



Indiana University – Purdue University Fort Wayne

Department of Engineering

ME 487 – 488

Capstone Senior Design Project

Report #2

Project Title: Braking System for a Manual Stair-Climbing Wheelchair

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Abstract

Pelico LLC is a startup company with interests in the medical equipment industry, specifically with wheelchairs. The company is currently designing and prototyping a manual stair climbing wheelchair. This specialty wheelchair will be capable of climbing stairs with only the power of the user or a caregiver.

Since the wheelchair will be used in the ascent and descent of stairs, a different type of braking mechanism is needed, instead of the traditional wheelchair brake. The design team has been tasked with creating a braking solution to be implemented on this wheelchair. The main difference between a traditional wheelchair brake and the one to be used on this wheelchair is that it must be activated and deactivated on a stop and go basis.

The subsequent report gives details on the design and testing processes for the braking mechanism of a manual stair climbing wheelchair, conducted by an IPFW mechanical engineering senior design team in the spring and fall semesters of 2015. The focal points of this report include: detailed design descriptions, component fabrication and assembly, cost analysis, and testing of the braking mechanism prototype.

Section I: Detailed Description

Final Design from Senior Design I

The final design for the braking system from the first Senior Design semester consists of the axial coupling locking mechanism with a spring and damper assembly, illustrated in **Figure 1** below. The braking system can be decomposed into four subassemblies, described and illustrated in more detail below. The four subassemblies of the brake system are:

1. Actuation System
2. Spring and Damper System
3. Locking Mechanism
4. Closure System

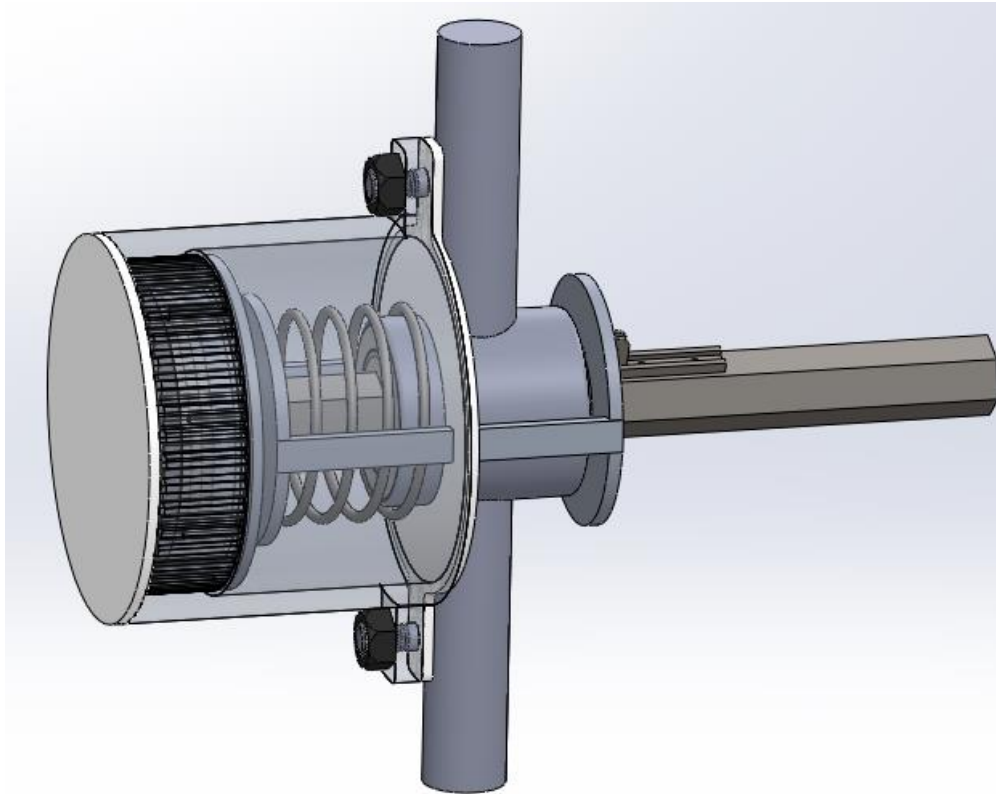


Figure 1: Braking mechanism connected to the frame and axle of the wheelchair

Figure 2 is an exploded view of the entire braking system with each component labeled with a part number. **Table 1** lists the components, quantity of each component, subsystem that each component belongs to, and the part number of each component.

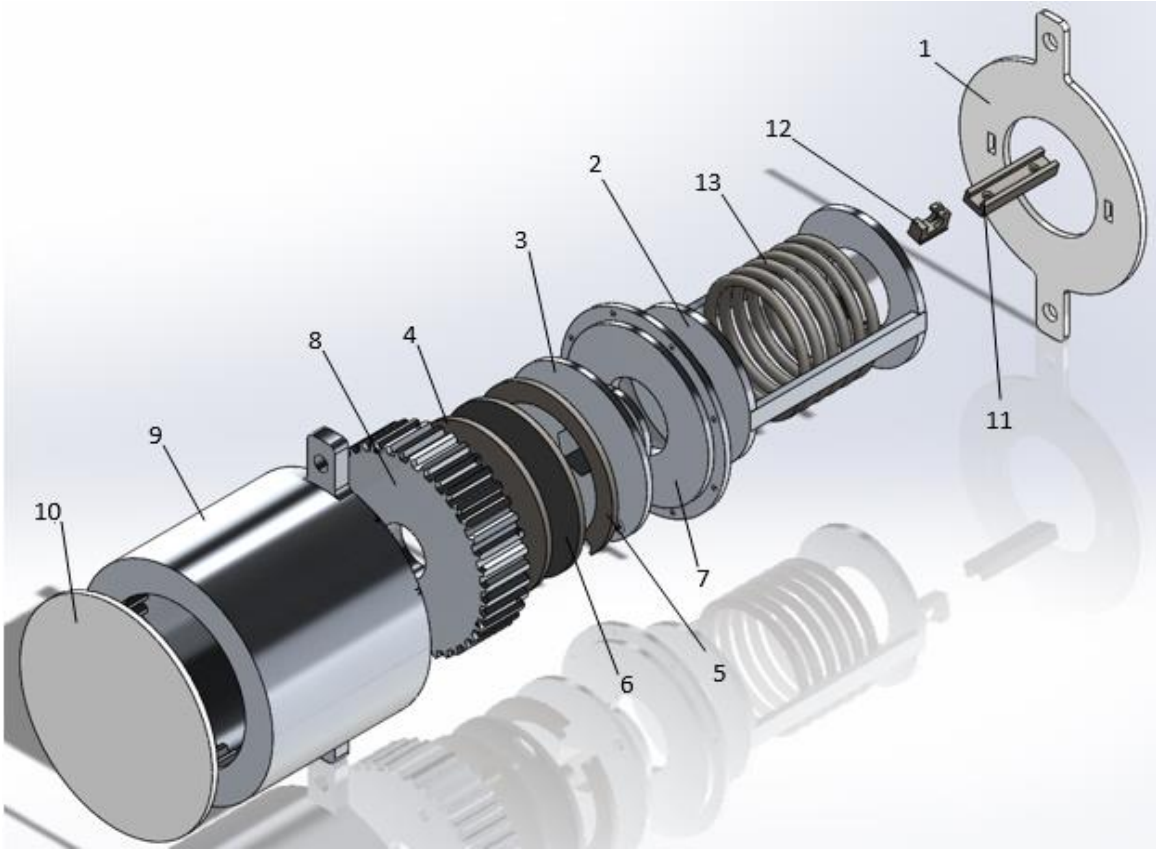


Figure 2: Exploded view of the entire braking system.

Table 1: List of components and their corresponding subassembly numbers.

ITEM NO.	PART NAME	SUBASSEMBLY #	QTY.
1	Frame Closure Plate	4	1
2	Aluminum Actuator	1	1
3	Assembly Slider	2	1
4	Interface Plate	2	1
5	C Spring	2	1
6	Friction Plate	2	1
7	Normal Force Plate	2	1
8	Inner Brake	3	1
9	Outer Brake	3	1
10	Brake Closure Plate	4	1
11	Actuator Hook Slide	1	1
12	Actuator Hook	1	1
13	Actuation Spring	1	1

Background

The primary initiative of Pelico LLC is to create a fully manual powered stair-climbing wheelchair. In countries without policies like the American's with Disabilities Act, people face significant obstacles due to the lack of accommodations necessary to meet their needs. As a manual wheelchair, the product will provide an affordable alternative to the existing electrically powered counterparts, making it more accessible to people both in the United States and abroad.



Figure 3: Manual stair climbing wheelchair

Figure 3 shows the first prototype of the manual stair climbing wheelchair. As it climbs the stairs in “stair climbing mode”, the large rear wheel has spokes which collapse; this causes the round wheel to take the shape of the stair. The front of the wheelchair has a linkage system which controls user stabilization as the wheelchair ascends or descends. The braking system has been designed to be placed under the user and attached to the inside of the frame.

Requirements and Specifications

The requirements and specifications form the basis for the design. These are stipulations that drive how the design of the system progresses. The current system has some flaws that have not been worked out and it is desired to redesign the system in an attempt to bypass those problems. The wheelchair is to be used in a manner that could potentially cause harm; this means there must be a braking system which must work statically, as well as dynamically, when engaged in the stair climbing mode. Some things that must be considered for the braking system requirements are:

- It must be multi-directional (i.e., able to perform a braking action whether going up or down a staircase)
- The user, or caregiver, must be able to instantaneously activate/deactivate the braking system with a mechanical input (e.g. lever)
- Total weight of the braking system should be less than 5lb.
- No electrical components of any kind will be used in the braking system
- The system shall apply braking to the rear wheels
- The system will be designed to have the user apply the lowest amount force necessary to engage/disengage the system
- Design for a five year system life.
- Minimum factor of safety of 1.8.

Parameters

The fixed parameters that cannot be changed or varied in the design process of the wheelchair include, but are not limited to; materials, dimensions, and geometry. Though the primary focus of the design is concerned on the braking system of the wheelchair, there are components of the wheelchair that affect the braking system, and the fixed parameters listed below.

- The braking system must be applied on the rear wheels
- The axle is to be a hexagonal shaft with a width of 5/8"
- The driver to the system shall be a hollowed female hexagonal shaft.
- The braking system must be able to be applied by both the primary user and a caregiver
- The maximum weight of the entire wheelchair must be less than 25 pounds. The user's weight is to be restricted to ≤ 220 pounds to ensure safety of the user

Design Variables

Quantities that may be varied in the system in order to satisfy the given requirements.

- The braking system may use, but is not limited to, a Bowden cable system or levers to activate/deactivate
- The activate/deactivate mechanism may be activated from more than one location
- The materials can range from metals such as aluminum and steel to polymers such as thermosets and thermoplastics

Limitations

The braking system must be designed to provide adequate stopping force to ensure that the wheelchair user will not roll down the chairs in an uncontrolled fashion while keeping the weight and cost of the system within given ranges and attaching to the existing wheelchair axle.

- The system must be easy to manufacture
- The cost of a prototype must be \leq \$1000 with a manufacturing cost that must be \leq \$150
- The maximum weight of the braking system should be \leq 5 lbs.
- The braking system should be able to be attached to a $\frac{5}{8}$ " hexagonal shaft
- The braking system cannot use any electrical components
- The braking system needs to be as compact as possible so that the wheelchair is easy to ship internationally

Safety, Environmental, and Economic concerns

The braking system must be manufactured in a way to ensure no environmental or human harm will come from the manufacturing of the components. The system should also be designed to reduce the possibility of injury to all users.

- The braking system should not use any toxic or harmful materials
- The braking system should be safe for wheelchair occupant and any present caregiver at all times of use by reducing the number of possible pinch points of the system
- The braking system must be made with lean manufacturing techniques in mind

Section II: Fabrication and Assembly

Introduction

The fabrication and assembly processes consisted of three phases: fabrication of the braking mechanism components, assembly of the braking mechanism, and construction of the test stand.

The components requiring fabrication and/or modification include the:

1. Inner Brake
2. Outer Brake
3. Actuator Hook
4. Actuator Hook Rail
5. Actuator Rings (brake side and wheel side)
6. Actuator Ring Link
7. Assembly Slider
8. Brake Closure Plate
9. Frame Closure Plate
10. Interface Ring
11. Friction Plate
12. Normal Force Plate
13. Assembly Slider Contact Ring
14. 5/8" Hexagonal Shaft
15. Actuation Compression Spring
16. Torsion Spring

In this section, the methods used to create the braking mechanism components and the test stand are listed in detail. The complete assembly of the completed prototype is also discussed and illustrated.

Component Fabrication

Inner Brake

The Inner Brake is the part of the locking mechanism that rotates with the wheel of the chair. This part is designed to actuate in and out of the Outer Brake, causing the teeth of the gears to mesh and prohibit rotational motion. This 40-tooth inner gear houses the spring-damper assembly components and is made of machined 6061-T6 aluminum.

In order to fabricate this component, it was taken to Randal's Machining and Welding for the turning of the outer and inner diameters as well as milling of the slot for the leg of the torsional spring. The turning and milling were done on manual machining centers. The teeth of the Inner Brake were cut by Quality Tool using wire EDM. Chamfers were added to the front edge of the teeth of the Inner Brake using a draw file. The finished component and a close-up of the filed teeth are shown in Figures 4 through 6.



Figure 4: Completely fabricated Inner Brake (top view)



Figure 5: Completely fabricated Inner Brake (bottom view)

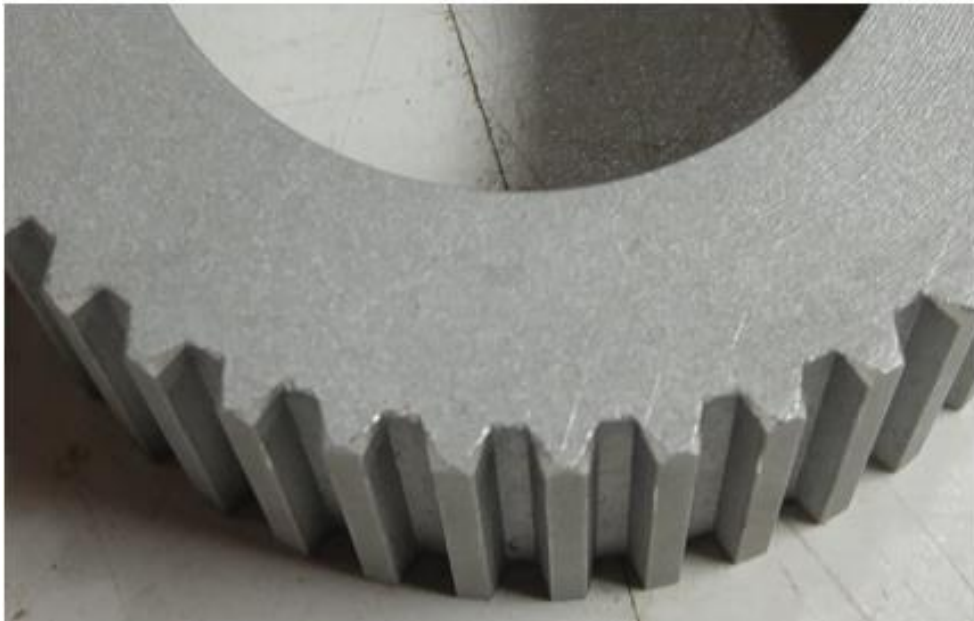


Figure 6: Close-up of filed gear teeth of the Inner Brake.

Outer Brake

The Outer Brake is attached to the frame and is the stationary part of the brake. When the Inner Brake is engaged into the Outer Brake, the teeth on the two components mesh and prevent rotation. It is made of machined 6061-T6 Aluminum.

In order to fabricate this component, it was taken to Randal's Machining and Welding. The outer diameter and the counter bore was turned using a manual lathe. The teeth were cut by Quality Tool using wire EDM. The two mounting flanges were machined after the EDM cutting by Randal's using a manual milling center. The pictures of the finished component are shown in Figures 7 and 8.



Figure 7: Completely fabricated Inner Brake (top view).



Figure 8: Completely fabricated Inner Brake (bottom view).

Actuator Hook

The Actuator Hook is the interface between the user input and the braking system. The user input is transferred from the user to the Actuator Hook via a cable. The Actuator Hook is used to compress the spring via the actuator as well as deactivate the locking mechanism.

In order to fabricate this component, it was taken to Superior Machine & Tool. A vertical CNC milling center was used to cut the actuator hook out of a small block of 1018 CRS. Tooling for the vertical mill that was used include various sized end mills and a keyway cutter. The pictures of the finished component are shown in Figure 9.

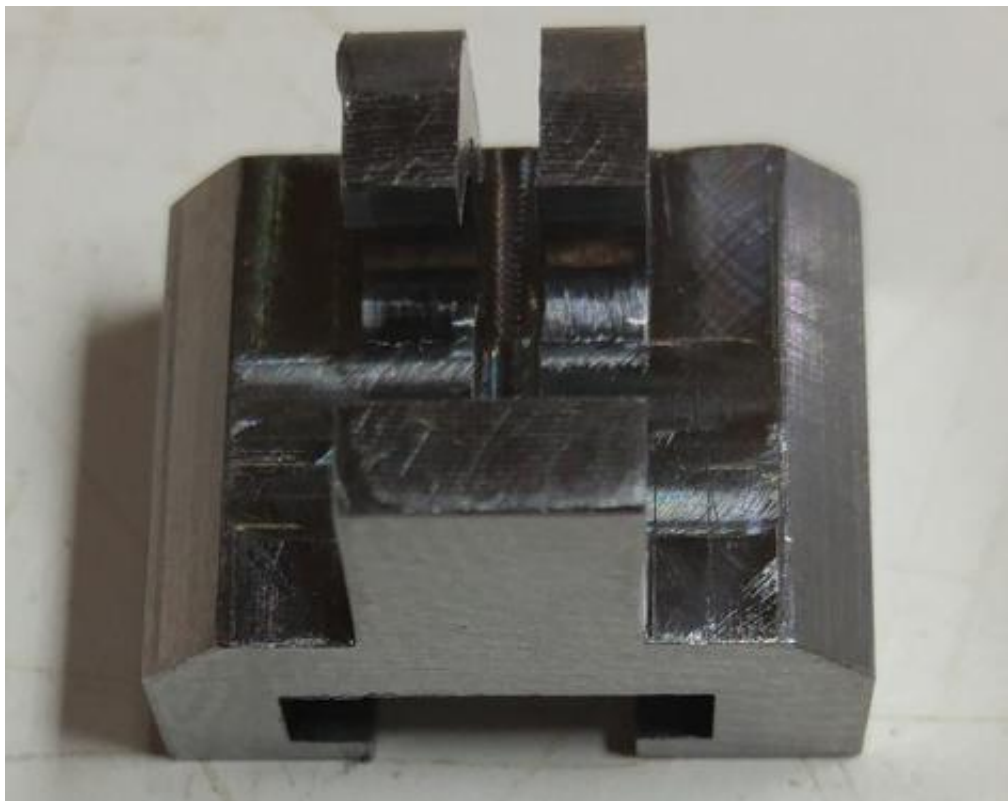


Figure 9: Picture of the Actuator Hook.

Actuator Hook Rail

The Actuator Hook Rail is to be attached to the axle of the wheelchair by two small screws. The purpose of this component is to hold the Actuator Hook on the axle while allowing the hook to slide along the axle during the actuation of the brake.

The Actuator Hook Rail was machined in the IPFW machining lab. It was manufactured using one of the Bridgeport milling centers located in the lab. A mill was used to cut the T shape out of bar stock steel and drill the through bolt holes. Countersinks were then drilled around the holes to accommodate the countersink screw placement. After the Actuator Hook Rail was attached to the shaft, the heads of the countersink screws were ground flat with the top surface of the rail to create the flat surface necessary for smooth actuation. Pictures of the finished component and the rail with the ground countersunk screws are shown in Figures 10 through 13.



Figure 10: Top view of the Actuator Hook Rail.



Figure 11: Bottom view of the Actuator Hook Rail.



Figure 12: Grinding down faces of the Actuator Hook Rail and countersunk screws.

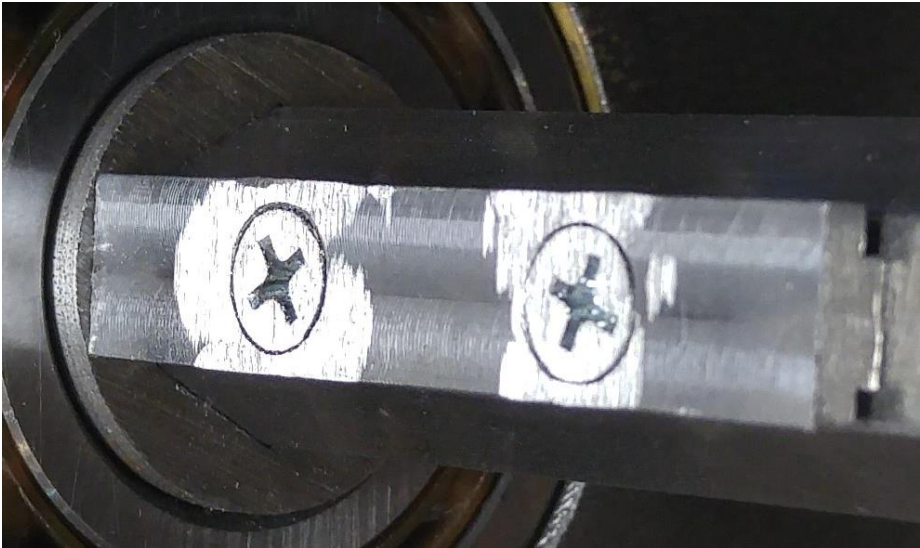


Figure 13: Ground face of the Actuator Hook Rail with countersunk screws.

Actuator Rings

The Actuator Rings interact with the Actuator Hook and Assembly Slider Interface Ring to transfer the actuation input of the user (which will be rotating) to the locking mechanism (which will be non-rotating) while remaining nonrotating. The non-rotation of the wheel-side Actuator Ring is important so that the caregiver's input can easily be attached to the system. One of the two ring designs in the braking mechanism contains tabs to prohibit a rotational degree of freedom of the Actuator Ring Links.

In order to fabricate this component, it was taken to WickFab. Both Actuator Rings were cut using a laser cutting center. A press brake was used to bend the tabs to 90 degrees on the Actuator Ring with tabs. Pictures of the finished components are shown in Figures 14 and 15 below.



Figure 14: Actuator Ring with tabs (wheel side).



Figure 15: Actuator Ring without tabs (brake side).

Actuator Ring Link

The Actuator Ring Link is to be attached to both of the Actuator Rings. The purpose of this component is to transfer the input of the user (which will be rotating) from one side of the frame to the other. This motion will then be transferred to the locking mechanism while the brake side Actuator Ring remains nonrotating so that the caregiver's input can easily be attached to the system. The Actuator Ring Link is composed of a small rectangular aluminum beam with a 90 degree bend. There are two of these in the design of the braking mechanism.

In order to fabricate this component, it was taken to WickFAB and cut using a laser cutting center. The 90 degree bends were added using a press brake. The inner corners of the bracket were filed down to allow assembly with the Actuator Ring. Pictures of the finished component are shown in Figures 16 and 17.



Figure 16: Top view of one of the Actuator Ring Links.



Figure 17: Side view of one of the Actuator Ring Links.

Assembly Slider

The Assembly Slider houses one side of the spring and uses the torsional spring to resist rotation. This component is made of 6061-T6 aluminum. It also attaches the spring and damper system and the Inner Brake to the shaft. All of the torque exerted on the shaft will be transferred through the Assembly Slider into the locking mechanism when the brake is engaged.

The Assembly Slider was fabricated by Superior Machine & Tool. First, it was turned in a CNC lathe to create the outer profile. Next it was sent to Precision Die Services to wire EDM the 5/8" hexagonal hole. Finally the parts were sent back to Superior Machine & Tool to machine the tapped holes and the slot for the leg of the Torsion Spring using a vertical CNC mill. The inner sides of the central hex were deburred and flattened using a file to reduce interference with the hex shaft. Pictures of the finished component are shown in Figures 18 and 19.



Figure 18: Top view of the Assembly Slider.



Figure 19: Bottom view of the Assembly Slider.

Brake Closure Plate and Frame Closure Plate

The primary functions of the Brake Closure Plate and Frame Closure Plates are to reduce the possibility of debris entering the braking mechanism and to restrict access to pinch points. The Brake Closure Plate is made of PMMA and the Frame Closure Plate is made of rigid PVC.

Both components were cut via water jet at WickFab. The openings on the sides of the Frame Closure Plate were filed down to minimize interference with the Actuator Ring Links during actuation. A picture of the Frame Closure Plate is shown in Figure 20 and the clear Brake Closure Plate can be seen in Figure 21.



Figure 20: Top view of the Frame Closure Plate.



Figure 21: The Brake Closure Plate.

Interface Ring

The Interface Ring's purpose is to create a sustainable interface with the chosen friction material within the spring and damper system. This piece is expected to wear slightly over years of use and has been manufactured out of $\frac{1}{4}$ " steel to allow for the wear and still be functional.

The Interface Ring was laser cut at WickFab. The counter bores for the screws used to attach the ring to the assembly slider were made using a manual drill press. Pictures of the Interface Ring are shown in Figures 22 and 23.



Figure 22: Friction plate Interface Ring with countersinks added.



Figure 23: Drilling counter bore holes into interface ring.

Friction Plate

The friction plate is made out of PMA's product number PMA070482. The team received free samples from PMA of several types of industrial friction material. Product number PMA070482 was chosen due to its friction and wear characteristics. The friction plate is held in place by 2 dowel pins which pass through the Inner Brake.

To manufacture this component a Bridgeport vertical mill was used to machine the material to the proper thickness. After the desired thickness was achieved, the material was sent to WickFab to be cut using water jetting. A picture of the friction plate is shown in Figure 24.



Figure 24: Friction plate with countersinks added.

Normal Force Plate

The Normal Force Plate is made out of 1018 CRS. The part was produced by Randal's Machining and Welding in a CNC Lathe. The through holes for the normal force screws were also drilled by Randal's Machining and Welding using a vertical CNC milling machine. Top and bottom views are shown in Figures 25 and 26.



Figure 25: Bottom side of the Normal Force Plate.



Figure 26: Top side of the Normal Force Plate.

Assembly Slider Contact Ring

The Assembly Slider Contact Ring is made out of 6061-T6 Aluminum. To manufacture this component, we sent it to Wickfab to be made in their Laser Cutting Center. We then used a hand file to remove the burs and reduce interference with the shaft. A picture of the Assembly Slider Contact Ring can be seen in Figure 27, which shows it attached to the Assembly Slider.



Figure 27: Finished Assembly Slider Contact Ring bolted into place.

5/8" Hexagonal Shaft

The shaft required for the system was a 5/8" hexagonal shaft. In order to mate the Actuator Hook Rail to the shaft, we required the shaft to have two 6-40 tapped holes in it. We acquired the raw bar stock from Metal Supermarkets in Fort Wayne, and cut it to length, shown in Figure 28. To cut it to length we used a horizontal band saw. The next step was to use a drill press to drill the holes for the thread into the shaft. This process can be seen in Figure 29. Finally, we used a T-handle tap wrench to tap the 6-40 threads.



Figure 28: Hex shaft blank after being cut to length.



Figure 29: Drilling the holes for the thread into the shaft using a drill press.

Actuation Compression Spring

The Actuation Compression Spring is used to apply a force to the Assembly Slider to engage the Inner Brake to the Outer Brake. For this we ordered a stock compression spring (part number 12678) from Century Springs Corp, shown in Figure 30.



Figure 30: Actuation Compression Spring.

Torsion Spring

The Torsion Spring is mounted within the Inner Brake Assembly and is used as the spring in the spring and damper system. For this part we ordered a custom spring from W.B. Jones Spring Company. The torsion spring has 3 coils with an outer diameter of 1.59 inches in a left hand twist. The spring material is .312 inch diameter oil tempered spring steel. After receiving the spring, the legs were shortened in order to fit into the Assembly Slider and Inner Brake. A bench grinder was used to manually grind the legs to length. A picture of the Torsion Spring can be seen in Figure 31.



Figure 31: Picture of the Torsion Spring with shortened legs.

Test Stand

A test stand was fabricated to properly perform the necessary testing on the braking mechanism. The test stand consists of a welded A-frame composed of four bar stock steel bars, which houses a double race bearing with a pressed hex shaft sleeve. The first step in creating the test stand was cutting the steel bar stock to correct lengths and geometries using a band saw. Next the pieces were welded together. After this was completed the stand was taken to the IPFW Machining Lab where the mounting face was machined flat and the mounting holes, the bearing hole, and slots for the Actuator Links were machined to ensure proper alignment. The fabricated stand can be seen in Figure 32 below.

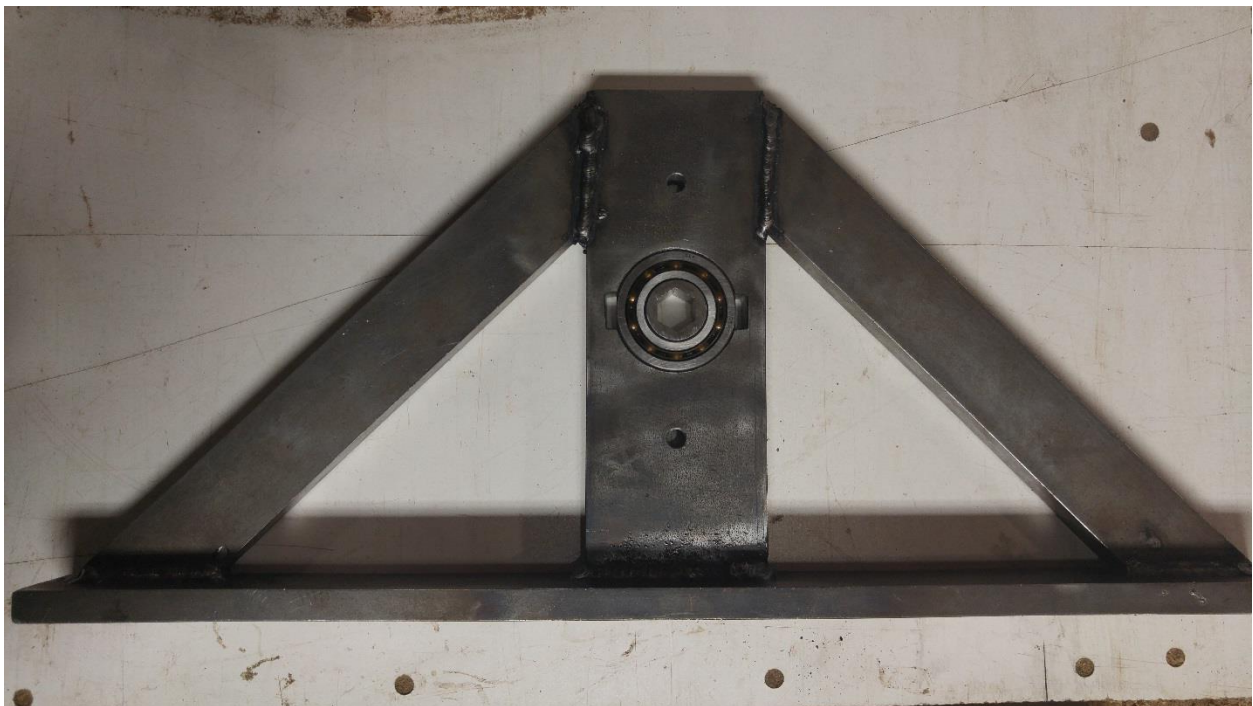


Figure 32: The completed test stand with the bearing pressed into it.

Component Assembly

The braking system was assembled in two main phases, Inner Brake assembly and mounting of Inner Brake assembly and outer brake.

Phase 1: Inner Brake assembly:

The Inner Brake was laid with the counter bored side upward, so that the spring and damper system could be installed into the Inner Brake, as seen in Figure 33. The friction material was placed into the counter bore and onto the guiding dowel pins, shown in Figure 34.



Figure 33: Dowel pins placed into the Inner Brake, ready for assembly of the Friction Plate.



Figure 34: The Friction Plate inserted into the Inner Brake.

Once the friction material was placed into the counter bore of the Inner Brake, the torsional spring was placed into the assembly slider, as seen in Figure 35. After the spring was in place, the interface ring was placed over the spring and onto the assembly slider and screwed into place, shown in Figure 36.



Figure 35: The Torsion Spring is placed into the Assembly Slider.



Figure 36: The Interface Plate is screwed into the Assembly Slider, over the Torsion Spring.

The Assembly Slider with the attached spring and interface plate was then placed into the counter bore of the Assembly Slider so that the free end of the torsional spring fit into the corresponding slot in the Inner Brake, shown in Figure 37. Once the Assembly Slider was properly positioned, the normal force plate was placed over the top of the Assembly Slider and screwed into place using 8 2-56 machine screws, seen in Figure 38.



Figure 37: The Assembly Slider placed inside the Inner Brake.

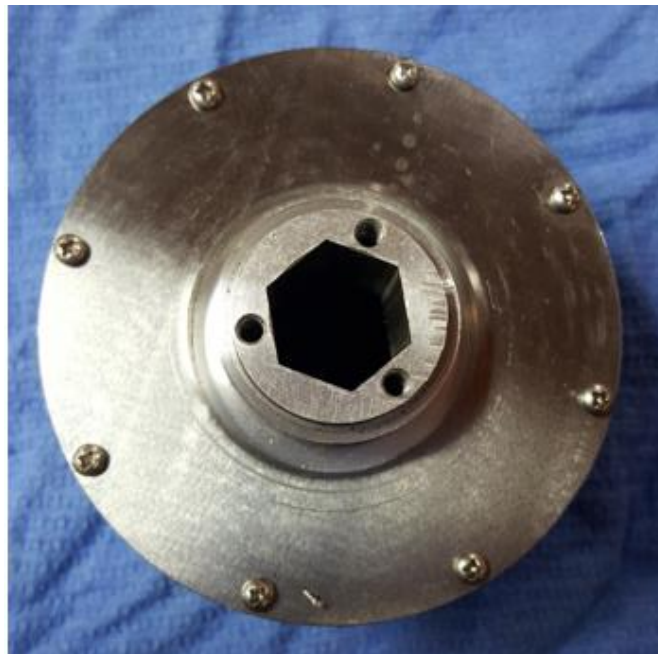


Figure 38: The Normal Force Plate now attached to the Inner Brake Assembly.

The Actuator Ring, without tabs, and the Assembly Slider Contact Ring were screwed down using 3 6-40 machine screws. Caution was taken to ensure that the actuator ring was allowed to spin freely after the screws were tightened. This can be seen in Figure 39. The final step of the first phase of building the prototype was attaching the actuation links using 6-32 machine screws and nuts, shown in Figure 40, on the next page.

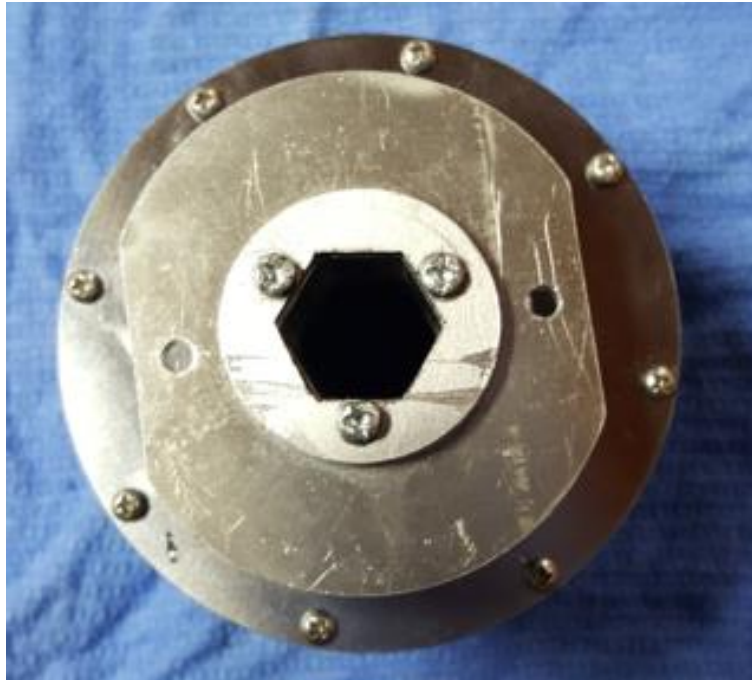


Figure 39: The Actuator Ring (without tabs) and Assembly Slider Contact Ring are assembled onto the Assembly Slider, allowing the Actuator Ring to rotate freely.



Figure 40: The Actuation Ring Links are now screwed into the Actuator Ring using 6-32 Machine Screws.

Phase 2: Mounting

The Frame Side Closure Plate and Normal Force Spring were positioned around the shaft by one person while a second person slid the Inner Brake Assembly, phase 1 of the building process, onto the shaft, shown in Figure 41 and Figure 42.



Figure 41: The Frame Side Closure Plate and Normal Force Spring are held in place.



Figure 42: Sliding the Inner Brake Assembly onto the shaft.

Once the Inner Brake assembly was on the shaft, the outer brake was fit over the Inner Brake, as seen in Figure 43. Two quarter inch bolts were then used to attach the outer brake to the test stand, which can be seen in Figure 44 on the next page.

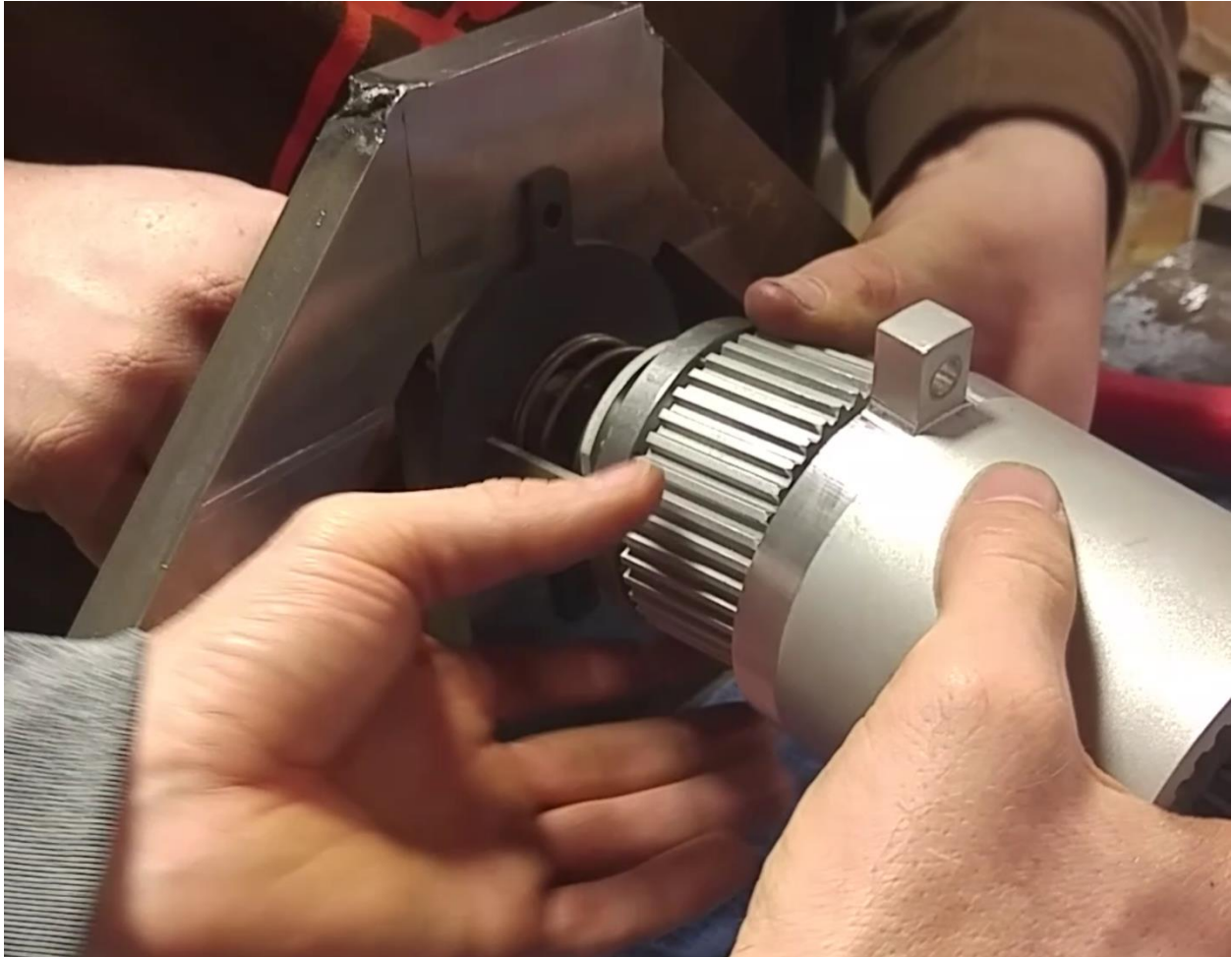


Figure 43: The Outer Brake is placed over the Inner Brake Assembly.

Next, the Brake Side Closure Plate was screwed onto the Outer Brake using 5 6-32 Screws. This step can be seen in Figure 44.

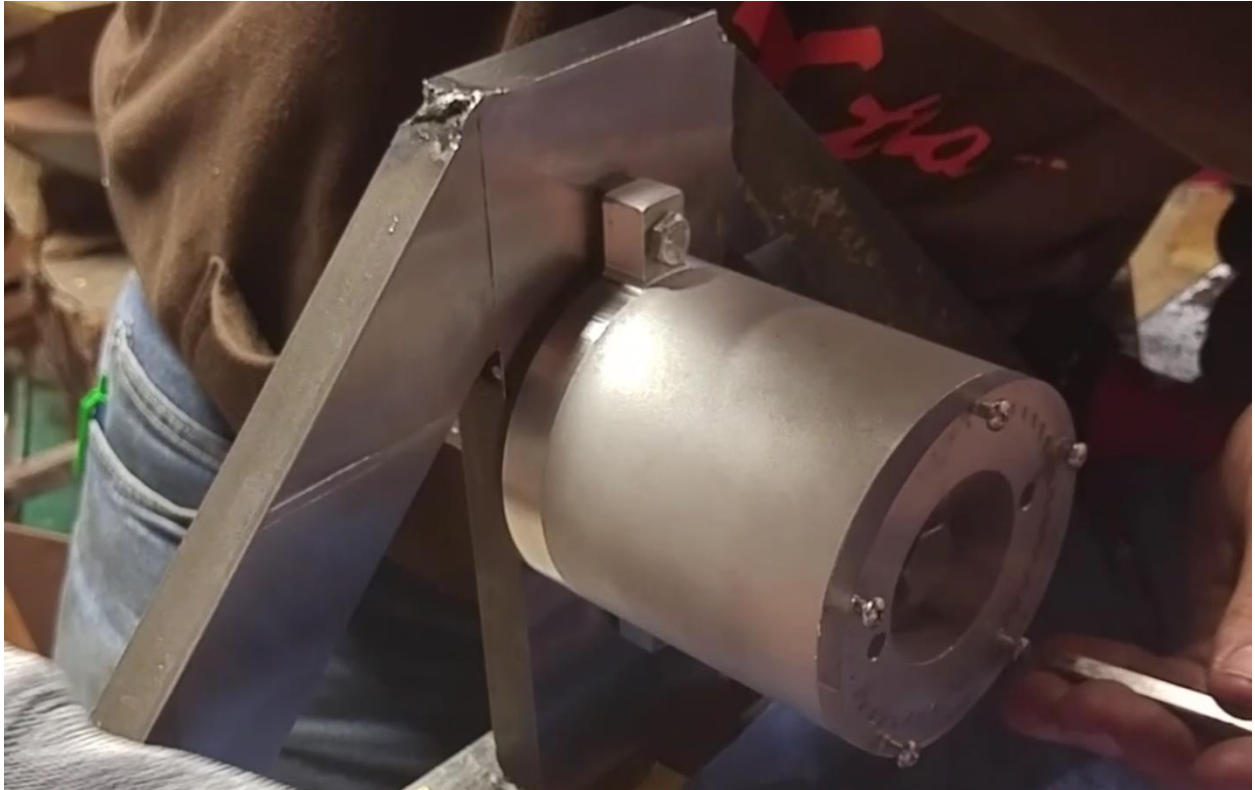


Figure 44: The Brake Side Closure Plate being attached to the Outer Brake.

Once the Outer Brake and Brake Side Closure Plate were assembled, the Actuator Hook Rail was then screwed onto the 5/8" Hex Shaft using 2 6-40 Machine screws. This can be seen below in Figure 45.



Figure 45: Actuator Hook Rail assembled into the Shaft using 6-40 Machine Screws.

Finally, the Actuator Hook was slid onto the Actuator Hook Rail. At the same time, the Actuator Ring (with tabs) was slid over the shaft. The Actuator Ring (with tabs) was then attached to the Actuator Ring Links using 6-32 machine screws and nuts, shown in Figure 46.

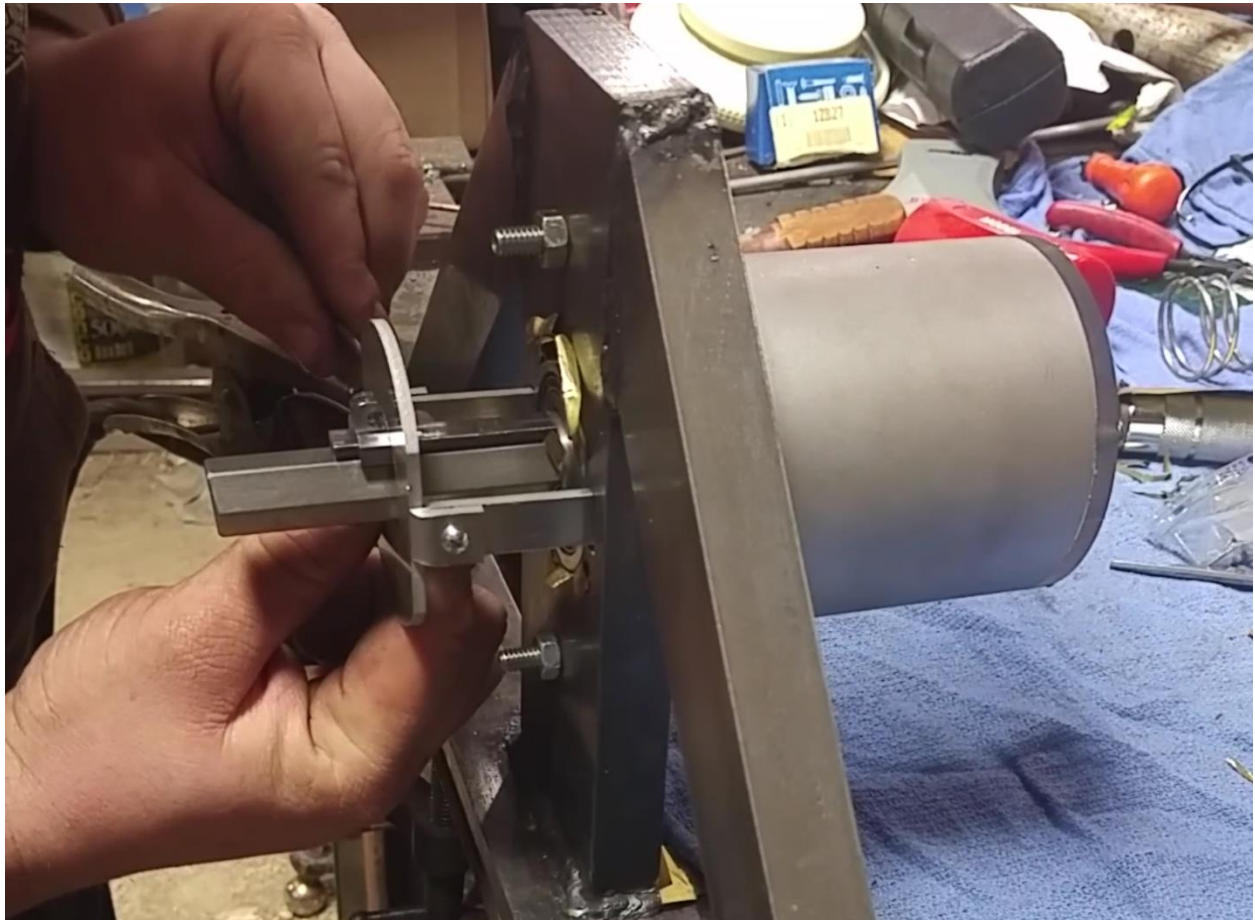


Figure 46: Completion of component assembly with link and ring attachment.

Section III: Testing

Introduction

This section will lay out in detail the test design and parameters as well as the results of the testing.

Testing Parameters

The testing parameters have been split into two major groups: activation/actuation and braking functionality. The following is a list of the parameters for each category and a step by step testing procedure to collect data on each of these parameters.

Activation/Actuation Testing

Parameters to be tested

- Actuation force of the brake should be ≤ 10 lbf
- Brake must engage automatically during user input (visual)
- The actuating system is capable of deactivating the brake while the brake is under torsional load (visual)

Step by step testing procedure

1. Mount the brake assembly to the testing stand provided by Pelico LLC.
2. Ensure that all components are properly assembled and are freely moving.
3. Attach spring scale to the actuation hook on the actuation system.
4. Rotate the shaft of testing stand so that the brake engages fully.
5. Use spring scale to pull on the actuation system to disengage the brake. Record the amount of force required to disengage the brake.
6. Repeat step 5 fifteen times to ensure the results are consistent.
7. If the brake does not engage automatically once the force pulling on the actuation system is removed stop testing and check to ensure that the system is clear of debris.
8. Attach a torque wrench to the exposed end of the shaft.
9. Apply 5 lbf-ft to the brake using the torque wrench. While the torque is applied attempt to deactivate the brake. Record if the brake disengages. This will simulate wear in user input system.

Table 2 shows the recorded data for the actuation force testing. Figure 47 shows how the actuation force testing was conducted. A zip tie was used to attach the spring scale to the actuator hook since using a cable was not feasible.

Table 2: Recorded actuation force data, including the average actuation force during testing.

Trial Number	Actuation Force	Trial Number	Actuation Force
1	9	9	9.5
2	9	10	9.75
3	9	11	9.5
4	10.5	12	10
5	9.75	13	10
6	9.5	14	9
7	10	15	11.5
8	11	Average Force:	9.8



Figure 47: Actuation testing of the braking mechanism.

Braking Functionality Testing

Parameters to be tested

- The system must be capable of withstanding a minimum torque of 67 lbf-ft
- Maximum angular deflection after engagement shall be $\leq 10^\circ$
- Must be bidirectional
- Total system weight of ≤ 5 lbs

Step by step testing procedure

1. Mount the brake assembly to the testing stand provided by Pelico LLC.
2. Ensure that all components are properly assembled and are freely moving.
3. Rotate the shaft of the testing stand so that the brake is fully engaged.
4. Attach torque wrench to the test stand shaft.
5. Apply a torque of 67 lbf-ft to the shaft clockwise. If the shaft slips or turns beyond 10° , stop testing. If the shafts turns more than 10° skip steps 6&7.
6. Measure the angle of deflection 10 times using a max torque of 67 lbf-ft clockwise.
7. Measure the angle of deflection 10 times using a max torque of 67 lbf-ft counterclockwise.
8. If steps 6&7 are skipped, apply 10 lbf-ft clockwise and counterclockwise.
9. Apply torque to the shaft 10 times recording the angle of deflection each time, starting at 10 lbf-ft. Increase torque in increments of 10 lbf-ft, If shaft deflects more than 10° stop testing.
10. Detach the brake from the test stand and weigh all components of the braking system.

To record the angle of deflection during torque testing, videos were taken of the testing. After testing, the length of the torque wrench was measure along with the horizontal distance across the 10 degree gauge that was being used to ensure we did not go beyond our deflection limit, as shown in Figure 48. The videos were then watched at a slower than normal speed to ensure that the video was stopped just after the torque wrench broke over. A screen shot of the video was taken after it had been stopped. The screen shot was loaded into PowerPoint for analysis. Once the picture was uploaded into PowerPoint, two lines were drawn on the picture, one between the two gauge lines at the height the torque wrench would cross the 10 degree line and one from the end of the torque wrench to the 0 degree line. Once these two distances were known, they entered in all the known data into an excel sheet and found the angle of deflection, equations 1 through 5 show the steps used to find the angle once the above lengths were found. Tables 3 through 5 show the collected data for the torque testing completed. All components of the braking system were weighed using a small household scale, shown in Figure 50. All components weighed a total of 2.5 lbs.

$$\frac{Y_{RL@10^\circ}}{Y_{V@10^\circ}} = \frac{Y_{RL@X^\circ}}{Y_{V@X^\circ}} \quad (1)$$

$$Y_{V@X^\circ} \left(\frac{Y_{RL@10^\circ}}{Y_{V@10^\circ}} \right) = Y_{RL@X^\circ} \quad (2)$$

$$L \sin \emptyset = Y \quad (3)$$

$$\emptyset = \sin^{-1} \left(\frac{Y}{L} \right) \quad (4)$$

$$\emptyset = \sin^{-1} \left(\frac{Y_{RL@X^\circ}}{L} \right) \quad (5)$$

Where:

$Y_{RL@10^\circ}$ = the distance across the 10 degrees at the length of the wrench in real life

$Y_{V@10^\circ}$ = the distance across the 10 degrees at the length of the wrench in the video

$Y_{V@X^\circ}$ = the distance from the 0 degree line and the end of the torque wrench in the video

$Y_{RL@X^\circ}$ = the distance from the 0 degree line and the end of the torque wrench in the video

L = Length of the torque wrench

\emptyset = Angle of deflection



Figure 48: Picture showing the two lines used to determine the angle of deflection.

Table 3: Angle of deflection data at 10 lbf-ft.

	Actual length at 10 degrees	Picture length at 10 degrees	Picture length at x degrees	Actual length at x degrees	Length of wrench (in)	Angle of deflection (degrees)
1	3	3.25	1.5	1.38	16.5	4.34
2	3	2.17	0.83	1.15	16.5	3.51
3	3	2.42	1	1.24	16.5	3.83
4	3	2.75	1.17	1.28	16.5	3.96
5	3	2	0.75	1.13	16.5	3.43
6	3	1.83	0.67	1.10	16.5	3.34
7	3	1.75	0.67	1.15	16.5	3.52
8	3	2.42	1.08	1.34	16.5	4.18
9	3	1.92	0.83	1.30	16.5	4.03
10	3	2.42	0.83	1.03	16.5	3.10
	Average angle of deflection (degree)	3.7				

Table 4: Angle of deflection data at 20 lbf-ft

	Actual length at 10 degrees	Picture length at 10 degrees	Picture length at x degrees	Actual length at x degrees	Length of wrench (in)	Angle of deflection (degrees)
1	3	4.17	3	2.16	16.5	7.04
2	3	3.67	2.32	1.90	16.5	6.12
3	3	3.95	2.17	1.65	16.5	5.26
4	3	2.42	1.5	1.86	16.5	6.00
5	3	2.83	1.83	1.94	16.5	6.28
6	3	2.92	1.73	1.78	16.5	5.71
7	3	2.42	1.58	1.96	16.5	6.34
8	3	2.33	2	2.58	16.5	8.50
9	3	2.5	2.15	2.58	16.5	8.52
10	3	3.17	2.75	2.60	16.5	8.60
	Average angle of deflection (degree)	6.8				

Table 5: Angle of deflection at 25 lbf-ft

	Actual length at 10 degrees	Picture length at 10 degrees	Picture length at x degrees	Actual length at x degrees	Length of wrench (in)	Angle of deflection (degrees)
1	3	2.75	3.08	3.36	16.5	11.27
2	3	3.42	3.67	3.22	16.5	10.78
3	3	3.67	3.33	2.72	16.5	9.02
4	3	3.08	3.08	3.00	16.5	10.00
5	3	2.58	2.75	3.20	16.5	10.70
6	3	2.67	2.83	3.18	16.5	10.64
7	3	3.58	3.58	3.00	16.5	10.00
8	3	3	2.98	2.98	16.5	9.93
9	3	3.17	3.2	3.03	16.5	10.10
10	3	3	3.08	3.08	16.5	10.28
	Average angle of deflection (degree)	10.3				

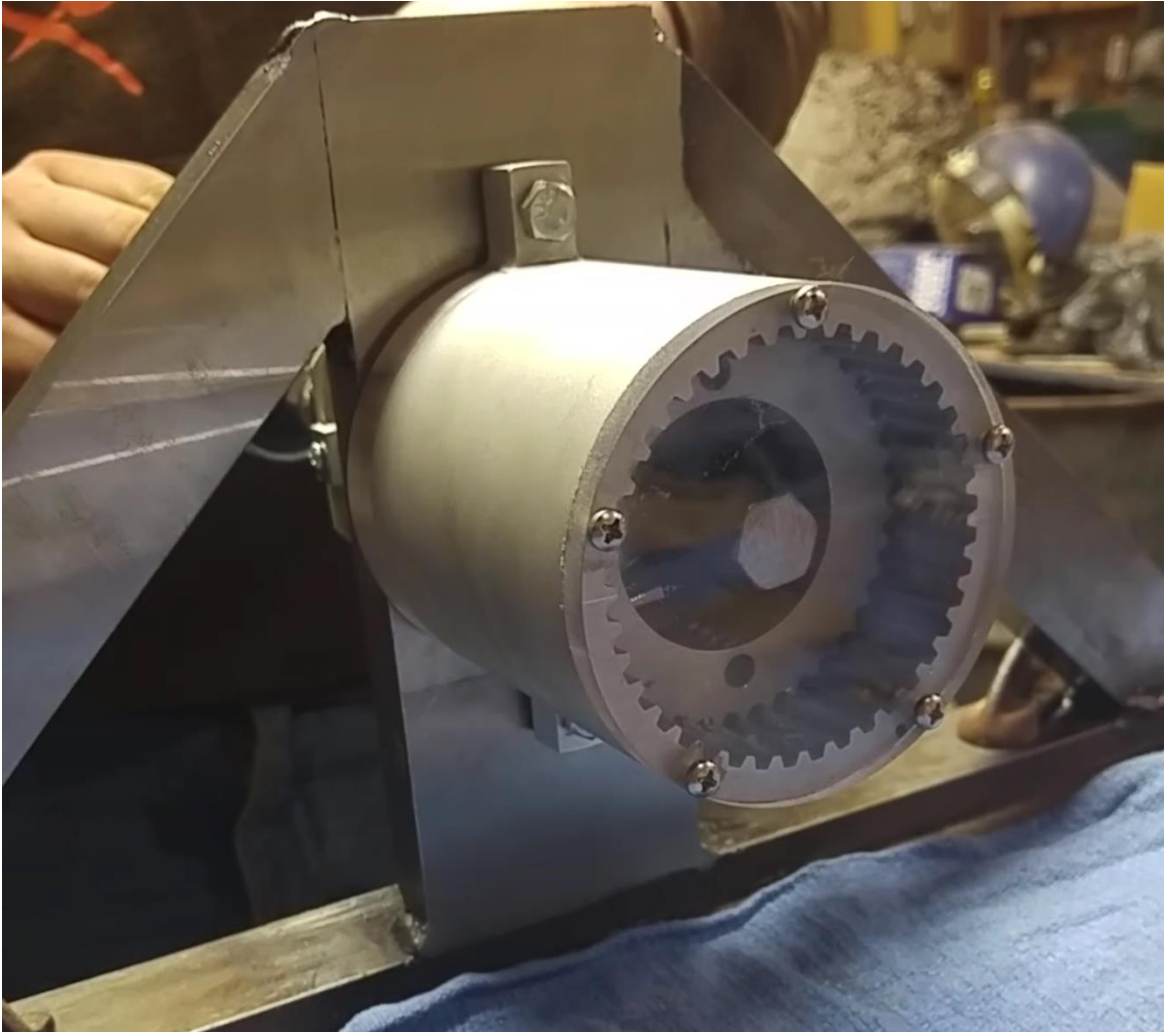


Figure 49: Brake functionality testing.



Figure 50: Weighing of all components and fasteners.

Section IV: Final Evaluation and Recommendations

Evaluation

Cost Analysis

The team was given \$1000 dollars to complete the prototype. The total cost building of the prototype was \$631.66, which is 63.166% of the total budget. A detailed cost analysis can be seen below in Table 6.

Table 6: Component prices and total cost of the prototype braking system

--BRAKE SYSTEM PROTOTYPE COST--			
PART NAME	PART NUMBER/SIZE/LENGTH	PART MATERIAL	COST [\$]
INNER BRAKE	BM_INNERBRAKE_02	6061-T6 ALUMINUM (SS)	10.00
OUTER BRAKE	BM_OUTERBRAKE_01	6061-T6 ALUMINUM (SS)	10.00
TORSION SPRING	BM_TORSIONSPRING_##		176.00
ACTUATION SPRING	12678 (from Century Spring)	STAINLESS STEEL	6.19
ASSEMBLY SLIDER	BM_ASSEMBLYSLIDER_03	6061-T6 ALUMINUM (SS)	50.00
ASSEMBLY SLIDER CONTACT RING	BM_ASSEMBLY SLIDER CONTACT RING_04	6061-T6 ALUMINUM (SS)	12.00
ACTUATOR HOOK	BM_ACTUATORHOOK_14	1018 CRS	40.00
ACTUATOR HOOK RAIL	BM_ACTUATORHOOKRAIL_13	1018 CRS	0.00
NORMAL FORCE PLATE	BM_NORMALFORCEPLATE_07	1018 CRS	0.00
FRICTION PLATE	BM_FRICTIONPLATE_06	PMA070482	0.00
ACTUATOR RING (BS)	BM_ACTUATORRING(BS)_11	6061-T6 ALUMINUM (SS)	150.00
ACTUATOR RING (WS)	BM_ACTUATORRING(WS)_10	5051 ALUMINUM	
ACTUATOR RING LINK	BM_ACTUATORRINGLINK_12	5051 ALUMINUM	
FRICTION PLATE INTERFACE RING	BM_FRICTIONPLATEINTERFACERING_08	1018 CRS	
BRAKE CLOSURE PLATE	BM_BRAKECLOSUREPLATE_16	PMMA	
FRAME CLOSURE PLATE	BM_FRAMECLOSUREPLATE_15	PVC	
FATENERS (MACHINE SCREWS & NUTS)	BM_FATENERSMACHINESCREWS&NUTS_05		10.00
AXLE	5/8" HEX SHAFT	1018 CARBON STEEL	6.25
DOUBLE ROW BALL BEARING	SKF_4205ATN9 (from Applied Industrial Tech)		56.67
HEX SLEEVE	A 7C20-10 5/8" HEX HOLE WITH 1" OD	C1117 CARBON STEEL	31.79
DOWEL PIN, BLACK OXIDE	98381A328 1/4" DIAMETER, 3/4" LENGTH	ALLOY STEEL	7.20
--TEST FRAME--			
SQUARE BAR STOCK	CF1018/1334 1.75 X 3.0 X 8.0" LENGTH	1018 CARBON STEEL	34.18
SQUARE BAR STOCK	CF1018/12112 0.5 X 1.5 X 20.0" LENGTH	1018 CARBON STEEL	13.96
SQUARE BAR STOCK	CF1018/34112 0.75 X 1.5 X 11.3" LENGTH	1018 CARBON STEEL	17.42
TOTAL----->			631.66

Actuation Force

The force needed to actuate the braking system during stair climbing is needed to be kept low to ensure that the user or their caregiver can use the majority of their strength to ascend the stairs. A value of 10 lbf was chosen as a benchmark for the prototype to achieve. As seen in the test data listed in the testing section, this value was achieved, with an average actuation force of 9.8 lbf.

Functionality Testing

The greatest amount of torque that the braking system is expected to see is 67 lbf-ft. This value was determined by our sponsor in the calculations for the structural design of the wheel and shaft of the wheelchair. The second constraint was that the torsional spring and damper system would not allow the shaft to turn more than 10 degrees once the brake was activated and the max expected torque applied to the shaft. The above two constraints were not met due to the maximum limits of the spring purchased. The third testing parameter tested during Functionality testing was the weight. A constraint of 5 lbs was chosen by the team to ensure that the braking system would add as little weight as possible to aid the user and/or caregiver in ascending the stairs. This constraint was met since one brake weighed 2.5 lbs.

Recommendations

Actuation Force

The actuation force was under the 10 lbf constraint. However, if our sponsor wishes to reduce this force in the future, two things are recommended. Firstly, add some type of lubricant to the teeth of the inner and outer brake; this will not cause any reduction in effectiveness of the brake but will allow the brake to actuate easier. The second recommendation is to change the material of the inner and outer brake to steel, however this will increase the overall weight of the system.

Functionality Testing

Both the angle of deflection at 67 lbf-ft and the maximum torque of 67lbf-ft was not achieved. This is due to the spring that was purchased does not have the required spring constant. This spring was chosen due to the size of the braking system. This variable was driven by the wishes of our sponsor to keep the system under 4 inches in diameter. However, this dimension caused us to go with a spring with a smaller mean diameter and a smaller wire diameter than is sufficient to achieve the require spring constant. It is recommended that the design be increased in diameter by 1 inch, which would allow a much stronger spring to be used.

Section V: Conclusion

Conclusion

The metrics utilized in assessing the degree of success of the final design are based upon the requirements specified by the sponsor, Pelico LLC, at the beginning of the project. Those requirements are that the braking system of the wheelchair must:

1. Accommodate multi-directional travel
2. Be able to be instantaneously activated and deactivated with a purely mechanical input
3. Apply braking to the rear wheels
4. Weigh less than 5lb
5. Have the user apply the lowest amount force necessary to engage/disengage the system
6. Have a five year system life
7. Have a minimum factor of safety of 1.8 for all components
8. Not utilize any electrical components of any kind

The design of the braking system fulfills all of those requirements by:

- Utilizing a pre-existing sliding mechanism on the rear wheel to toggle between travel modes to allows instantaneous activation while stair-climbing mode is on (fulfilling requirements 1-3)
- Minimizing braking mechanism size, weight, and activation force (fulfilling requirements 4 & 5)
- Ensuring that all components have been designed for an infinite system life (fulfilling requirements 6 & 7)
- Refraining from incorporating electrical components (fulfilling requirement 8)

However, modification to the diameter of the braking system is necessary to accommodate the larger spring that is needed to achieve resistance of the maximum expected torque requirement. By incorporating this design, the stair-climbing wheelchair designed by Pelico will be augmented as exemplified via the prototype manufactured by the group this semester.

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