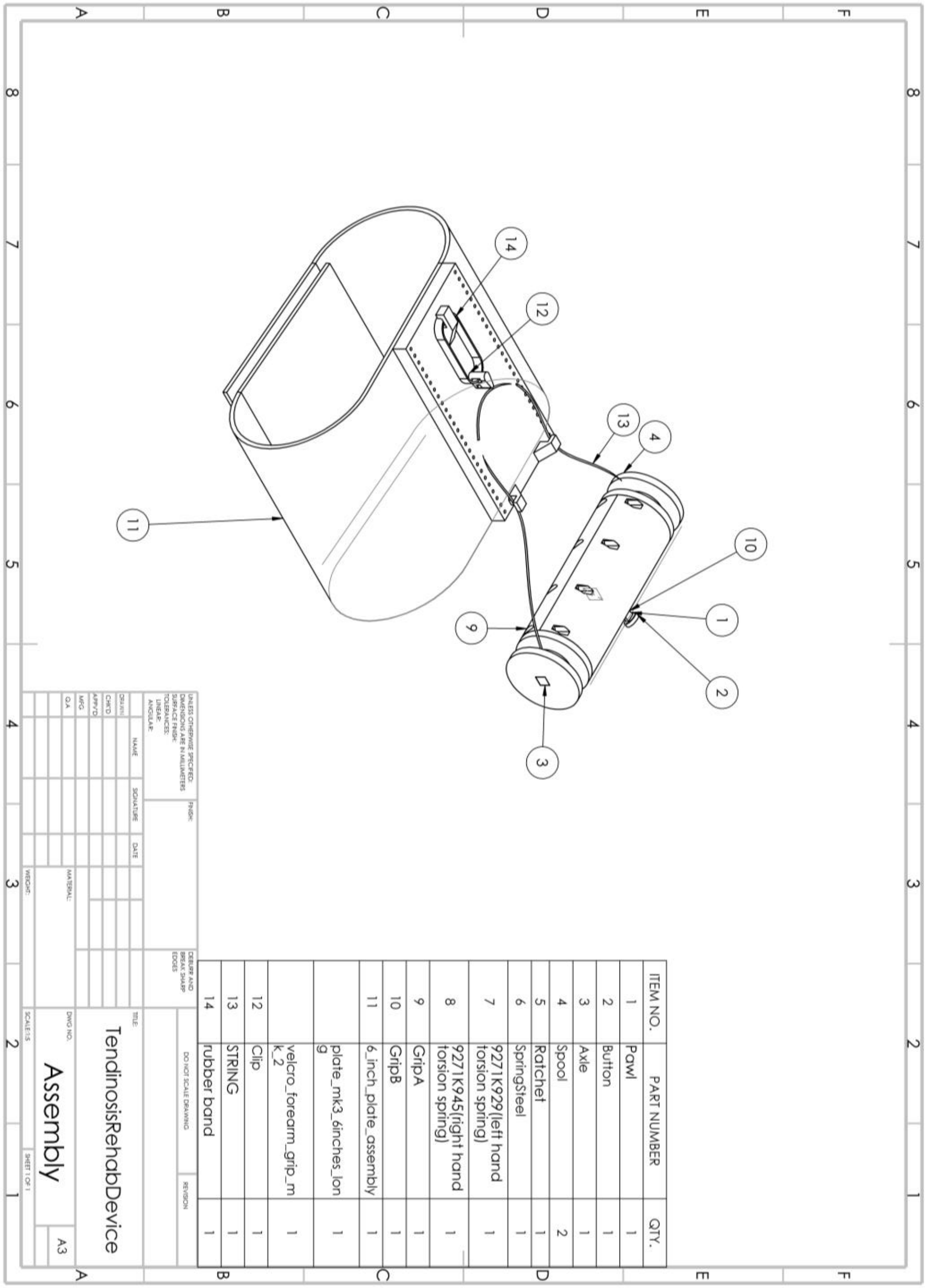


Figure 26. Isometric assembly view with BOM

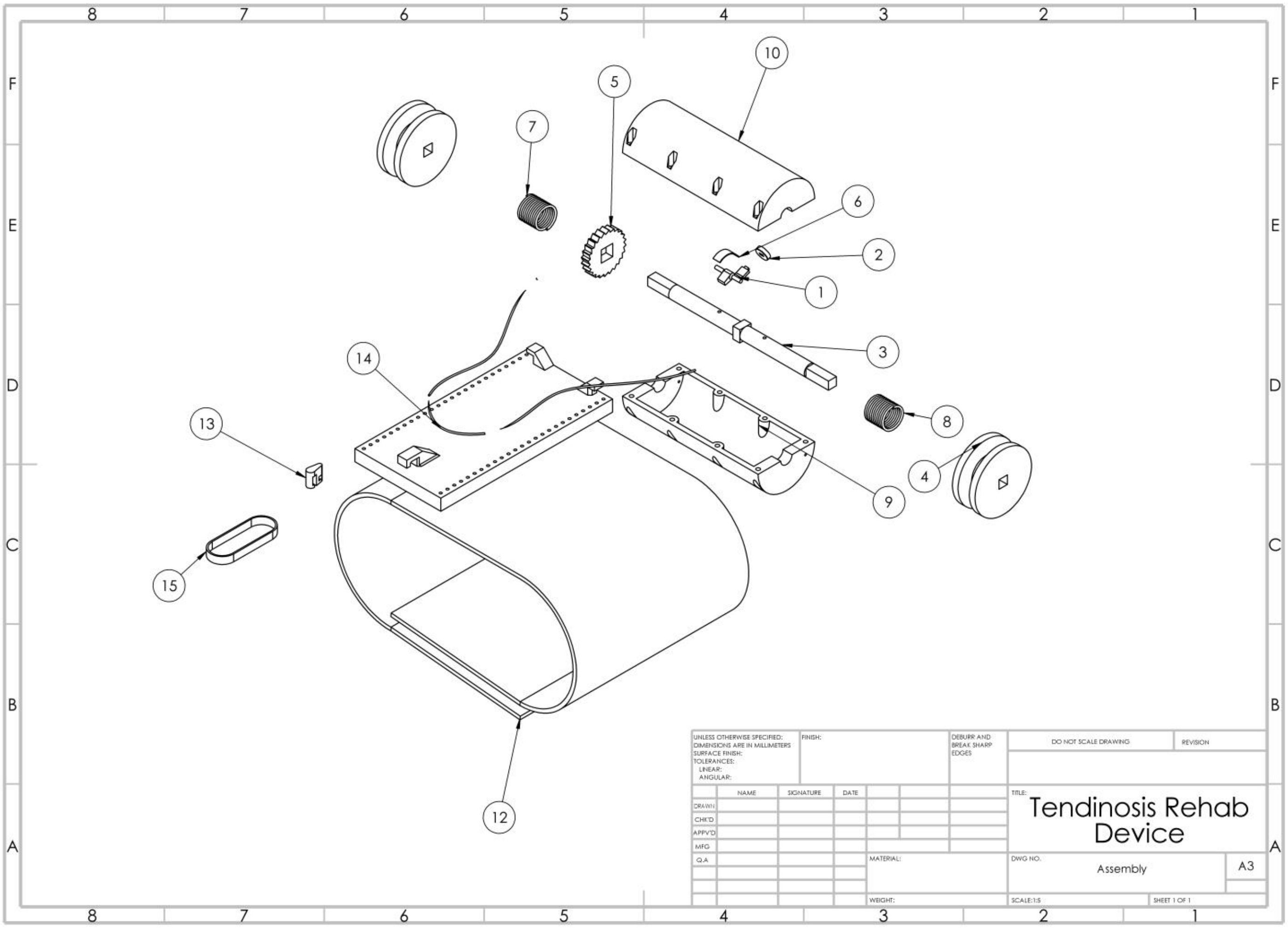


Figure 27. Isometric exploded assembly view with BOM

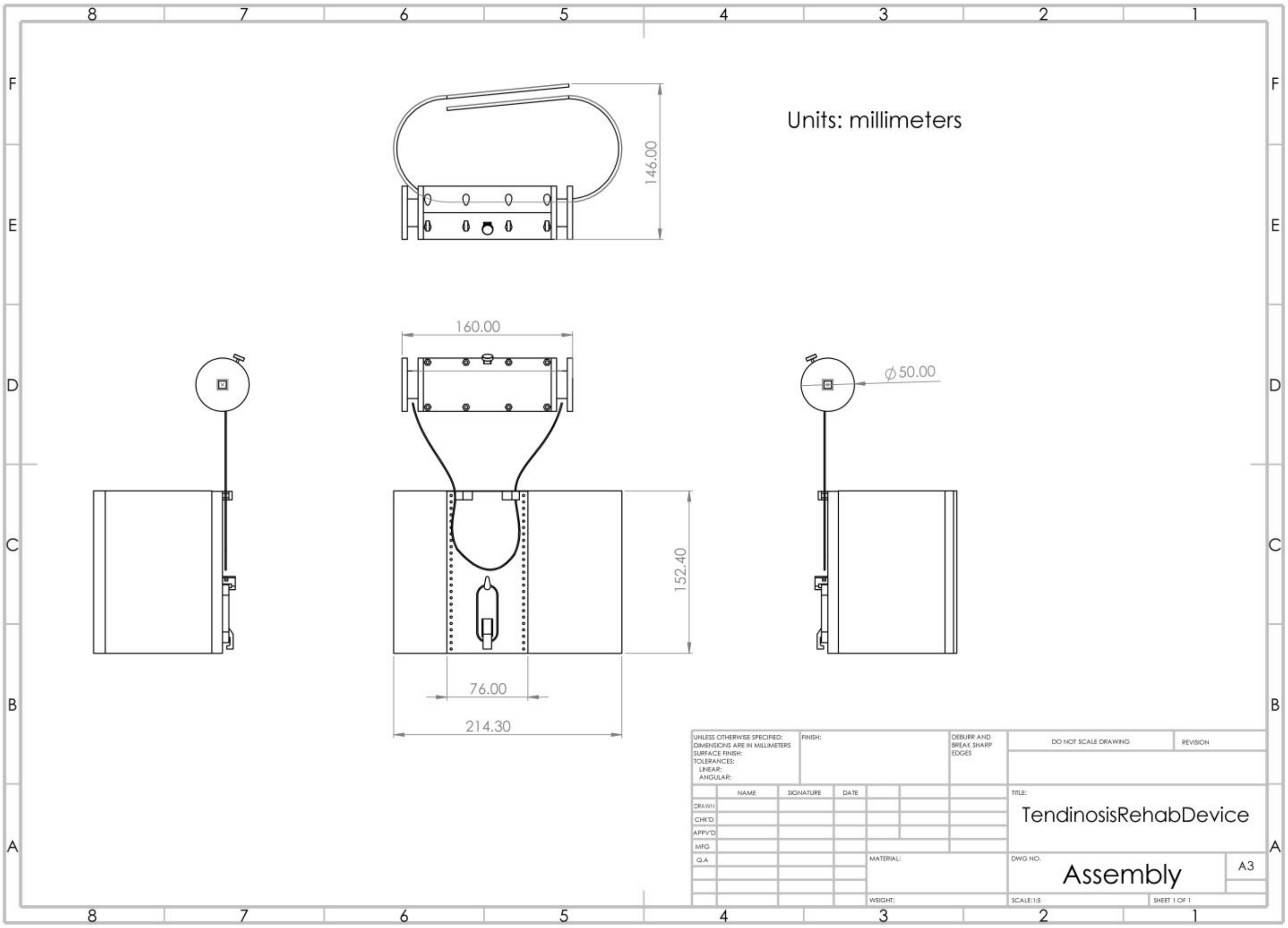


Figure 28. Orthographic views with basic dimensions

	Part	Source Link	Supplier Part Number	Color, TPI, other part IDs	Unit price	Quantity	Total price
1	M3 Screw	McMaster	92290A118	M3x14mm Stainless Socket Screw	$5.33	1	$5.33
2	M3 Nut	McMaster	90592A085	Steel	$7.82	1	$7.82
3	Torsion Spring	McMaster	9271K929	Left Hand Wound	$8.18	1	$8.18
4	Torsion Spring	McMaster	9271K945	Right Hand Wound	$8.18	1	$8.18
5	Fishing Line	Amazon	21100650150E	PowerPro Spectra 150yd Moss Green 65lb	$12.81	1	$12.81
6	Rubber Bands	Amazon	28618-CC	#64 Postal Bands	$8.23	1	$8.23
7	Strip Spring	McMaster	9074K27	.002in Thick Spring Steel Strip	$14.79	1	$14.79
8	Velcro Loop	Amazon	B0731ZM499	6in x1 yrd, Loop side only	$5.69	1	$5.69
9	Velcro Hook	Amazon	B0731XZPBY	6in x1 yrd, Hook side only	$5.69	1	$5.69
Total:							$76.72

Figure 29. Prototype parts list

5.2 PROOF-OF-CONCEPT

Prototype Performance Goals

1) Tendon Rehabilitator must change proximo-distal location on the forearm less than or equal to 1 cm after 15 cycles.

2) Tendon Rehabilitator engages resistance within 10 degrees of initial extension from maximum palmer flexion.

3) Tendon Rehabilitator has resistance range that simulates dumbbell weights between .45kg (1 lb) and .9 kg (2 lb).

Design Rationale

One of the rationales for our prototype design was based around the design of the spools for the fishing line. These spools needed to have an interior diameter large enough so that the entire length of the line could spool for the motion of the wrist. In original designs this diameter was the same as for our axle, however, we realized that the line would not completely spool for the range of motion of the wrist. The amount of extension was calculated by measuring the range of motion of the wrist and by multiplying it by the distance from the point of rotation of the wrist to the center point of the grip. This value was found to 80 mm; therefore, this is the amount of string needed to be wound onto the spool. Knowing the axle will rotate 380 degrees we divided 80 mm by pit to get a diameter of 25.4mm needed.

Next, we had to figure out the thickness of the grip shell. This was done using a beam stress analysis. In order to analyze the grip we made a couple assumptions. First, we treated the hand as a wall since the beam will be moving in reference to the hand. This simplified the system to a cantilever annulus. Second, we assumed that the distributed load from the axle onto the grip would be replaced with a single load directed on the bottom of the interior of the annulus. We picked a thickness of 4mm because it was well under the breaking strength of PLA plastic and allowed the part to have screws placed in it. The calculations can be seen below in Figure 31.

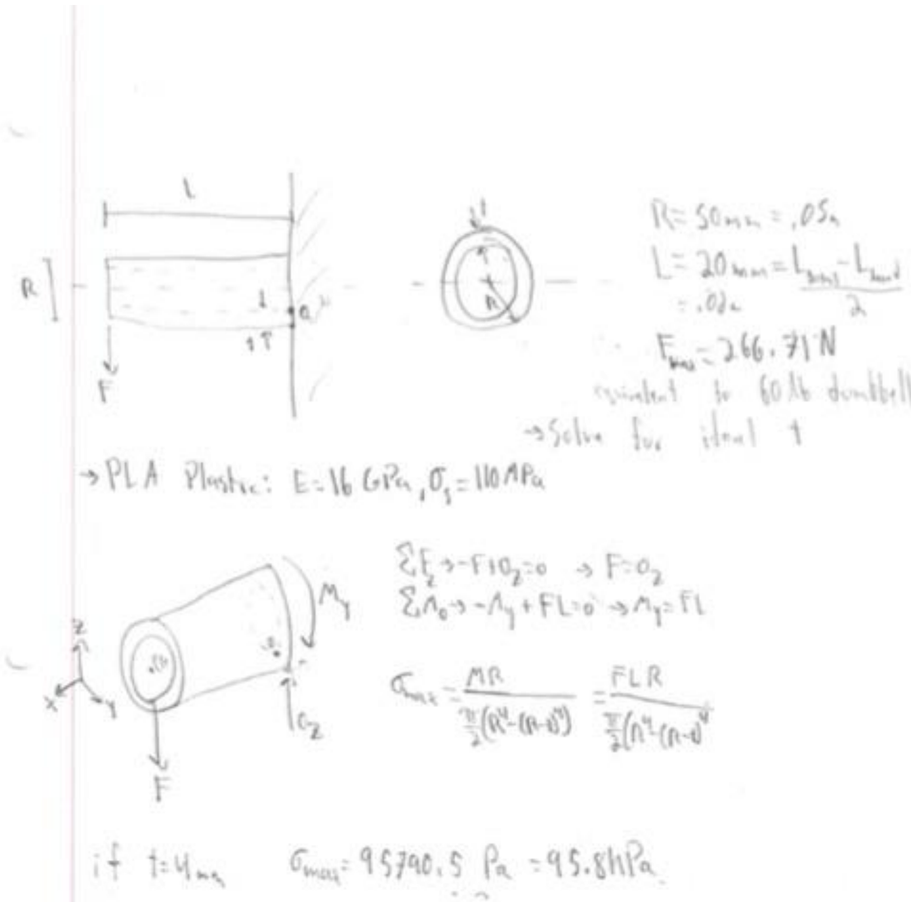


Figure 30. Grip thickness calculation

To determine the necessary width, number, and locations of the Velcro bands anchoring the plate to the forearm, analysis needs to be performed on the setup. Looking at the forearm structure and referring back to the engineering model of the Velcro bands attached to the wrist, starting at the elbow, the forearm is thickest and has the largest circumference near the elbow, and peaking and then tapering inwards when moving towards the wrist. This will affect the placement of the Velcro bands, as they all endure a force pulling them towards the hand. Assuming a constant coefficient of static friction and a band circumference just about equaling the circumference of the forearm sections the bands are wrapped around, the taper of the arm affects the effectiveness of the bands. Bands located near the elbow joint, and on the outwards taper of the forearm, are affected on one way. If the pull from the hand is greater than the resistance friction force, the bands are pulled towards the outwards taper, where the circumference of the forearm is greater than their circumference. The hook and loops of the Velcro prevent them from expanding their circumference, and thus the Velcro bands are prevented from moving further. Bands located on the inwards taper, unfortunately, are ineffective once the force of pulling exceeds the static resisting force. Once static friction is overcome, they are pulled towards the inwards taper, where they become free as their circumference exceeds the circumference of the new section of the forearm they are on. Hence, the Velcro bands are to be concentrated near the elbow region of the forearm. If a long plate is used, Velcro bands will only be used in the region of the forearm closest to the wrist, where the taper has leveled off, to prevent the board from twisting too much.

To further detail the forearm engineering model, different variables need to be found. Different surface materials between the Velcro bands and the skin of the forearm, as well as the quantity of sweat present, will change the static friction. The dynamic friction may apply when the band moves, but the hook-and-loop preventing the increase of the circumference of the band means dynamic friction can be neglected.

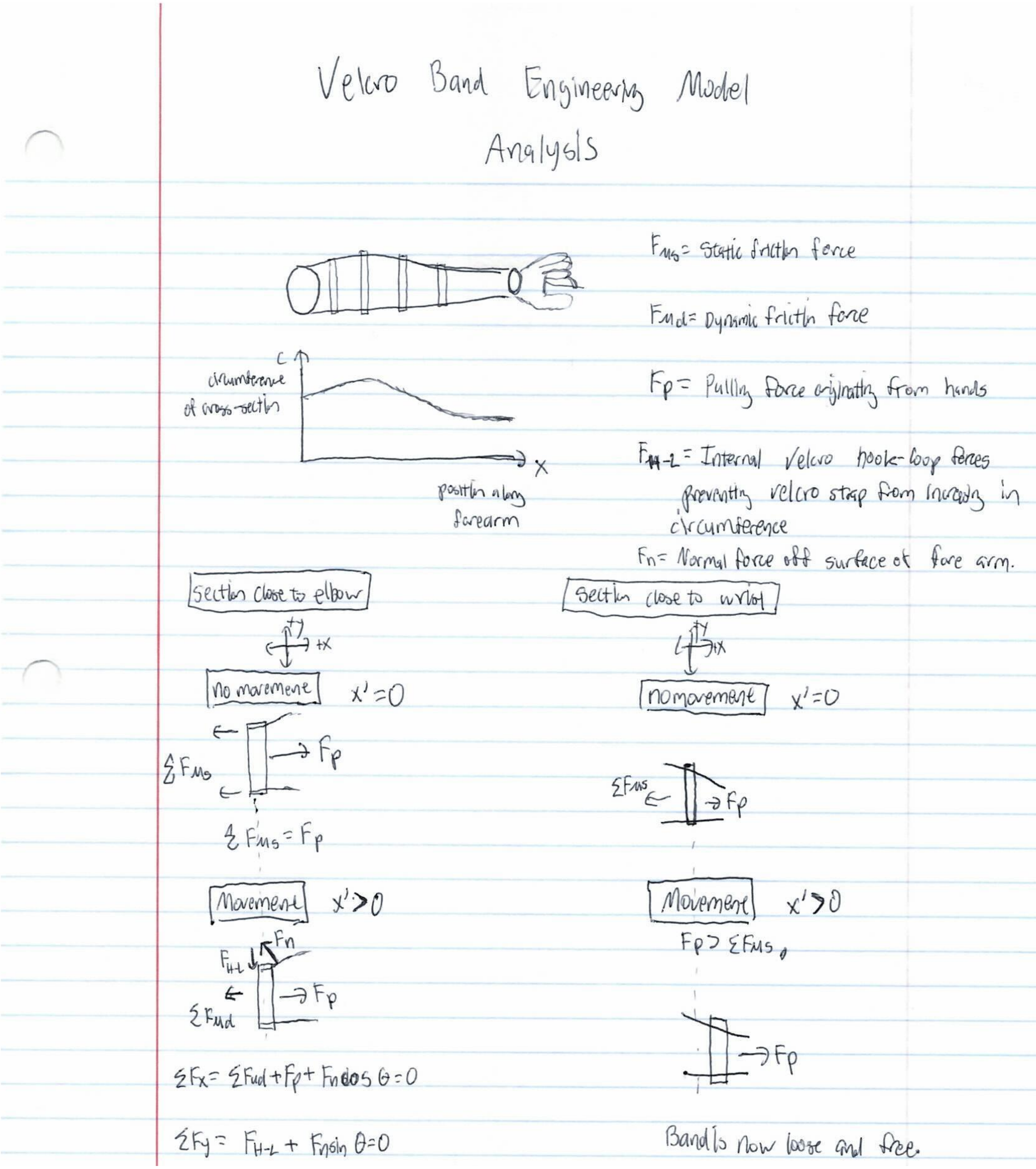


Figure 31. Analysis of Velcro band effectiveness at two parts of the forearm

The following Figures 33, 34, and 35 show the 3d printed arm mount, ratchet/axle/spool, and pawl. Some of the parts are printed with acrylonitrile butadiene styrene (ABS) and some are printed with polylactic acid (PLA).

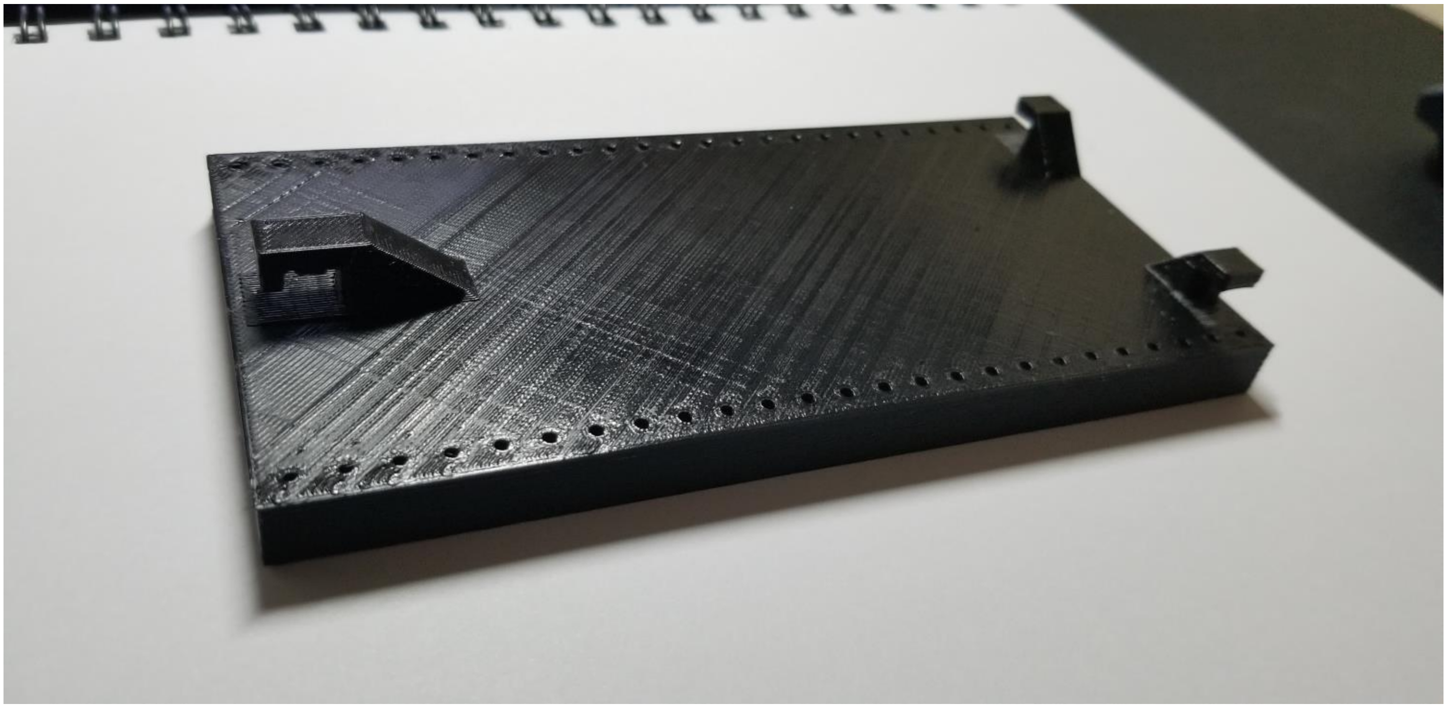


Figure 32. Proof of concept photo 1

Figure 33. Proof of concept photo 2

Figure 34. Proof of concept photo 3

6 WORKING PROTOTYPE

6.1 OVERVIEW

From our proof of concept demonstration, we found many problems with our current design. The first being that fitting a ratcheting mechanism into a decently sized grip was extremely difficult with 3D printing. The second flaw being that there had to be a very careful balance between the torsion springs and the rubber bands to get the system to reset properly. This careful balance required for the system to work properly is very counterproductive for a device meant to be portable, carried around, and functional at different angles and resting position of the arms. The torsion springs can come loose, requiring time-consuming replacement in their mounts, especially since the arms performing the replacements have tendon problems. The third flaw being that mounting the device on the forearm inhibited the motion of the exercise and caused slipping in the system. The forearm mounting also made the system difficult to deal with. Moving on from our proof of concept the decision was made to overhaul the design and go for a desk mounted version. The design was changed then to a box that could sit on a table. This box containing a rest on top for the forearm and a grip connected by string and a pulley to a rubber band bank, or later a spring system. This rubber band bank is connected to a servo which upon the press of a button can tension and detention the system. The resistance of the system is adjusted by changing out rubber bands in the hooked rubber band bank. This new design required a battery and an Arduino to control the servo, but removed the need for a clunky torsion spring and ratchet-and-pawl system located within a small handle. This change of design meant that our performance goals also had to change since they were no longer applicable. The new goals can be found in section 6.3.

6.2 DEMONSTRATION DOCUMENTATION

Figure 35. New Grip and Pulley System

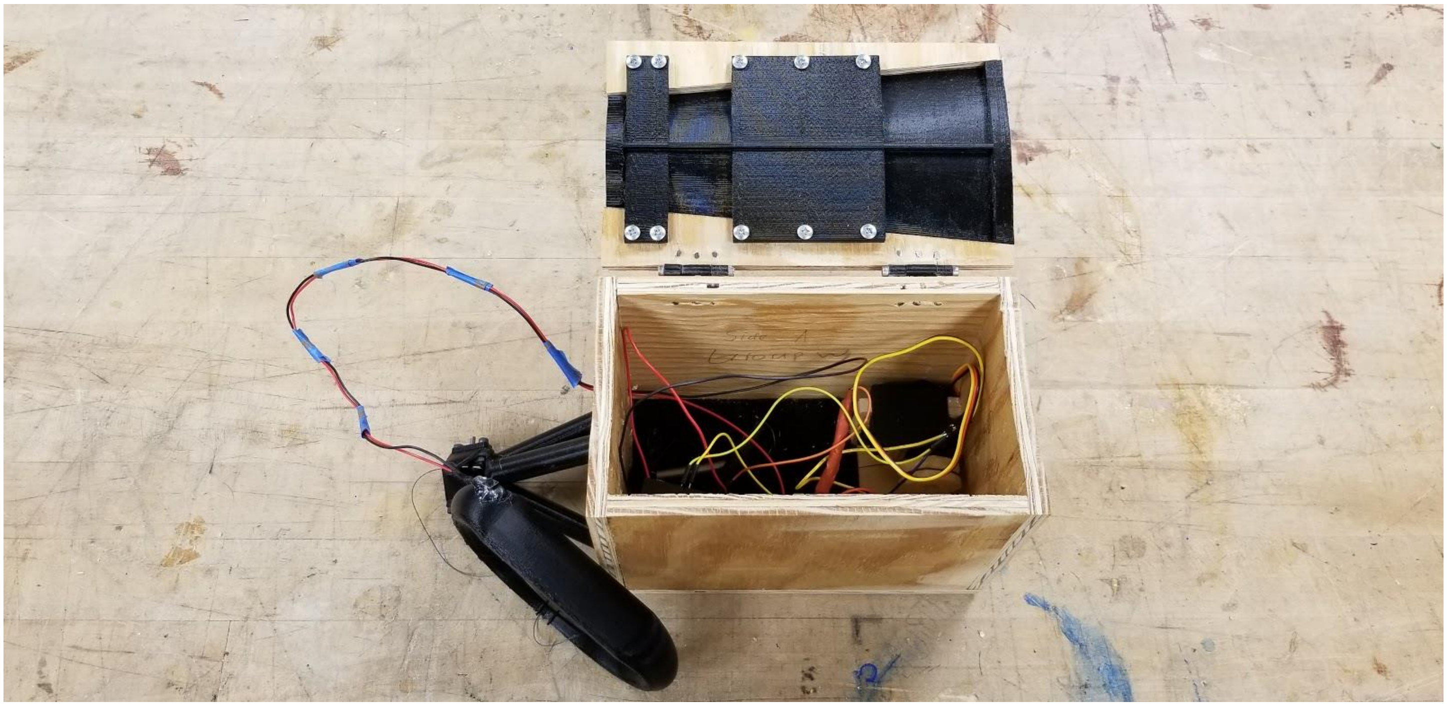


Figure 36. Servo and Arduino

Figure 37. New Working Prototype Design

6.3 EXPERIMENTAL RESULTS

Goal 1: Tendon Rehabilitator simulates dumbbell resistance range between 1 and 10lb.

Upon initial testing the device did not meet this performance goal. The reason being that the servo was not large enough or strong enough to pull a spring that would give a 1lb weight equivalent. Using the servo on a 1lb metal weight caused rotation and servo gear issues, making a likely probability for the servo to not perform its duties. This goal is important because the one-pound weight is the minimum value of the weight range often used for the rehabilitation exercise. This weight range was simulated by adding and subtracting springs from the devices bank of springs. After changing out the servo for one with much more torque the servo was able to pull a full bank of springs. This new servo is able to support and pull equivalent weights between 1 and 10lbs.

Goal 2: Tendon Rehabilitator engages resistance during full eccentric range of motion.

This test ensured that tension would be applied to the system for any users range of motion. We found during our initial test that the servo motor was not strong enough to reset the rubber band in the system. However, after the servo was changed to one with a much larger torque, the system was able to be properly apply tension to the springs and thus the hand. The servo, unlike the proof of concept, ensured that resistance would be 100% engaged at any location along the eccentric route. While the initial tension values may be low during the initial servo turning and stretching of the rubber bands, this works for therapy as it is a gradually-increasing force that acclimatizes the user-applied hand resistance when the hand resists the pull. If for some reason resistance is not engaged at a point in the motion the motion of the servo can be adjusted to make sure that a complete reset of the systems tension is achieved. This goal, although not reached at the time of testing, was reached in the testing since.

Goal 3: Tendon Rehabilitator functions without maintenance for 10 cycles.

This test made sure that the device would work for the average repetitions done for one set of the exercise. Typically, stopping mid set for this exercise can hinder and rehabilitation, therefore the device must not stop during this set. From our initial testing the servo was not large enough to consistently pull back the springs. This meant that we got about 2 cycles before maintenance was required. This servo was later changed to a significantly larger motor with a larger torque possibility. This addition proved to be enough to get the device to complete 10 cycles before any maintenance was needed. However, the maintenance needed switched from the servo to the bank of springs tangling.

7 DESIGN REFINEMENT

7.1 FEM STRESS/DEFLECTION ANALYSIS

The following analyses are made specifically for the proof-of-concept prototype. The proof-of-concept prototype, more specifically the arm-strap forearm-mounted rehabilitation device, has the most complex 3-d printed parts of the two designs developed, is more mechanically complex, and benefits most from the analysis process. These analyses results, combined with the actual physical inspection of the assembled proof of concept, gave weight to the decision to completely change the working prototype to a box-shape version detailed in section 6, as the risk of component breakage is constrained by their presence inside the box, and the possibility of overextension or large amounts of force pulling the hand negated by simply releasing the handgrip.

For the FEM stress/deflection analysis, the pawl of the ratchet mechanism was analyzed. We decided to analyze the pawl because it was a thinnest part that we thought might not be able to handle the applied force from disengaging the ratchet. The mesh was created automatically with Solidworks. The mesh resolution was fine enough for a converged solution, as tweaking the element size yielded similar results. The pawl was fixed on part where it engages the ratchet and hinges to simulate a lot of friction between the ratchet and pawl. Then, a 50 Newton force was applied where the button would be attached on our model. The material we chose to apply to our model was ABS, or acrylonitrile butadiene styrene, which was what we used for our 3D-printed prototype. In reality the pawl would be weaker, as we did not 3D print our parts with 100% infill, though solid infill can be done for later, fully-refined parts. 3D printing also results in weak points between the parallel-printed layers, which are much weaker to shear forces, and is not accounted for in our Solidworks analysis. Therefore our factors of safety and displacement requirements should consider the fact that the static analysis is somewhat ideal and not fully realistic performance of our actual parts.

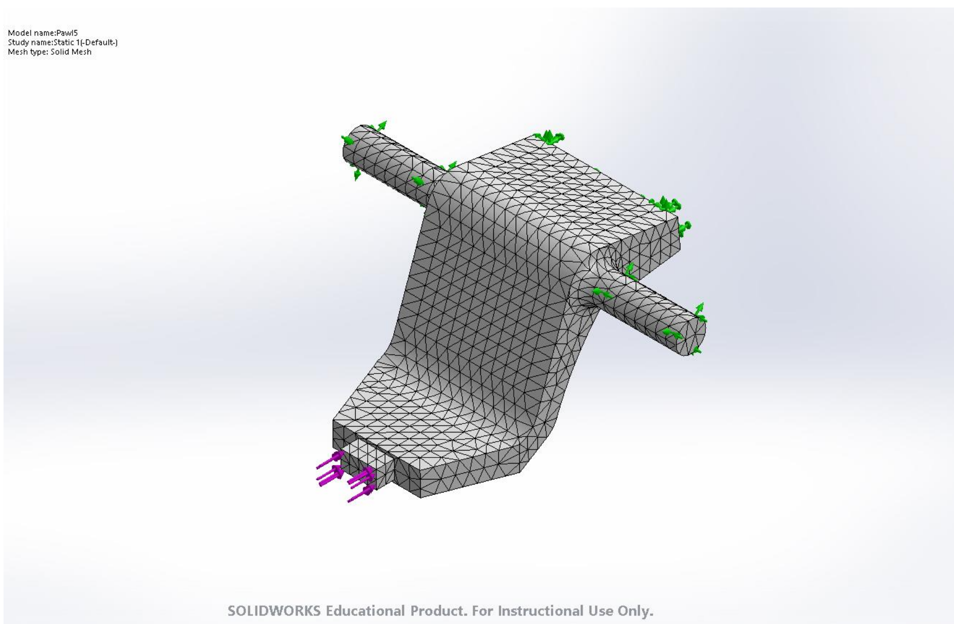


Figure 38. Model showing mesh, loads, and boundary conditions

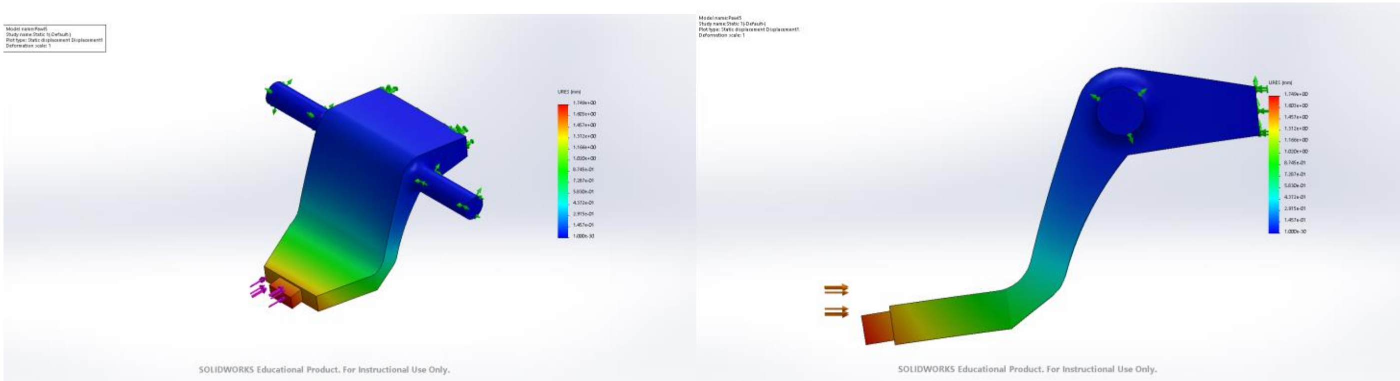


Figure 39. Model displacement, true deflection

On the Solidworks assembly, the gap between the pawl and the grip was measured to be 4.5 mm. Therefore, the deflection of the pawl should be significantly less since the pawl needs to rotate almost the entire gap to disengage the ratchet. The static study showed a maximum deflection of 1.749 mm, so the deflection is substantial and therefore likely problematic, and would be even bigger on the actual 3d-printed pawl itself. Such forces would compress or fracture the layers making up the pawl. A better design might use a stronger material such as aluminum or a strong thermoset plastic to reduce the amount of deformation.

7.2 DESIGN FOR SAFETY

Risk Name: Rubber band shooting off or snapping/breaking

Description: When the rubber band is loaded at the bottom of the exercise motion it is under the maximum amount of tension. If the components it connects to on the plate or on the clip were to fail the rubber band could shoot off in an unpredictable manner. The rubber band will also shoot off if it were to slip off the attachment point. This could also happen if the band were to break. If the band were to get wet the likelihood of slippage happening will most likely increase. Tears in the rubber band will serve to have concentrations of stress in the rubber band and promote breakage. If the band were to shoot into an eye this could be a large liability. The lifetime of cycles of use of a rubber band can be considered to find how often they need to be replaced.

Impact: 3. This only is an issue if it launches into the user or others' eyes or delicate appendages. However, if the rubber band attachment point is the point of failure then there is a potential for flying plastic.

Likelihood: 3. The likelihood of the rubber band slipping, or the rubber band breaking is low, provided care is taken to replace the rubber bands often. However, the likelihood of a 3D-printed plastic piece to break is relatively high considering its strength often depends on the 3D printer and the amount of force needed to be loaded on the rubber bands, as well as the design of the rubber band anchor point.

Risk Name: Plate Coming Loose

Description: If the stitching for the plate comes loose then the plate will shoot towards the hand. Depending on how the plate flies the plate may remain connected to the rubber band and may hit a body part. However, if the band disconnects from the plate then the plate will be launched outward potentially hitting someone else. This may also happen if the Velcro is pulled loose.

Impact: 3. This could be a very painful failure with the possibility of the plate creating a cut upon contact.

Likelihood: 2. It is unlikely that the stitching will come loose considering the amount of stitches applied to the plate. The likelihood of the Velcro coming loose is rather low, considering the large area of the Velcro band, and would only occur in the most degraded of Velcro surfaces.

Risk Name: Spool Separation

Description: If the spools were to separate from the axle under load of the rubber bands they could shoot toward the user. The spool being one of the larger parts of this machine could cause some injury to the user upon impact.

Impact: 2. Injury by this part would likely be small, unless the parts fragment or strike delicate areas.

Likelihood: 2. Depending on the way the axle is 3D printed it may snap at different loads. The axle has been made thick to make sure that this happens less often. Locks, either mechanical or frictional, can also be added to prevent complete slippage off the axle.

Risk Name: Choking hazard

Description: The clip, the hardware, and several of the internal ratchet pieces are small enough to choke on. This could be a danger when assembling the machine around small children.

Impact: 2. This could result in a trip to the hospital but in most cases would involve the person being given the Heimlich maneuver.

Likelihood: 1. The likelihood of this is low since the machine should not need to be disassembled/reassembled once originally built.

Risk Name: Grip collapse

Description: If the grip were to be 3D printed with improper settings then it could crush under the load of the rubber band or under the load of the hand. This could cause bending and shattering of the part. There is a potential for sharp pieces with a grip collapse, especially with the springs, ratchet, and fractured plastic posing as hazards.

Impact: 2. Could cause lacerations in the hand. Unlikely that those injuries would require anything more than a Band-Aid. Possibly 3, depending on the sharpness and orientation of the hazards when they contact skin, and how deep they embed from the forces involved, but unlikely as the grip is not made of thin brittle plastic that undergoes shattering under fracture failure.

Likelihood: 1. If 3D print instructions are followed it is unlikely this part will fail

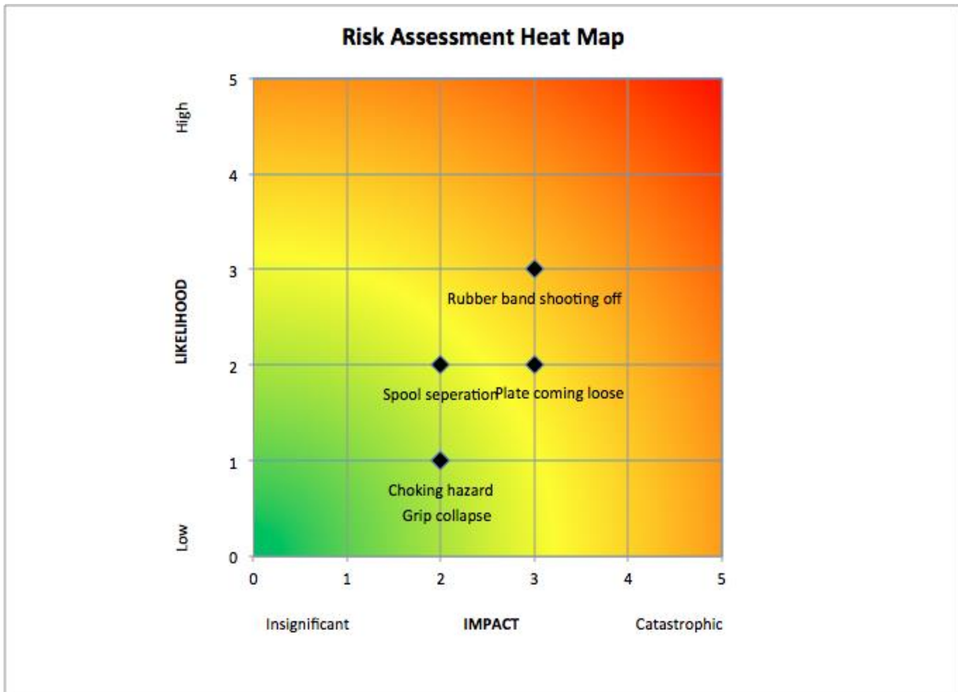


Figure 40. Risk assessment heat map

According to the heat map in Figure 39, the risk to be given the greatest prioritization must be the shooting off of the rubber band. This failure has the highest likelihood and highest impact of all the potential risks. This failure should be the highest considering that it has the most points which could fail causing the rubber band to shoot off. The next most important failure was the plate coming loose. Although this failure is uncommon it could cause injury. After this came the spool separation, a failure that has an equally low likelihood as impact. Finally, tied for least important is the choking hazard and grip collapse, both of which should not happen very often but could cause some damage to the user.

7.3 DESIGN FOR MANUFACTURING

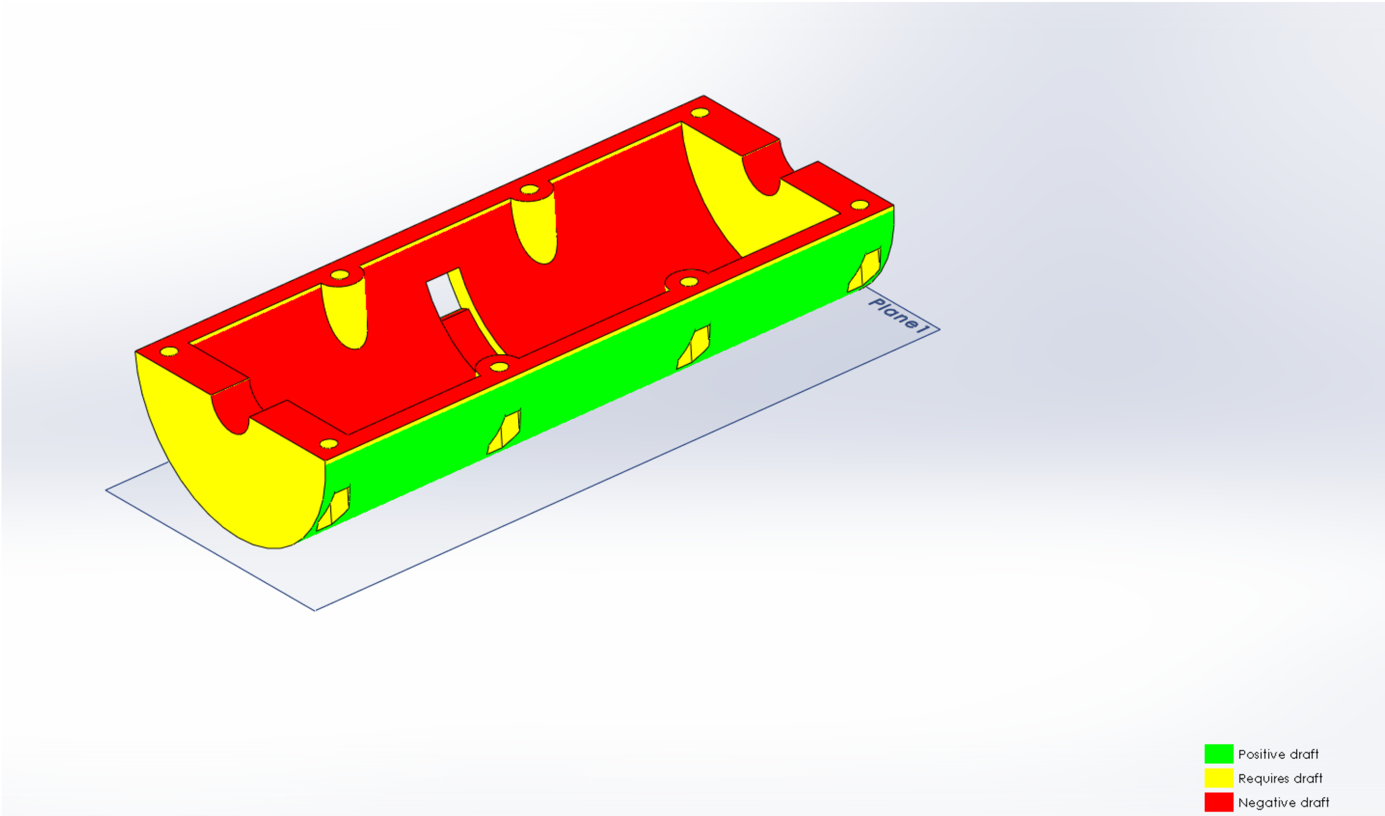


Figure 41. Initial draft analysis of Bevel grip half

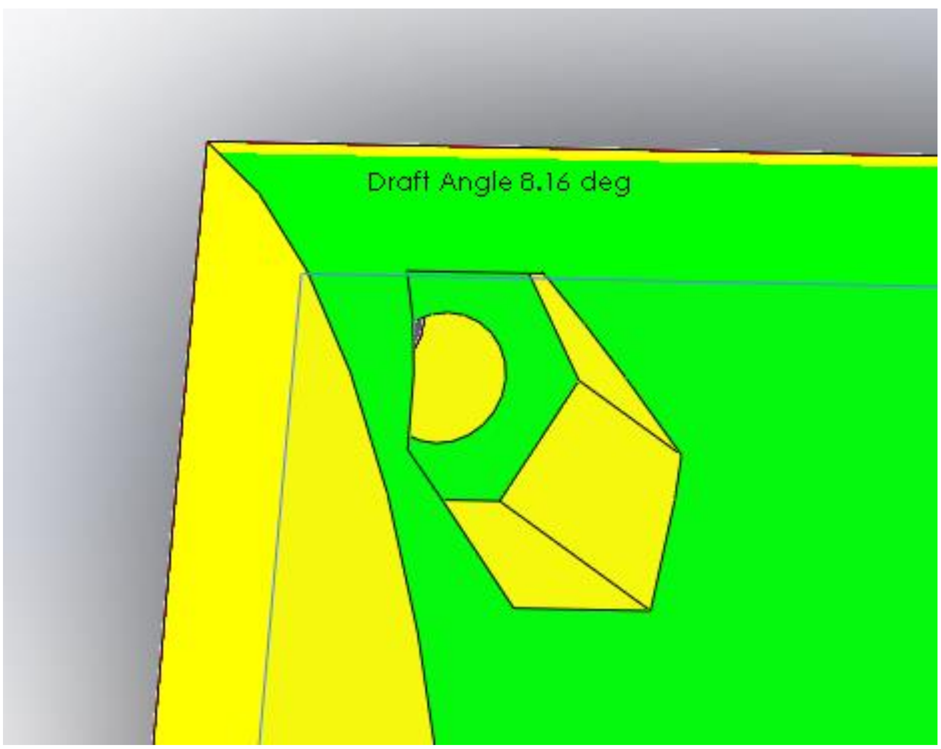


Figure 42. Closeup of screw section near end face

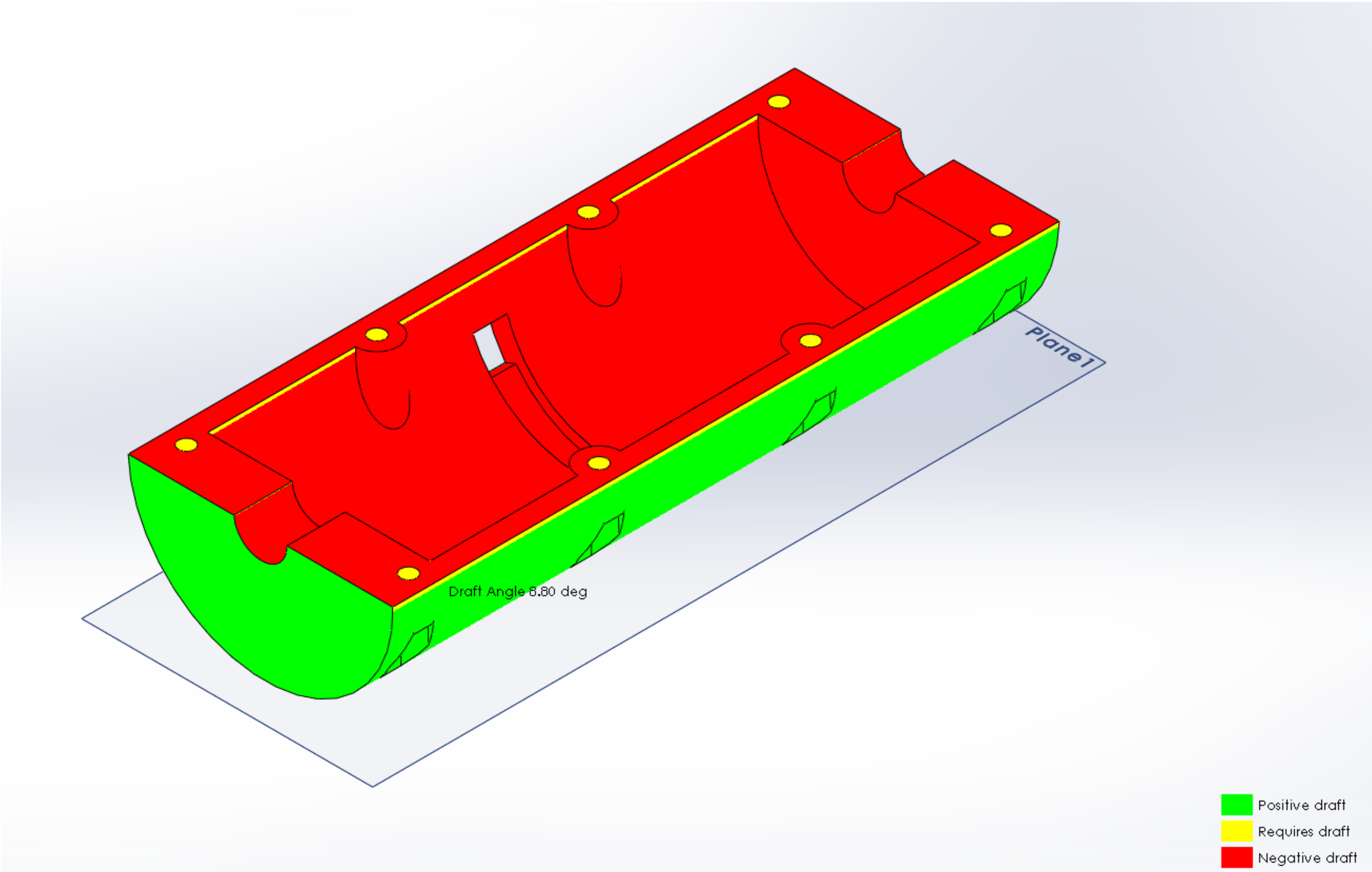


Figure 43. Final analysis of bevel grip half after draft corrections

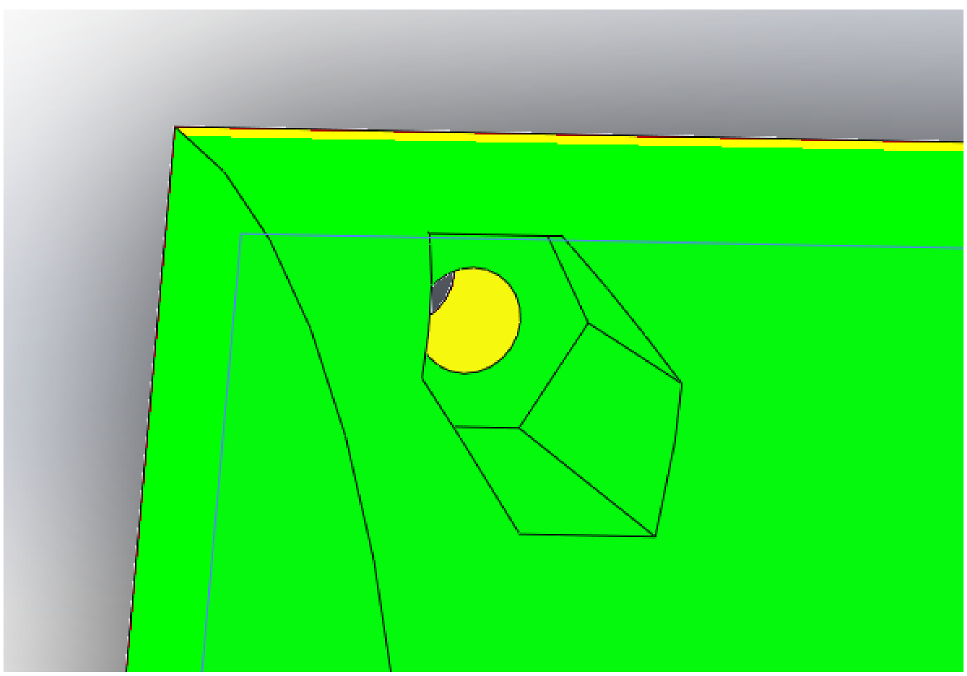


Figure 44. Closeup of screw section near end face 2

An extension of the sides and a draft located on the end faces and drafted in towards the center of the rod was added so the bevel grip half would be easily removed from the mold drag, with the curved bottom located at the lowest part of the mold. The extension of 3 mm per face was added as drafting the screw holes outwards would bring the distance between the end faces and the walls of the outer screw holes precariously small. The screw hole walls were drafted outwards towards the bottom, as to facilitate easier removal, again, from the mold drag. The inner end face and cylindrical walls drafted and expanded outwards towards the bottom, as to make removal of the upper mold cope easier. The screw holes were left as-is, as 3-degree drafts would affect their diameter for screw insertion.

7.4 DESIGN FOR USABILITY

1. **Vision**

If the user is vision impaired, it may be difficult for them to attach the rubber bands to the machine. The opening to add the rubber band would have to be either larger or chamfered to assist the band in seating properly. Color blindness should have no influence since the color of the machine is dependent of 3D printing filament used to build it.

2. **Hearing**

Hearing impairment should have no influence on the machine since there is no auditory component. The only sound the machine should make is the releasing of the ratchet mechanism and the winding of the torsion springs. However, this is not an issue for the hearing impaired because they should both be able to feel and see the release of tension.

3. **Physical**

This machine is designed for those with tendon injuries. However, it does require some motion of the wrist and the ability to close the hand on and tightly grip a handle. Due to the specific nature of the exercise we cannot change the machine to work for other injuries other than that it intends to work. The machine could potentially be changed such that gripping the handle is not necessary.

4. **Language**

The machine will be equally usable to those speaking any language other than English. The directions for the machine can be made entirely with demonstration videos and informational pictures. The machine contains no text on it. The only part that may need text is the number for the rubber band. However, the rubber band used it left to the user, although recommendations will be given. Therefore, no changes will be needed to make the machine bilingual.

5. **Control**

The machine is designed to primarily provide exercise to the tendons. However, there will be some working of the forearm muscles. If the user is experiencing excessive fatigue in the forearms, then it is due to the user using too much resistance. This will be detailed in the instructions. Since this is an exercise device it should not be used while under the influence of any drugs you wouldn’t use in a gym. This can also be detailed in the instructions.

8 DISCUSSION

8.1 1.1 PROJECT DEVELOPMENT AND EVOLUTION

8.1.1 1.1.1 Does the final project result align with its initial project description?

The final, working prototype does fulfil the goals of providing a portable rehabilitation device that engages the tendons of the elbow while providing a variable resistance. While the actual design shape drastically changed from a forearm-and-hand-mounted device to a box, the overall functionality still fulfils the customer needs.

8.1.2 1.1.2 Was the project more or less difficult than expected?

In the middle of the semester, the design for the rehabilitation device needed to be changed from its initial arm-based proof-of-concept prototype to a completely different box-based prototype. Rather than being technically difficult, the project consumed quite a lot of time, as a new design was brainstormed, discussed, modeled up, and finally produced during the month of November.

8.1.3 1.1.3 On which part(s) of the design process should your group have spent more time? Which parts required less time?

More time should have been spent on the box containing the servo and electrical components, as well as testing out the final prototype. Separating these components would have caused less interference between parts. As well, it would have allowed a space for the handle to stow into for travel. Less time could have put into the mount for the servo. Rather than crafting it out of wood it could have been easily 3D printed and mounted in a more solid manner. It would have been simpler to design the part in CAD than create it on the fly.

8.1.4 1.1.4 Was there a component of the prototype that was significantly easier or harder to make/assemble than expected?

The hand grip of the proof-of-concept prototype was the hardest piece to assemble together of the two designs. In order to work satisfactorily, the torsion springs need to be firmly connected to the innermost axle, which was then placed between the handgrip shaft and connected to the end spools. In practicality, too much rotation of the axle from its initial position could misalign the torsion springs and pull them from their hole mounts, requiring disassembly, fixing, and reassembly of the entire handgrip.

8.1.5 1.1.5 In hindsight, was there another design concept that might have been more successful than the chosen concept?

Yes. The proof-of-concept design turned out to be too mechanically complex and unwieldy, especially with the ratchet and pawl system located within the thick handgrip, compared to the drastic change that is the final physical prototype. The box-like shape of the final prototype has multiple functions: it can support the arm, replacing the Velcro strap connecting a anchor plate to the forearm; it’s internals holds the mechanisms necessary for performing eccentric exercise on the tendons; and it is relatively simple to transport, compared to two separate and cord-connected devices.

8.2 1.2 DESIGN RESOURCES

8.2.1 1.2.1 How did your group decide which codes and standards were most relevant? Did they influence your design concepts?

Our standards were decided by researching standards pertaining to gym equipment. We also researched into medical equipment but gym equipment seemed to be more relevant to our project. Most standards involving gym equipment dealt with large equipment with heavy moving parts, so finding one that applied to our project was difficult. We knew we would have some moving parts so locating pinch points was important. The part needed to be held by the hand made the existence of sharp edges and possible burrs important to remove. They did not influence our design very much because our prototype was a rough proof of concept model, so we figured we could make changes later in the process.

8.2.2 1.2.2 Was your group missing any critical information when it generated and evaluated concepts?

Each of our concepts initially involved some sort of arm mounting. This proved to be a critical issue in the design that was only discovered later on in the design and prototype testing process. If we had another concept that involved a desk mount, we most likely would have seen earlier on that this was the best plan of action. As well, we assumed that the less electronics we had the simpler the design would be. This proved to not be true, as the ratchet mechanism for storing energy was quite large and too unstable and unreliable in the handgrip, forcing us to go over to a servo motor.

8.2.3 1.2.3 Were there additional engineering analyses that could have helped guide your design?

We could have analyzed the bank of springs closer. In our later design we ended up with two bars that held the springs. It would have been useful to study the strength of this bar under the oscillating force loads created by the springs and servo. This would have helped us to pick a reasonable resistance range and choice for the materials we were designing with.

8.2.4 1.2.4 If you were able to redo the course, what would you have done differently the second time around?

In the creation of the first mockup and the proof-of-concept prototype, we had our thoughts of the rehabilitation device specifically limited to an arm-mounted, given that the similar products we looked up were of that type. This restricted us in our initial designs and wasted time working on the arm mounted design. We could have reached out to more possible users to gain a larger knowledge pool of user needs.

8.2.5 1.2.5 Given more time and money, what upgrades could be made to the working prototype?

A more complicated command system of the servo could be made. The current programming code simply has the servo turn at a code-set speed when the trigger button is pressed. Any customizations would require pulling up the Arduino software, and adjusting the code using a computer. This does require a certain skill level or understanding of Arduino programming. A good update could be the creation of a control panel that lets the user of the device adjust the rotational speed of the servo. This extends or shortens the length of the exercise cycle the elbow was subjected to.

8.3 1.3 TEAM ORGANIZATION

8.3.1 1.3.1 Were team members' skills complementary? Are there additional skills that would have benefitted this project?

I think some of the team's skills were complementary. We had one member who was really strong in CAD, one member who was really strong with their engineering theory and another member who had experience working with wood. Additional skills that would have been useful are more Arduino coding experience and circuits experience. This would have sped up the servo control design process greatly. One member had some experience with Arduino coding but it was limited. Even during the actual construction of the prototype, member skills came in handy in selecting how parts would be made or added to the box, or the selection of the best of the available wood materials.

8.3.2 1.3.2 Does this design experience inspire your group to attempt other design projects? If so, what type of projects?

This project has inspired us to attempt other projects. Specifically, it has inspired us to search deeper into the world of medical technology. We believe that this is a sect of engineering that is extremely important. Projects that involve sports rehabilitation are also extremely interesting to us. Working to heal other climbing related injuries, such as finger pulley tears and rotator cuff tears could go along with our current project.

APPENDIX A – COST ACCOUNTING WORKSHEET

Table 6: Cost Accounting Worksheet

Parts Cost	
Arduino Uno	$22.00
Servo	$28.62
Push Button	$0.21
10 Ohm Resistor	$0.01
Battery Pack	$2.95
Battery – 1 Duracell 9v	$1.60
Fishing Line – 12in of 65lb Power Pro	$0.04
Springs – x 3	$1.71
Ball Bearings	$7.52
Plywood	$1.50
3D Printed Material – 500g of TPE Plastic	$11.00
Labor Cost	
$12.50/hr - x 1.5 hours to build	$18.75
Total Cost of Device	$95.91
Suggested Retail Price	$120.00

APPENDIX B – FINAL DESIGN DOCUMENTATION

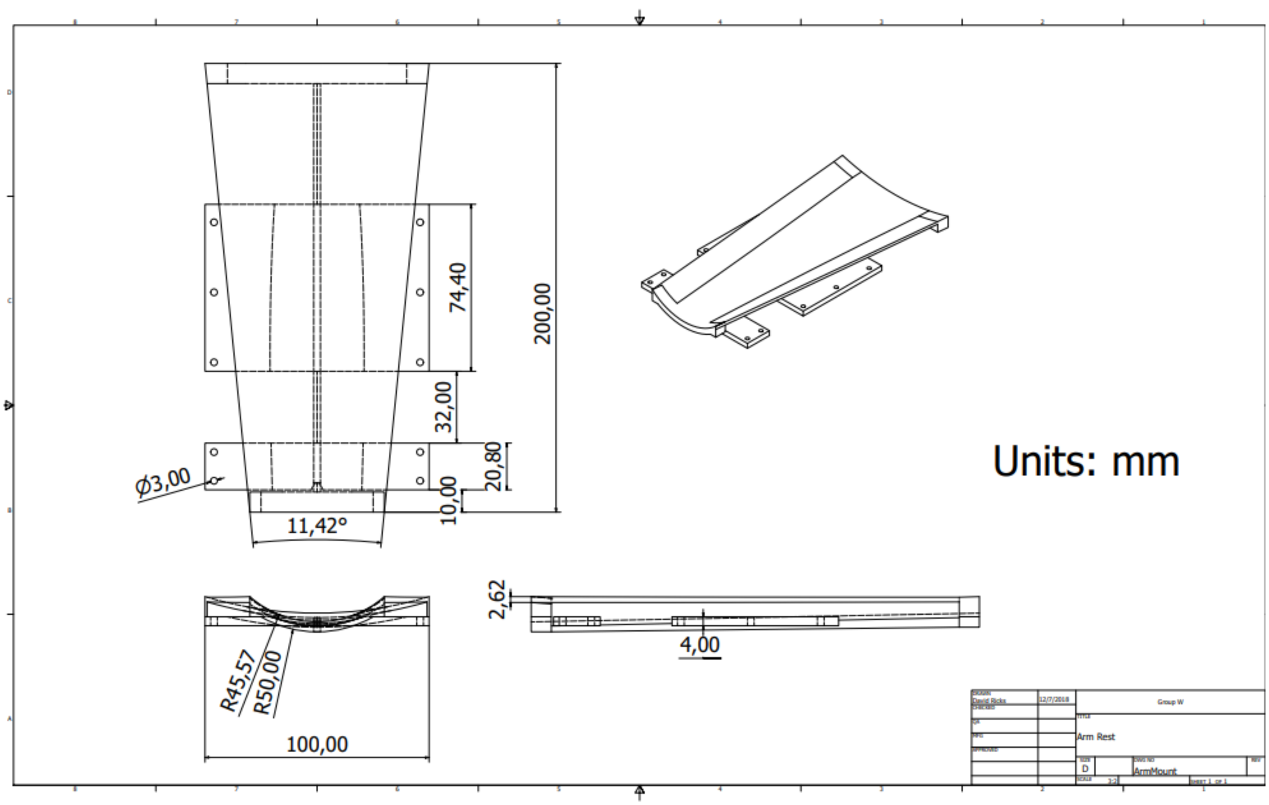


Figure 45. Arm Mount Drawing

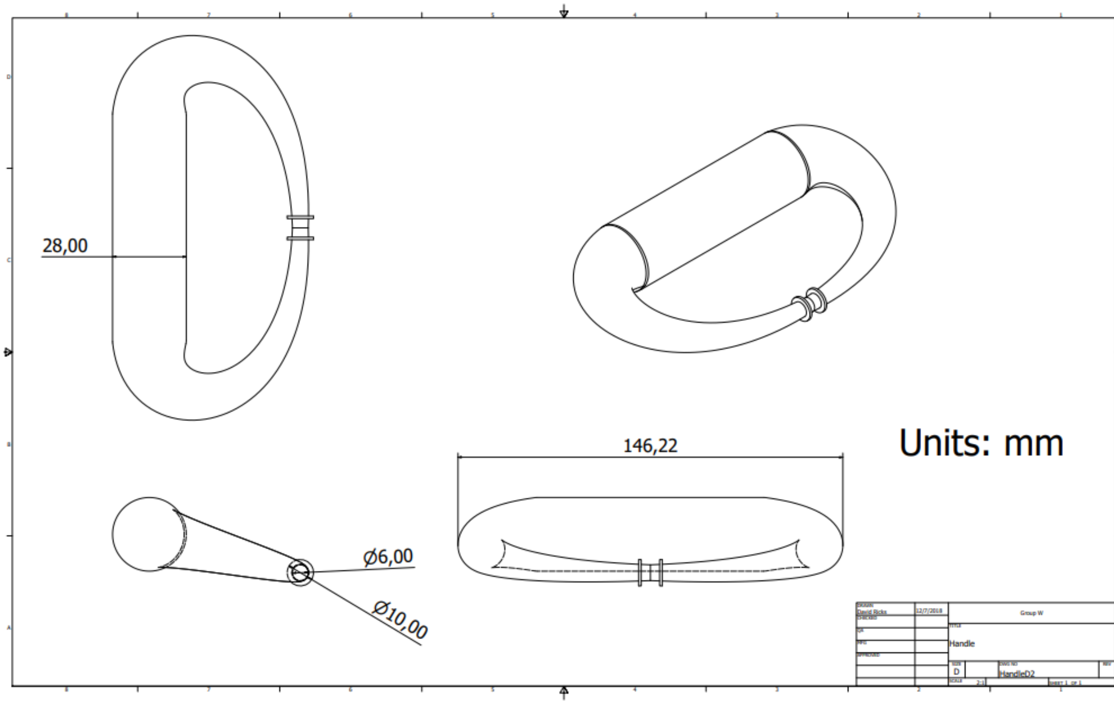


Figure 46. Handle Drawing

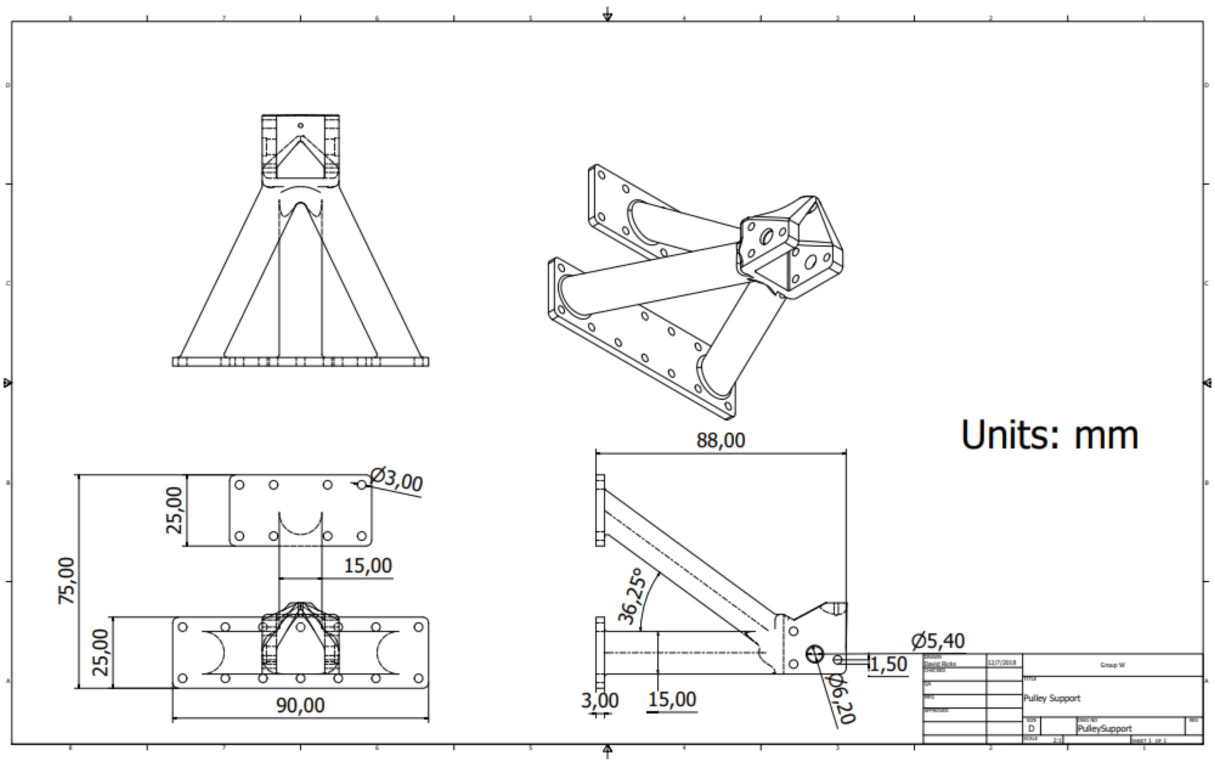


Figure 47. Pulley Support

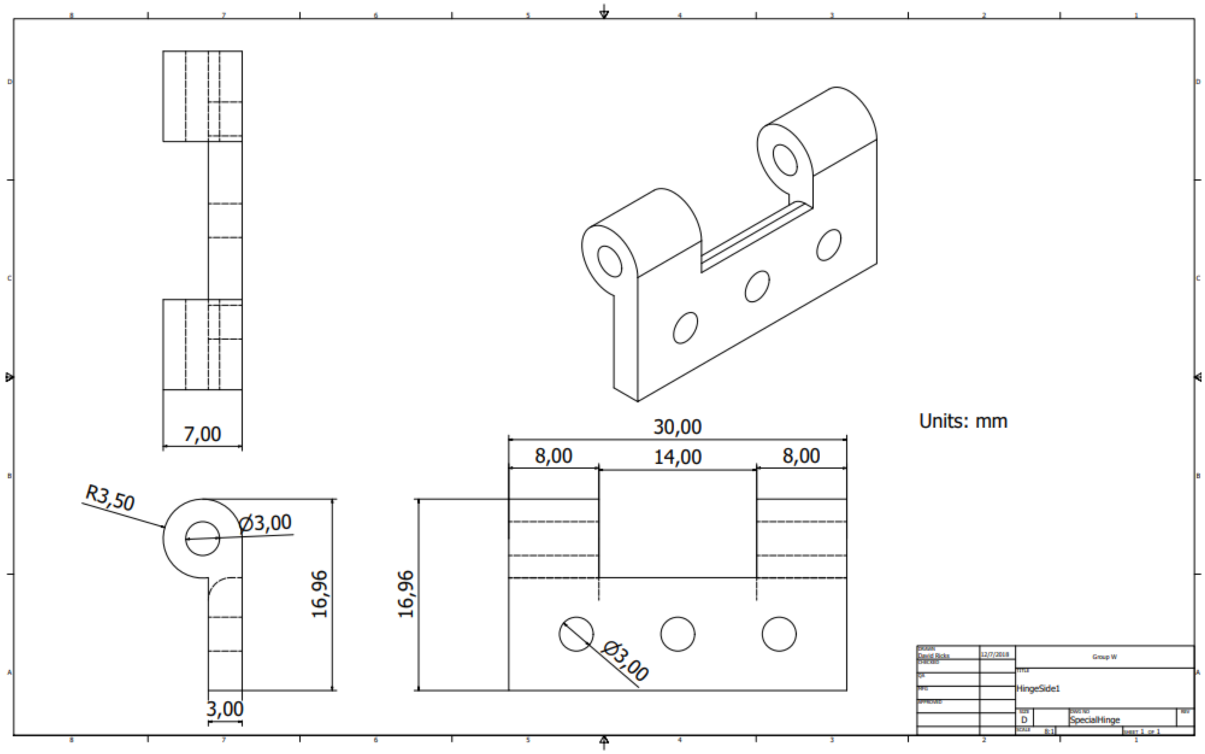


Figure 48. Hinge Side 1

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Flex Bar Exerciser

https://www.amazon.com/TheraBand-Tendonitis-Strength-Resistance-Tendinitis/dp/B000BPV3GO/ref=sr_1_3?ie=UTF8&qid=1536522512&sr=8-3&keywords=tendonitis+exercise

Spring Forearm Strengthener

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