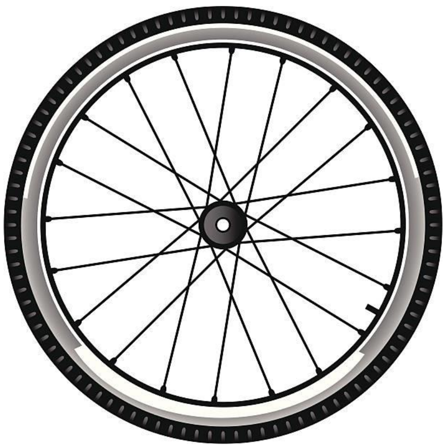
FINAL DESIGN REVIEW (FDR) REPORT

Spring Rate Measurement of a Pneumatic Mountain Bike Tire

June 7, 2024



ME428-30 SENIOR PROJECT DESIGN
TEAM F33

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Statement of Disclaimer

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Abstract

The Final Design Review (FDR) presents a comprehensive overview of the spring rate measurement project for a pneumatic mountain bike tire. This report details the project's design, its implementation, and how it met all specified requirements. It also includes a discussion of the project's findings and recommendations for future work, assuming continuation of the project. The primary goal is to develop a device that allows professional race teams or experienced mountain bike riders to parameterize tires based on their spring rate in addition to internal pressure.

Since the Critical Design Review (CDR), the design has undergone significant changes due to a switch to an in-line load cell from the original S-beam load cell. This design change allowed for a reduction in the overall dimensions and weight of the product, while still meeting the force requirements.

The project involved manufacturing various dynamic components including upper and lower bearing adapters as well as static components such as the wheel axle and frame. Most parts were custom-made using both subtractive and additive manufacturing processes. The electrical components used include the load cell, Arduino microcontroller and supporting products. This report verifies the design specifications by detailing each of the test guidelines.

The final design exceeded expectations in many areas but raised concerns about the design of the force application system. The switch to the smaller load cell initially introduced buckling of the force application system and eventual failure of the load cell as a result. A slight redesign was introduced to eliminate possible load cell failure. Key takeaways from the project include the importance of teamwork, a broad understanding of manufacturing processes, allowing sufficient project time for unexpected issues, and avoiding last-minute design changes.

For future work, we recommend modifying the design of the force application system actuation to eliminate buckling entirely. Additionally, collecting sufficient data will enable us to properly recommend a range of values to achieve consistent parameterization, aligning with the project's scope.

Contents

1 Introduction

Our team of engineering students set out to design and build a device to measure the spring rate of a pneumatic mountain bike tire. The theory behind this project is that each tire will produce a unique spring rate at a given pressure when all other parameters are kept constant. This unique spring rate can be attributed to variations in the tire's construction that arise during manufacturing. This idea can also be extended to explore how a tire's construction will affect spring rate. With a functioning verification prototype the team intends to measure the spring rate of several tires that will vary in their construction, across a range of internal tire pressures and displacement amounts. The current hypothesis is that the same spring rate can be achieved for a more robustly constructed tire inflated to a lower internal pressure as with a weaker constructed tire at a higher pressure. The device consists of an L shaped frame which supports a wheel mounting system, a loading system and a data acquisition system. The loading system compresses the tire a predetermined amount and measures the force via a load cell which allows for a spring rate to be calculated.

The following report details the overall design of the device, process of procuring materials, manufacturing components for a verification prototype, and assembling the prototype. Testing procedures to verify functionality of the prototype and their results are included in the report to verify how well the prototype met the engineering and user specifications set forth earlier in the project timeline. Project results are discussed, along with any necessary steps to remedy shortcomings or steps to advance the project.

2 Design Overview

This section will describe the final design of the device. This includes important changes to the design, overview of how to operate the device, potential risks associated with the device and measures taken to limit these risks.

2.1 Design Description

The final design of the tire spring rate measurement device is a manually actuated, lightweight device with an overall low risk. Figure 1 shows the completed final assembly except for the electrical components inside the electronics housing.

Figure 1: Isometric view of final tire spring rate measurement device.

The device features an aluminum 8020 frame, stainless steel force application rod, force application handle made from a mountain bike handlebar, custom machined aluminum components and custom designed 3D printed components. More details on the manufacturing and assembly can be found below in the Implementation section. Operation of the device is rather simple, and set-up is quick. The entire process of set-up, operation and maintenance is outlined in the User Manual in Appendix A. The main risk associated with use of this device is pinching between the tire and the tire contactor component. This risk has been addressed with a warning message in the User Manual. A comprehensive Risk Assessment was conducted and can been seen in Appendix B, which highlights all other associated risks.

2.2 Design Changes Since CDR

There have been quite a few notable changes to the design since the CDR. The most notable was the switch from the Omega S-beam load cell (borrowed from Cal Poly ME Department) to the FUTEK in-line load cell (donated by FUTEK). The FUTEK load cell the team selected was the LCM200 with a 500lb capacity, which was determined to be enough given the 450lb maximum load requirement in Table 1. This load cell was significantly more compact than the Omega S-beam which further helped the design conform to the size and weight specifications in Table 1. This switch to a new load cell drove some component design changes to adapt the load cell to the device.

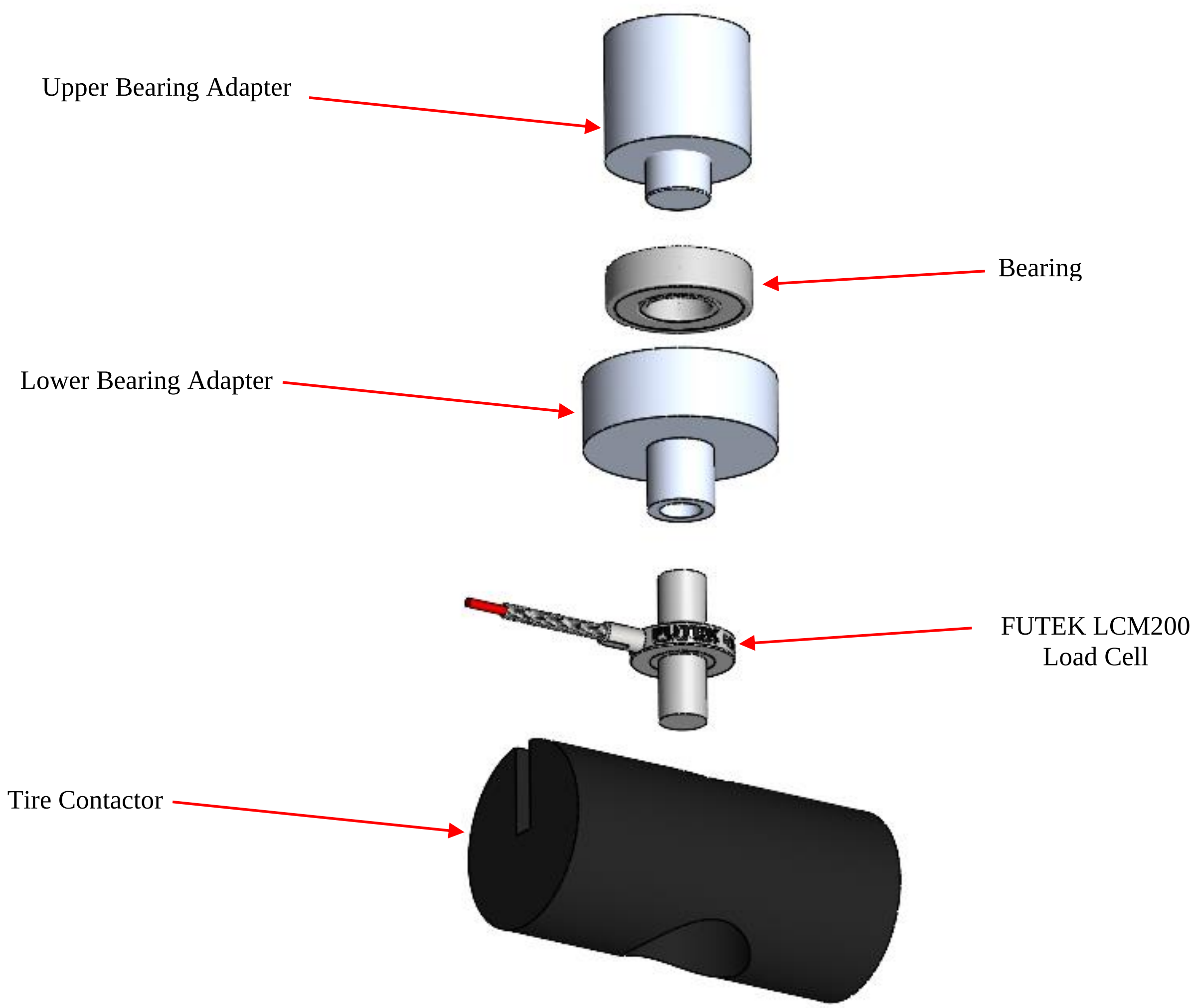


Figure 2: Exploded view of new load cell assembly.

The lower bearing adapter and the tire contactor, highlighted in Figure 2, got updated to mate to the new load cell. The tire contactor cap was also updated to fit the new tire contactor, shown in Figure 3. The previous version of the lower bearing adapter had a ½"-20 threaded stud on the bottom of it. This was updated to a 3/8"-24 tapped hole to mate with the FUTEK load cell's threaded stud. Updates for the tire contactor included a recessed hole for the load cell to slide into and a modified counter-bored hole for the other threaded stud of the load cell to fit in and be captured with a nut. The decision to have the load cell sit inside of the tire contactor was made after some initial testing with the new load cell on top of the tire contactor. Results of this testing were noticeable buckling with the load cell as the fulcrum. The goal of changing the design to an internal mounting was to limit the possibility of buckling due to slight deviations from purely vertical translation. A closer view of the updated tire contactor and the cap for the counter-bored hole is shown in Figure 3.

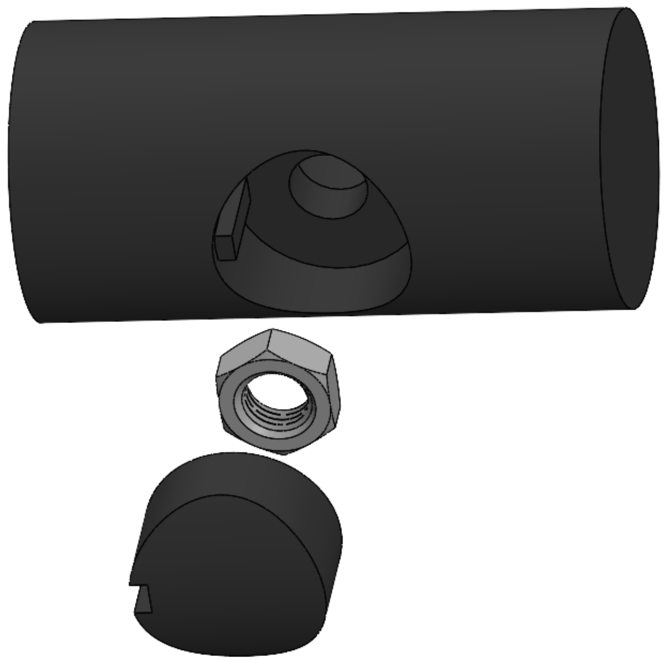


Figure 3: Close up view of the tire contactor assembly.

There were design changes to the main frame assembly and wheel mount assembly due to the FUTEK load cell as well. With the reduced height of the force application assembly, the vertical member of the main frame was able to be shortened. The overall length of the vertical member went from 25” to 22.625” and a new hole was drilled in the member for the wheel axle threaded insert to mount into. The horizontal member was shortened and re-drilled to bring the whole wheel assembly closer to the vertical member and reduce the system's moment arm. The wheel axle was updated to have a longer threaded section on the frame side to increase thread engagement and resistance to bending. In addition, the orientation of the wheel and spacers was changed to have the wheel mounted onto the axle first, then both spacers mounted after, followed by the wing nut.

A final design change was made to the force application system’s threaded insert. After the first rounds of testing with the Omega load cell, the aluminum threads were not holding up well against the stainless-steel force application rod. A new design made from steel was manufactured using 3/16” plate and a 2” long ½”-20 round coupling nut.

3 Implementation

This section will endeavor in the process that was followed during the build of our Verification Prototype. Our process consisted of procuring materials, manufacturing components, assembling of the overall system, and software development needed to generate a spring rate measurement with the force measured from the FUTEK in-line load cell.

3.1 Procurement

The manufacturing of materials and components for this project consists of a variety of parts such as fasteners, bearings, and structural materials needed for the frame and housing functions of the product. To reduce the need for complex/expensive manufacturing, we decided to make use of additive manufacturing to generate components of this product that don't require severe structural properties. The project scope is mostly aligned with being mechanically operated with electrical components to use the mechanical actuation for an output in data acquisition. The electrical components were primarily provided from our own personal inventories, apart from a few parts needed that were purchased from an online vendor such as Amazon, or from a local shop such as Coast Electronics RadioShack. Mostly all the mechanical/structural hardware was bought from a hardware store, McMaster Carr, or directly from a manufacturer, except for a handful of items such as the threaded inserts, bearing adapters, and the threaded wheel axle that were manufactured from raw aluminum stock that we provided from our own inventory. The load cell initially used was borrowed from the Cal Poly ME department, but the final design's load cell was donated from FUTEK.

3.2 Manufacturing

Many of the components for this device were custom manufactured. This section will describe the manufacturing process for these components.

Starting from the top of the device, the first manufactured component is the force application handle. It was made from an old mountain bike handlebar and an aluminum adapter plug. A band saw was used to cut the old handlebar in half. The plug was made from some 6061-T6 aluminum using a lathe and drill tap. The plug was turned down to the necessary OD to fit inside the handlebar. The whole assembly was then drilled through to create a hole for tapping. A ½"-20 tap was used to form threads in the plug so that the whole assembly could be threaded onto the force application screw. The force application screw was cut to the correct length using a horizontal band saw and the cut end was then deburred to allow for smooth threading of the handle.

The next manufactured component was the force application threaded insert. Steel was used for this threaded insert because of the stainless-steel force application screw. A rectangle of 3/16" steel plate was cut and drilled with three holes, two mounting holes and a center hole for a round coupling nut. A 2" long ½"-20 round coupling nut was used. The center hole was drilled with just enough clearance for the coupling nut to slip through for welding to the plate. Four spot welds on the top and bottom side of the plate were done with a mig welder to complete the part. Similarly, a threaded insert was made for the wheel axle, but this one was made from 2.5" round stock 6061-

T6 aluminum. The stock was turned down to create a 1.5” long boss at 0.75” diameter. A through hole was then drilled in the center of the boss to allow for tapping. The part was flipped in the lathe to face the other end down to a 3/16” flange. The through hole was then tapped with a ½"-20 tap. Once finished on the lathe, the two 5/16” mounting holes were drilled on a mill.

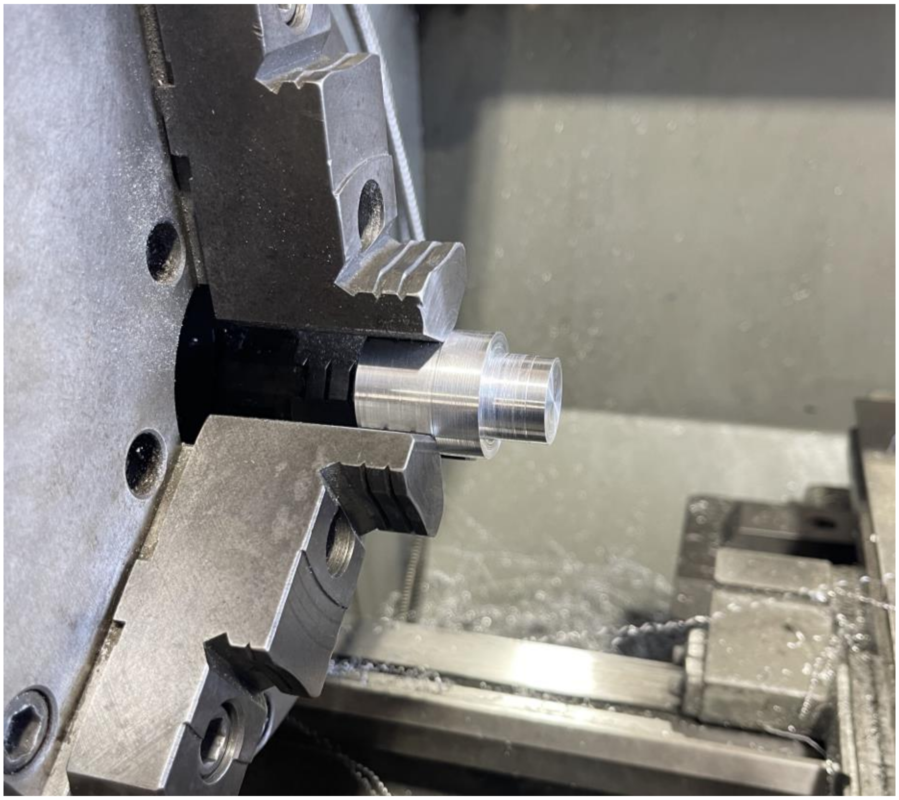


Figure 4: Upper bearing adapter in the lathe chuck during the first operation.

The next two components make up the bearing adapter assembly and were both made from 6061-T6 aluminum. The upper bearing adapter was turned down in the lathe to 1-1/8” OD and then further turned down on one end to create the bearing inner race stud shown in Figure 4. The part was flipped to drill a 5/8” deep hole to allow for tapping. A ½”-20 tap was then used to form the threads in the hole. For the lower bearing adapter, it was turned down on one end to 1.5” OD and then bored out to create the seat for the outer race of the bearing. The part was flipped in the lathe to create a 0.50” long stud at .520” diameter. The stud was then through drilled to allow for tapping with a 3/8”-24 tap. The completed lower bearing adapter is shown in Figure 5. The bearing mating features for both parts were challenging due to tight tolerances so the bearing would fit nicely.

Figure 5: Lower bearing adapter top and bottom sides after manufacturing was complete.

In the simplest manner, the main frame that is composed of the horizontal and vertical member, was manufactured out of stock 1-½” 8020 T-slotted aluminum framing. The members were measured and cut with a circular abrasive saw. Use of a file to debur the cut edges was very important at this point of the manufacturing due to the sharp edges created by the cut piece. Next, the cut 8020 sections had a7/8” hole drilled through them on a mill at specified locations to create mounting points for the manufactured 8020 threaded inserts.

Many of the components were 3D printed for the device as well. The tire contactor, wheel hub spacers, and the DAQ housing were all 3D printed with PETG filament on a Prusa i3 MK3S+. The DAQ housing required one post-print manufacturing step, which was the setting of the heat-set inserts for the lid screws. Setting of the #8-32 inserts was accomplished with a soldering iron and the appropriate adapter as shown in Figure 6.

Figure 6: Using a soldering iron to set the heat-set threaded inserts into the DAQ housing.

The wheel axle is another aluminum component that was manufactured on a lathe. Due to the length of the part, it was clamped in the chuck on one end and center point drilled and supported with a live center in the tailstock on the other end. The axle was turned down to 0.586” to match the ID of the wheel hub. The ends were turned down further to 0.495” to prep them for the ½"-20 die. A parting tool was used to cut the excess material off each end. The die was then used to cut threads on each end of the axle. The completed wheel axle is shown in Figure 7.

Figure 77: Wheel axle and threaded insert components.

3.3 Assembly

The assembly process for the device required only basic hand tools including Allen keys, channel locks, a ratchet with sockets and wrenches. Assembly of the main frame involved the 8020 fasteners, two 90-degree surface brackets and the horizontal and vertical 80/20 members. One 90-degree bracket was mounted on either side of the 8020 sections with the fasteners to create the L-shaped frame. Attention to the orientation of the vertical and horizontal members was taken when assembling so the threaded insert mounting holes were in the correct locations. The threaded inserts were assembled to the main frame through their mounting holes using the 8020 fasteners. Once the main frame was assembled the force application system was next.

The lead screw was threaded about halfway into the threaded insert in the horizontal member to allow for attachment of the load cell assembly and the force application handle. Two hex nuts were threaded onto the top section of the lead screw followed by the force application handle. A final hex nut was then threaded onto the lead screw to sandwich the handle. The desired handle height was measured and then the nuts were tightened down with wrenches to fix the handle position.

Figure 8: Ball bearing pressed onto the upper bearing adapter.

Next, the lower section of the force application system was assembled. For fitment of the bearing into each adapter, the upper adapter was turned down to make a hand press fit work, as shown in Figure 8. Once the inner race of the bearing was press fit onto the upper adapter, the outer race was pressed into the lower adapter. This fit ended up being a slip fit, so retaining compound was used to ensure the lower adapter would not fall off. The bearing adapter assembly was then threaded onto the lead screw followed by the load cell into the lower bearing adapter. To finish the force application system, a 3/8”-24 hex nut was threaded onto the lower stud of the load cell through the tire contactor. Finally, the tire contactor cap was pressed into the counterbored hole of the tire contactor.

The fully assembled force application system is shown below in Figure 9.

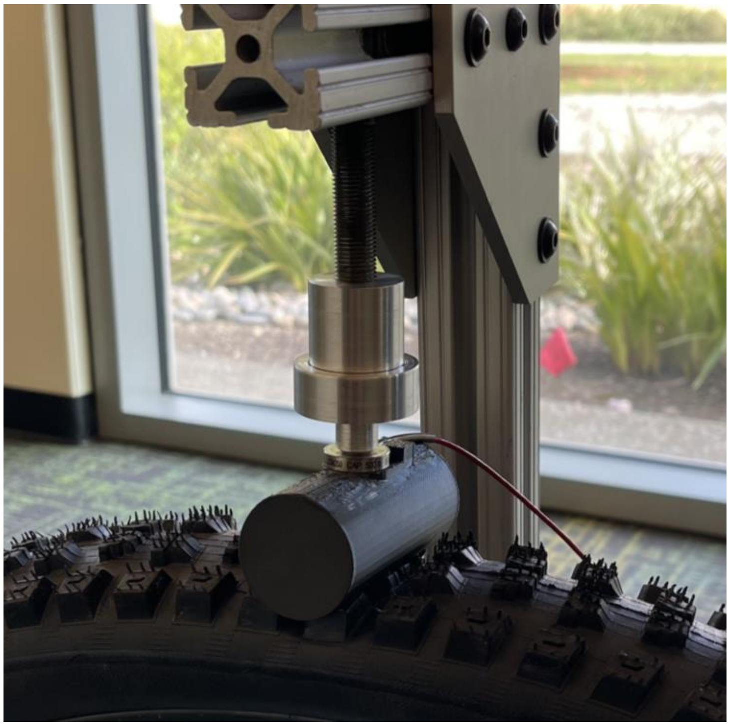


Figure 9: Completed lower section of the force application assembly.

Assembling the wheel axle was straight forward, by simply screwing the longer threaded end of the axle into the threaded insert of the vertical member. The other components of this sub-system are assembled during use of the device.

3.4 Software & Electronics

The electrical components of this project are composed of the load cell and Arduino products. The load cell being used from capturing the force signal induced by the compression of the tire. We used Arduino for their microcontroller processor and their Arduino IDE software development. Currently, we have connected the load cell to an amplifier to amplify the output signal from the load cell and load it into the linker of the Arduino. We have also connected an LCD screen to the Arduino board that displays the maximum value recorded during the measurement gathering process. All software programming has been developed using C++ programing language in the Arduino IDE program. Future plans for the electronic development will be to implement buttons to start/stop data collection, a power switch to power the electronics off/on, and to modify the code such that we can read out a spring rate measurement from our LCD screen.

4 Design Verification

4.1 Specifications

A set of design specifications for this project were synthesized through the application of Quality Function Deployment (QFD) and Failure Modes & Effects Analysis (FMEA). These methods highlighted important specifications that aligned with the stakeholders' needs and safety concerns. The specifications are shown in Table 1 below.

Table 1: *Engineering Specifications*

Spec #	Specification	Target Value	Tolerance	Risk*	Compliance**
1	Weight	7 kg (15 lb)	Max	H	A, I
2	Cost of Production	$500	±$50	M	A
3	Nice Appearance	N/A	N/A	L	S
4	Time for user to get measurement	2 min	Max	L	S
5	Force Application Repeatability	2%	±1%	H	A, T
6	Force Capability	2000 N (450 lbf)	Max	H	A, I, T
7	Number of Buttons	2	±1	M	I
8	Size	L: 76.2cm (30in) W: 25.4cm (10in) D: 20.3cm (8in)	Max	M	A, I

*Risk of meeting specification: (H) High, (M) Medium, (L) Low
**Compliance Methods: (A) Analysis, (I) Inspect, (S) Survey, (T) Test

These specifications helped the team create the Design Verification Plan (DVP) for the project. Based on the Compliance column of Table 1, different tests or criteria were developed for each specification. The details of these tests including measurement type, acceptance criteria, equipment needed, and more are outlined in the DVP. The full DVP can be found in Appendix E.

4.2 Testing and Results

A set of two tests and 5 inspections were designed to ensure that all specifications listed in Table 1 were in range of their target value with the added tolerances. These tests and inspections verified the weight, cost, appearance, measurement speed, repeatability, force capability, number of buttons, and size of the final device.

The repeatability of measurements test was conducted to verify the accuracy of measurements. These measurements relied on the minimal (or predictable) deflection of the frame and mounting axle, as well as the accuracy of the load cell and the electronics involved. The repeatability of measurements was tested by fixing the displacement of the force applicator, applying a force until the desired displacement is achieved, and extracting the maximum force value from the load cell. The test was conducted using three different displacement values, and for each displacement the force was measured ten times. Results of the test are shown below in Figure 10.

Displacement: 0.25"				
Test #	**Reading (g_f)**	**Reading Uncertainty**		**% Diff**
		+	**-**	
1	5.93	5.945	5.915	4.72
2	6.21	6.225	6.195	0.64
3	6.25	6.265	6.235	0.80
4	6.3	6.315	6.285	0.95
5	6.24	6.255	6.225	1.12
6	6.17	6.185	6.155	0.49
7	6.14	6.155	6.125	1.95
8	6.26	6.275	6.245	0.48
9	6.29	6.305	6.275	1.59
10	6.19	6.205	6.175	N/A
Avg	6.20	6.21	6.18	
Std. Dev.	0.10			

Displacement: 0.5"				
Test #	**Reading (g_f)**	**Reading Uncertainty**		**% Diff**
		+	**-**	
1	15.24	15.255	15.225	7.35
2	16.36	16.375	16.345	2.63
3	15.93	15.945	15.915	1.13
4	16.11	16.125	16.095	1.24
5	16.31	16.325	16.295	0.43
6	16.38	16.395	16.365	1.22
7	16.18	16.195	16.165	1.05
8	16.01	16.025	15.995	2.25
9	15.65	15.665	15.635	1.53
10	15.89	15.905	15.875	N/A
Avg	16.01	16.02	15.99	
Std. Dev.	0.34			

Displacement: 1.125"				
Test #	Reading (g_f)	Reading Uncertainty		% Diff
		+	-	
1	380.03	380.045	380.015	3.61
2	366.31	366.325	366.295	0.40
3	367.79	367.805	367.775	0.76
4	364.98	364.995	364.965	1.13
5	369.1	369.115	369.085	1.51
6	363.51	363.525	363.495	0.19
7	362.81	362.825	362.795	0.94
8	366.23	366.245	366.215	1.57
9	360.49	360.505	360.475	0.35
10	359.24	359.255	359.225	N/A
Avg	366.05	366.06	366.03	
Std. Dev.	5.29			

Figure 10 10: Summary of the force measurements gathered at each displacement with an average and corresponding standard deviation.

Our most significant challenge occurred while conducting the maximum force capability test using the updated load cell. The initial prototype included an S-beam style load cell provided by Cal Poly and was later changed for a more compact threaded in-line load cell provided to us by FUTEK. It wasn't until after the changes were made that the team realized the magnitude of structural rigidity the initial load cell had provided to the force application assembly. When conducting the test using the S-beam style load cell, the team was able to fully compress the tire such that it contacted the rim, thus achieving the maximum force value. While conducting the maximum force capability test using the new load cell, the force application system began to buckle after minimal force was applied. The test was stopped and after further inspection of the system, the load cell appeared to have significantly deflected and was later deemed broken. The force application assembly buckled because the tire contactor was not perfectly inline the tire it was contacting. A combination of the misalignment with the sheer amount of force being applied was enough to deflect the new load cell while the older, more robust load cell was better able to withstand the moment applied on it.

The weight of the device was measured using a digital bike scale. Our measured value for the weight was 7.54 pounds, which was substantially below our design specification to keep the device under 15 pounds as seen in Figure 11.

Figure 1111: Picture of device weighed using a digital bike scale.

After full assessment of our parts inquiry used to assemble the spring rate measurement device, we found that the total cost of production was $1204. Since our design specification was to keep the cost of production of the device under $500 with a tolerance of $50, we can conclude that the device did not meet the design requirement specified during our preliminary analysis. $948 of that cost is solely for the load cell from Futek, which was donated.

The size of the device was iterated throughout the design process to achieve a compact and portable final product. Our target size included values that could not exceed a length of 30 inches, a width of 10 inches and depth of 8 inches. The size of the device was determined with a measuring tape according to the dimensions shown in Figure 5. The final measurements of the device were as follows: final length of 29 in, width of 18 in and depth of 7 in. The device was out of spec on the width dimension due to the force application handle, which was deemed acceptable because the use of the mountain bike handlebar was wanted by the whole team.

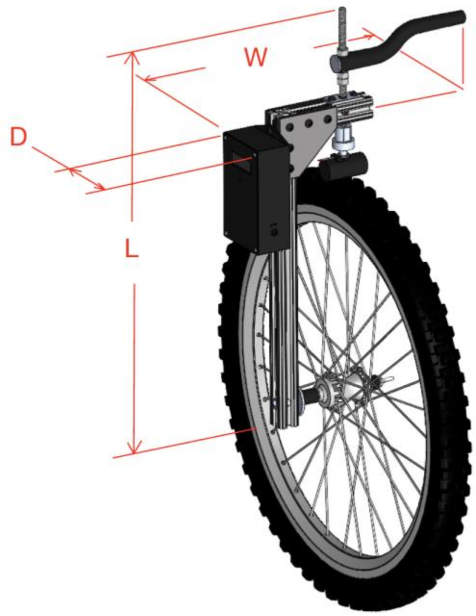


Figure 1212: Isometric view of the device with labeled dimensions for testing apparatus.

An appearance specification was set in the early stages of the project to try and make the device as visually appealing as possible. This subjective specification is based on inspection from people outside the design/build group. The consensus was that our device "looks nice".

The time to collect a measurement specification was initially established to make device use time as fast as possible. In building and testing we found that the desired displacement would influence this time-based specification. Less displacement would yield a low "time to measurement", while a higher displacement would increase that time. For 1.25" of displacement (chosen for expo display purposes) it takes 25 rotations of the handle to sufficiently advance the tire contactor. This took under 30 seconds and was paired with an electronically controlled sample time of 90 seconds. 90 seconds is sufficiently long enough to gather data for a full displacement (bottom out) test and can be changed by modifying the code stored in the Arduino.

The number of buttons specification was set at 3 in an attempt to limit the complexity of using the device. Currently there are 2 user interface buttons/switches. A switch to power on the device and a button to "test" and "retest". The desired simplicity of minimizing the user interface buttons was achieved.

5 Discussion & Recommendations

The following section will discuss learning outcomes of the project and propose ways to improve the design and/or manufacturing to further the product development for additional testing or production.

5.1 Discussion

During the project many challenges arose in the design, manufacturing, and testing phases. The general learning takeaways from the project were to work as a team, try to have a broad understanding of manufacturing processes, provide adequate project timing for things going wrong, and do not change the design at the last minute.

While designing our device we relied heavily on collaboration between teammates. Ideation sessions ended up being the most effective for overcoming design challenges as the team was able to think of an idea, expand on that idea which would often lead to multiple solutions and ultimately a feasible solution for the problem. Our limited experience with the manufacturing process would also prove to be a challenge, a time-consuming one at that. However, as we progressed so did our ability to recognize limitations of processes and material selection. Additionally, we were able to manufacture parts in a more timely and efficient manner. Material compatibility arose as a problem during the testing phase. While steel fasteners and aluminum thread inserts may be commonly used in industry, we could not achieve success with our manufacturing tolerances. A threaded steel force application rod would end up destroying the threads in one of our aluminum inserts during testing. Turning down a steel version on a lathe would have taken too long, so a threaded coupler was welded to a steel plate. The solution was far from beautiful but was extremely effective and allowed the project to keep going.

While the general pacing of the project was stress free, there were times when individual tasks were not given enough time to be completed which necessitated the team to work longer hours than we were used to. This timing aspect leads directly to the final lesson which is do not change the design right at the end. Initial designs and testing were centered around using a department supplied s-beam type load cell and the design was very effective during testing. The cell is very robust and relatively large and heavy when compared to newer options. Over the course of spring quarter, we were in contact with Futek who were going to donate a smaller, more modern load cell to us. Week 8 was when we were able to integrate the new button style load cell into our design and test it. Unfortunately, the load cell immediately broke as it experienced a buckling load. The Futek cells are designed to only be in compression and are structurally very weak in any plane outside of pure axial compression. What we had not realized was that the s-beam loaner cell was actually a structural component of the device. As a team we overlooked this error and even Futek did not catch this as we were required to send them CAD files of our design for them to review and determine if the requested load cells were appropriate for the application. Luckily, we had a spare load cell, we made some changes to the device to minimize those out of plane forces, and we were able to showcase it at the senior design expo. The changes made are still not sufficient to make the device effective for testing as the load cells are still experiencing some out of plane loading.

5.2 Recommendations and Next Steps

The main recommendation to restore intended device functionality at this point consists of two options. The first is to revert the design to use the s-beam style load cell. The second is to refine the current design to eliminate out of plane loading. Finding an s-beam load cell is the easier of the two options. It is proven to work and from some limited research a used load cell can be found for between $130-$450 depending on force capability. Refining the current design would likely increase the size and weight of the device, potentially to a point where portability is sacrificed in an appreciable way.

The final electronics subsystem featured an Arduino with external breadboard and other electronic components that utilized classic male-to-female Arduino wires. The male pins on the wires were thin and would often break and the connections weren't stable, meaning the structural integrity of the circuit would break under expected conditions. In order to produce the electronics for high volume purposes, the use of a PCB board in which wires could be soldered would be the most viable option. In addition, the electronics housing, 3D printed using PETG, could be scaled down to fit the new electronics and also made out of a more durable material, like aluminum, to resist fracturing in the event of the user dropping the device.

One recommendation we received during the senior expo was implementing a method that free's the displacement as well as the force. The current designs features a fixed displacement through the use of jam nuts, and a free force that was measured using a load cell. The implementation of a linear actuator coupled with the load cell would offer free force and free displacement. The benefits of free force and displacement is that it allows us to track a force with its corresponding displacement, plot a force vs displacement curve, and extract the spring rate from the slope of the linear portion of the curve. The downside of implementing a linear actuator as opposed to the current design of a manual force application system is that it would require more electronics and a stronger independent power source. A larger power source coupled with a linear actuator would increase the weight, cost and size of the device, potentially exceeding the specified limits stated in Table 1.

The frame was composed of 1515 8020 aluminum extrusion as well as 8020 brackets and hardware. The advantage of utilizing 8020 for this project was that it required minimal manufacturing and was cost effective given we were only building one model. The manufacturing of the frame just required cutting and drilling the aluminum extrusions. To manufacture the frame on a large scale, casting would be the most cost effective and efficient method. Purchasing large amount of 8020 framing and hardware would be expensive and inefficient. Casting the frame would also add structural rigidity. The current design uses 8020 hardware to connect two perpendicular extrusions, centralizing the loads on the hardware and relying on them to prevent considerable deflection. By casting the frame as one piece, no hardware would be required for the frame, there would be more structural rigidity as the frame material would experience the loading, and the frame size could potentially be reduced.

The current design is solely intended for a user to measure and fine tune the spring rate of a mountain bike tire with a with a 15 mm hole in the hub of the wheel. These limitations are due to the overall size of the frame, location of the force application system, and the diameter of the wheel axle specified in the user manual in *Appendix A.* Technically, a user could measure the spring rate of just about anything but would require custom designs of fixtures to mount the device, and potentially adjusting the size of the frame to fit the intended device.

6 Conclusion

Over the course of three quarters at Cal Poly, San Luis Obispo, our team was able to theorize, design, manufacture, test, and refine a novel design to measure the spring rate of a pneumatic mountain bike tire. The initial design was supposed to be much smaller, more portable, and mount in a way that would clamp around the tire and rim. After some research and per the advice of an industry professional it was apparent the design could damage some rims, so it had to change. The adaptation and timely implementation of a new design was a big success for the project's timeline but more so for the quality of our team. The final design consists of a few key areas of success in our design regarding the structural frame, electronics, and force application system. The frame provides enough rigidity to not deflect and influence the spring rate. The electronics take the maximum force and specified displacement to calculate a spring rate, and the force application system can apply sufficient force while isolating rotational and translational motion. In total, with the department loaner load cell, the device can measure tire spring rate across a wide range of pressures and displacements.

What we did not achieve was a more portable device. The current iteration is still relatively portable, but a bit larger than the initial goal of making something that can easily fit in a toolbox. A big limitation of this was the need to change designs and not have it clamp the tire and rim. While we were able to deliver a complete and functional device, we did not collect as much data as we initially set out to. Carrying the project forward Alex will use the device to collect data on more tires to evaluate how tire construction affects the spring rate.

Broadly speaking, the main lessons learned from this project are being adaptable and being able to problem solve are crucial. These are applicable to any project regardless of the specific details. While not possible in all cases, our team recommends choosing team members whose skills complement each other's and choosing members whom you get along with. We had the privilege of choosing our team ahead of time and this synergistic team environment undoubtedly contributed to our success in an appreciable way.

Appendices

Appendix A – User Manual

Spring Rate Measurement User Manual

Warning: This device features moving components that can cause pinching. Keep your hands clear of the tire sampling area when operating the device.
Design measures have been taken to limit the number of hazards with the device, but the compressive nature of the tire sampling area introduces the possibility of pinching.

Setup

The device can be set up two ways, clamped to a rigid vertical support (like a bike stand) for repeated use or held upright by the user for on-the-go use. Care should be taken when clamping to ensure the clamps do not interfere with use of the device.

Assembly

The assembly of this product requires only a few steps. The wheel mounting will be covered first, with the mounting orientation shown below in Figure 1.

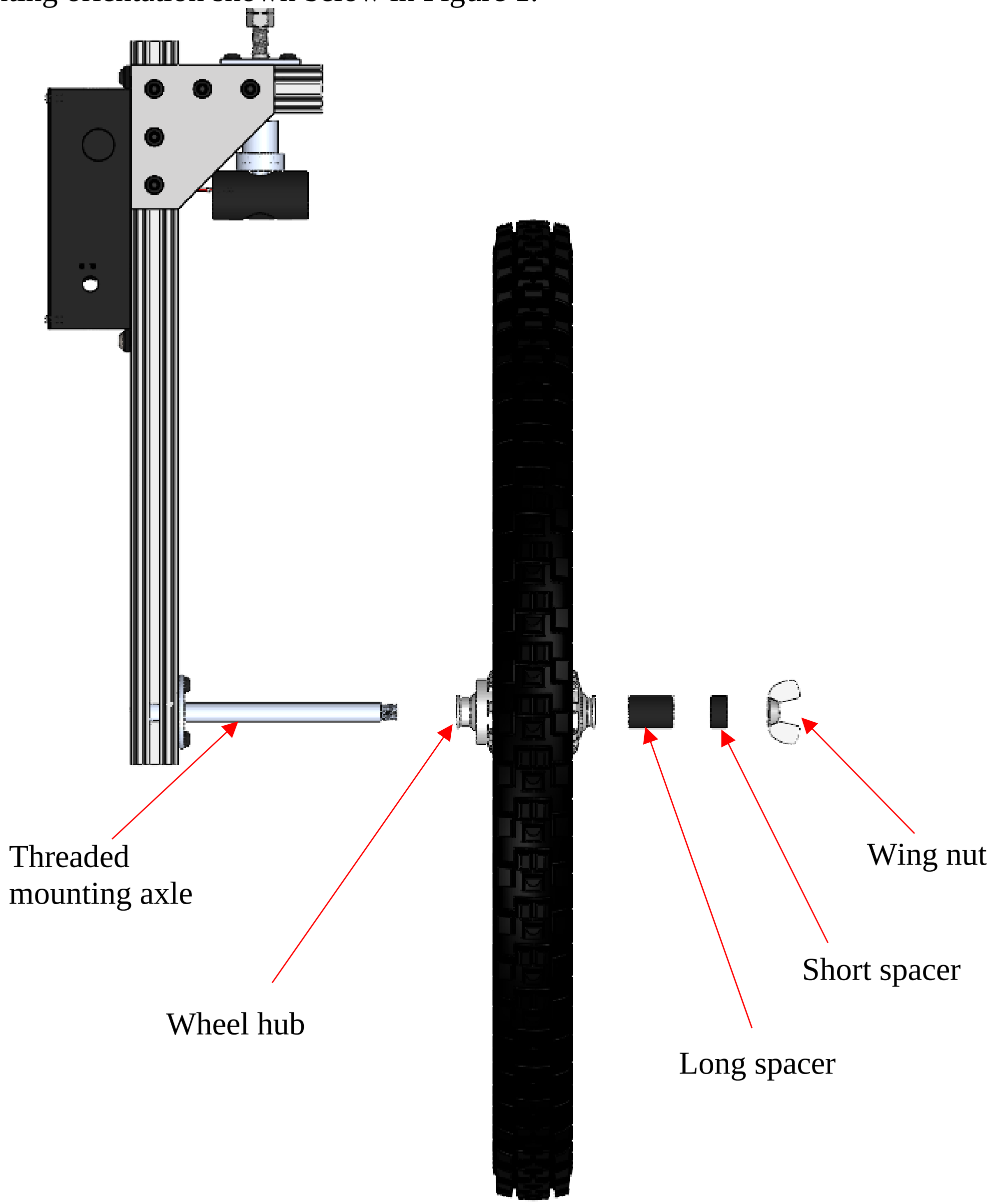


Figure 13: Exploded view of the wheel mounting assembly.

The first step is to mount the wheel assembly to the axle. The wheel hub will slide onto the axle until it comes in contact with the threaded insert as seen in Figure 2.

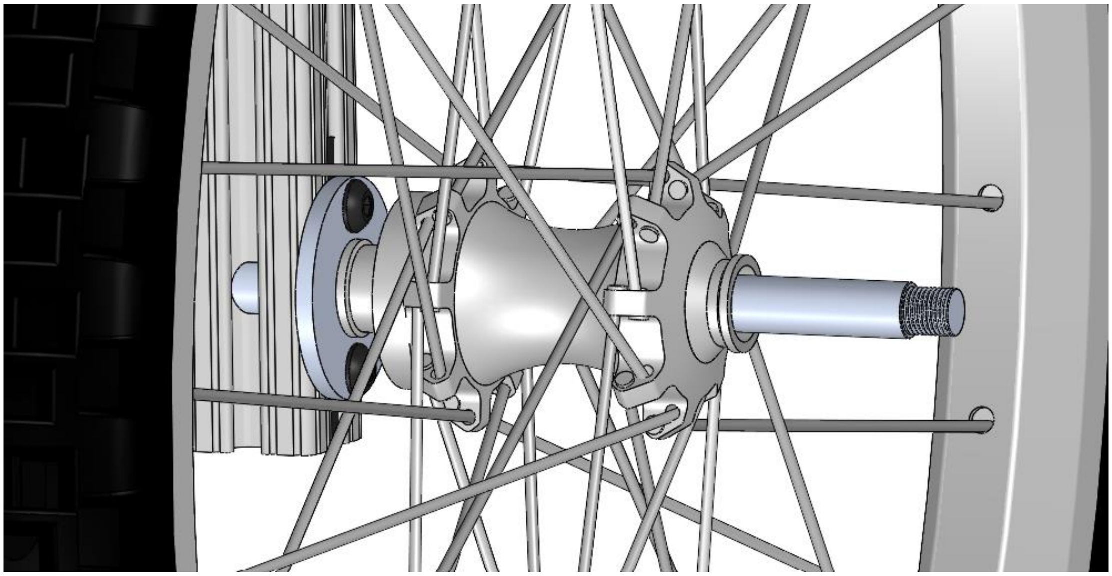


Figure 2: Zoomed in view of the wheel hub pressed against the spacer on the axle.

Next, slide the combination of the shorter and longer 3D printed spacers onto the axle until it contacts the wheel hub. Finish mounting the wheel assembly by screwing on the wingnut tightly against the spacer as shown in Figure 3. The wheel assembly should not be able to move side to side.

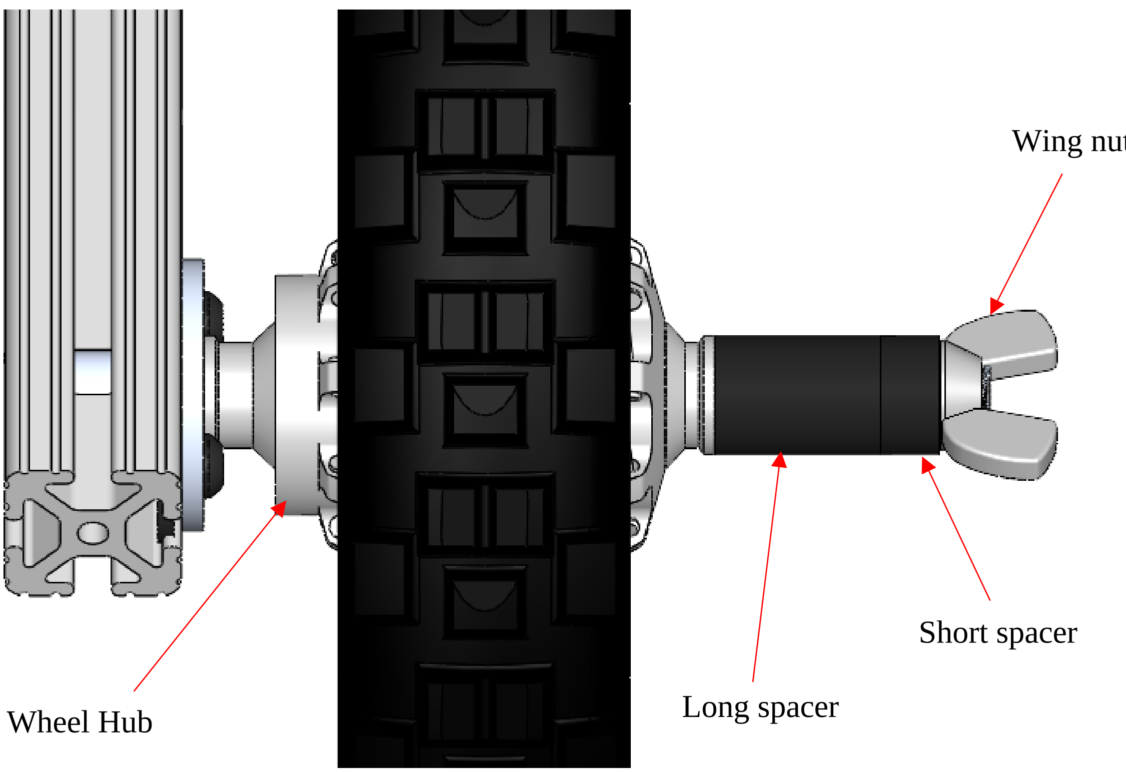


Figure 3: Side view of the complete wheel mounting assembly.

For the electronics, the only assembly needed is the installation of the battery. First, the user will need to remove the top plate of the electronics housing by removing the four screws using a 3/32" hex bit as shown in Figure 4.

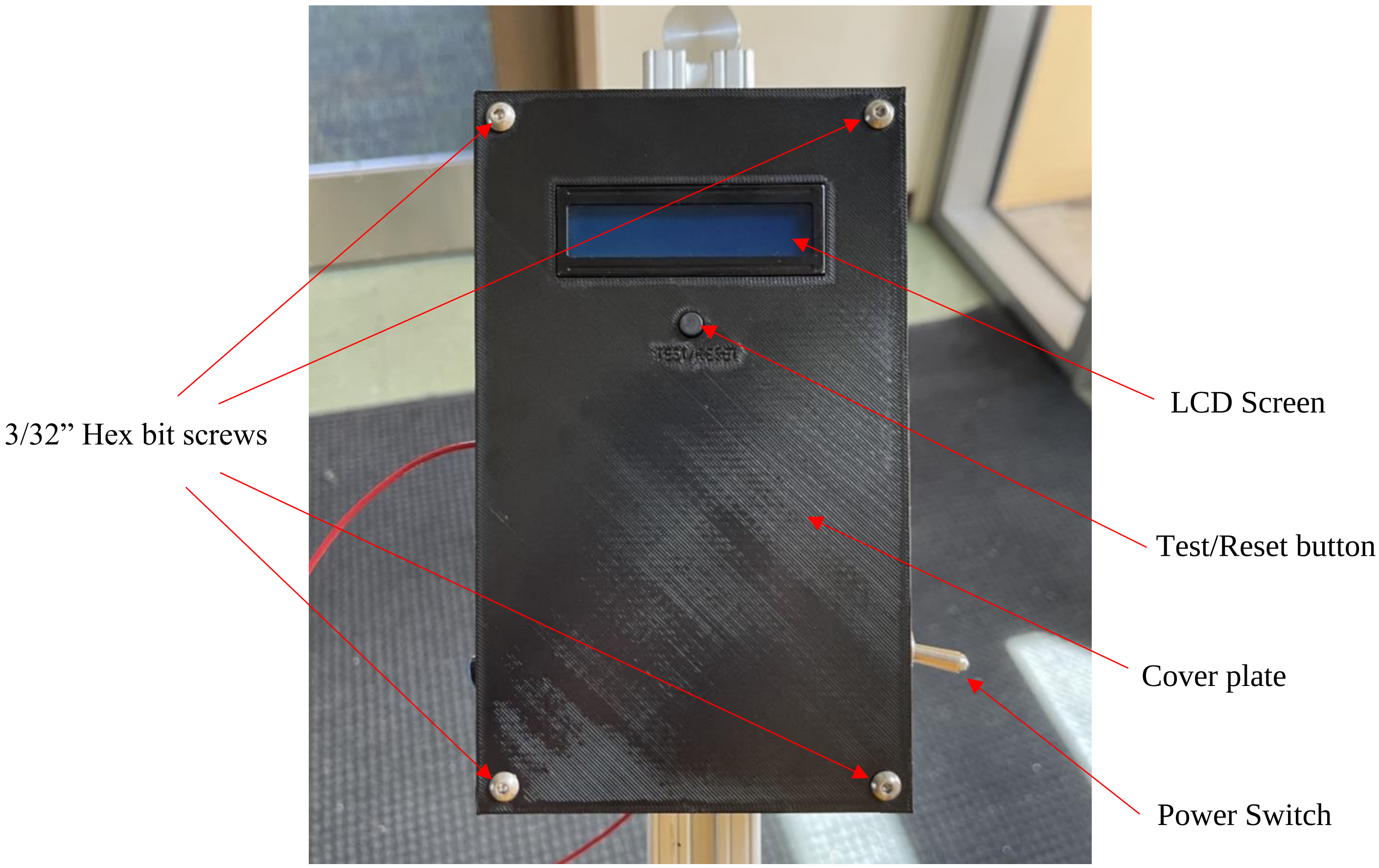


Figure 4: Electronics housing cover plate.

Next, install a 9V battery into the battery compartment by pressing it into the slot while ensuring that the battery is in the correct orientation (+ and – terminals) when installed as shown in Figure 5.

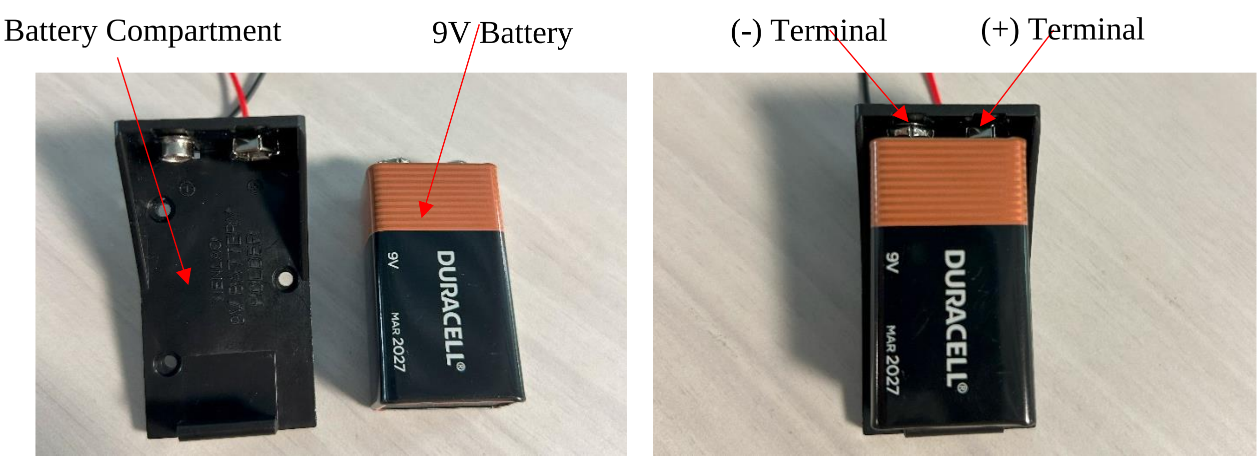


Figure 5: Installation of the 9V battery.

Lastly, reinstall the top cover plate by threading the four screws back into the electronics housing to complete the assembly process. The device will now be ready for the operational procedure.

Operational Steps

Once you have completed setup and assembly, the device is ready to operate. The components that are used in the following steps are labeled in Figure 6.

Figure 6: Isometric view of the tire spring rate measurement device with labeled components of operation.

The first thing the user needs to do is turn on the device by switching on the power switch located on the side of the electronics housing. Once the device is fully powered on, the user can begin advancing the tire contactor using the handle. Keep advancing the handle until the tire contactor is relatively close to the tire but ensuring that there is no contact yet as seen in Figure 7. It is very important that the user maintains proper safety precautions as outlined in the front page of this user manual. During the data collection process, the user is more susceptible to pinch points and/or other forms of injury, so prioritizing safety during operation is most crucial at this point.

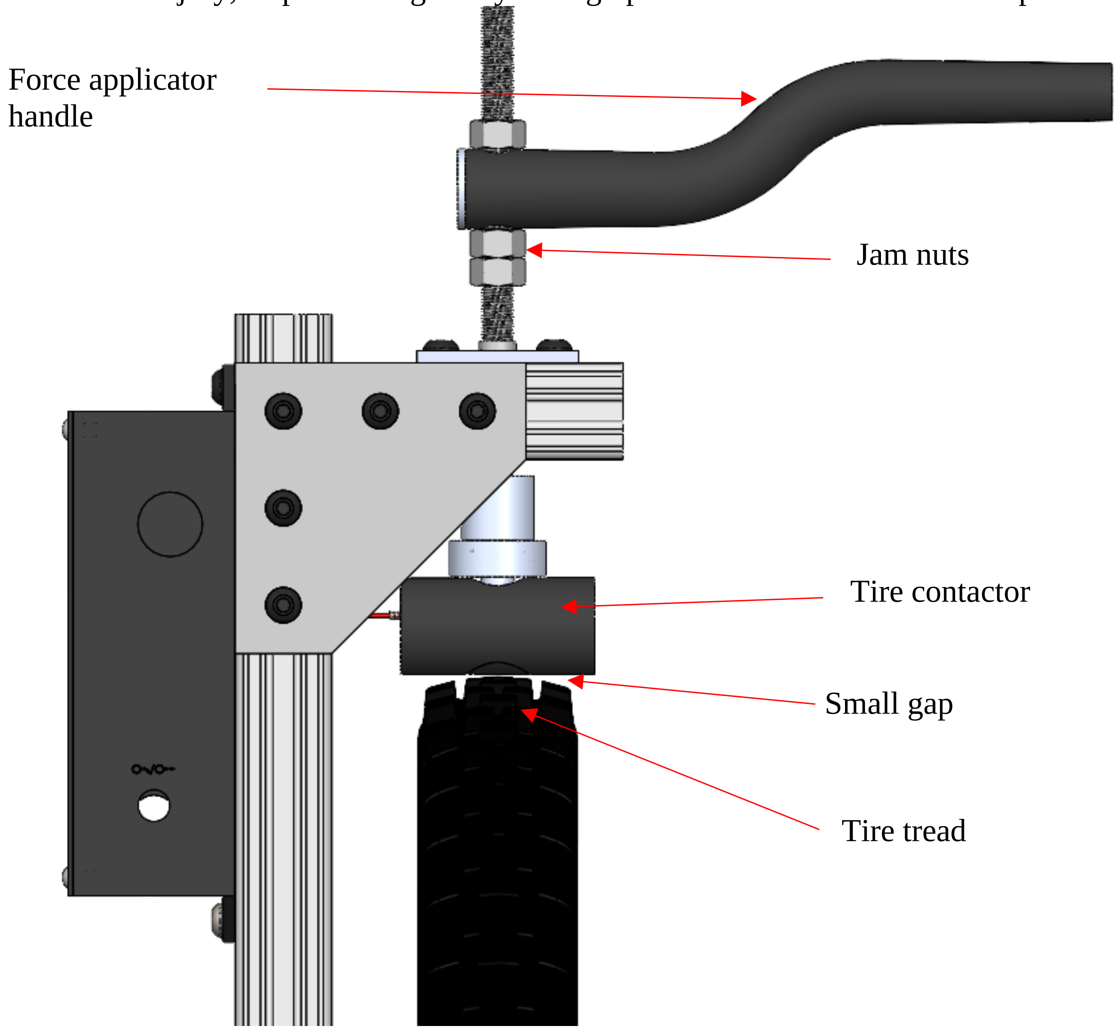


Figure 7: Tire contactor in position directly above the tire tread, ready for data collection.

Now the user can start the data collection process. Press the button marked “test/reset” on the electronics housing to initiate the data collection. The user can now begin to advance the tire contact plate into the tire by rotating the handle clockwise. The user will continue to advance the contactor down until it reaches the fixed displacement set by the jam nuts as seen in Figure 8.

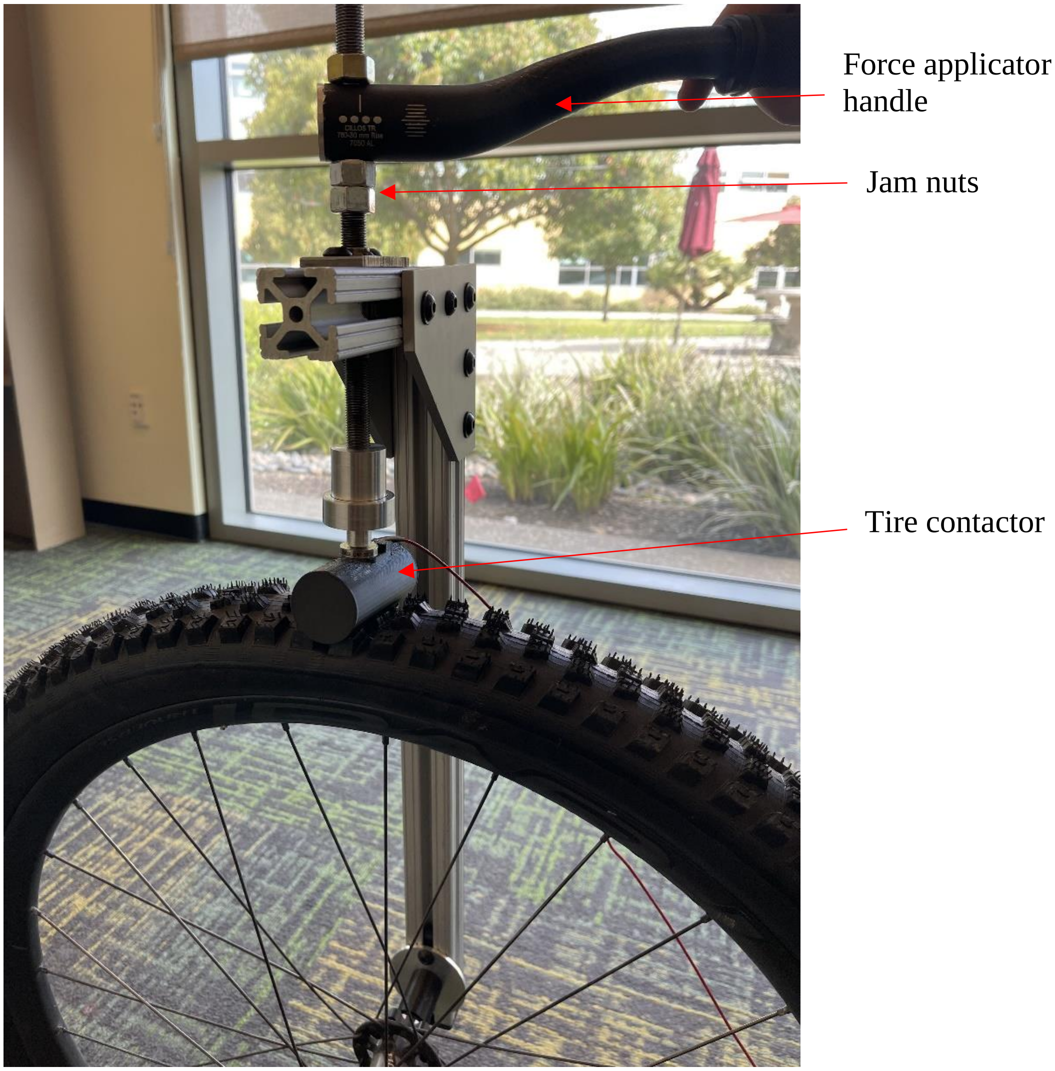


Figure 8: Compression of the tire after the fixed displacement set by the lock nuts has been reached.

The data collection will automatically stop on its own in 30 seconds. Once the data gathering sequence is completed, the LCD screen on the electronics housing will display the max value of tire spring rate ("Spring rate measurement = XX.XX lbf/in"). The user now has the choice to take the data being displayed or they can reset the data collection by clicking the same "test/reset" button as shown before. The user will have to unscrew the threaded force applicator before beginning the next data collection trial.

Maintenance

The only required maintenance designed for this product is to replace the battery when necessary. The process involves the reverse of the battery installation process. In the event that the product experiences component failure, the user will proceed to the troubleshooting/resources section of this user manual for more information.

Troubleshooting/Resources

This section comprehensively covers potential failure modes and corresponding recommended actions.

The aluminum components have undergone rigorous testing and manufacturing processes to mitigate the risk of failure. However, due to extensive operational cycles, there's a possibility of thread wear in the threaded insert used for force application, which could lead to compression failure. In such an event, the user should promptly unscrew the force application rod to release any applied loads. To remove the threaded rod, the user must first unlock the jam nuts and then unscrew the force applicator handle. Following this, they can unscrew the rod from the threaded insert, which is affixed to the aluminum framing using two 8020 fasteners. Removal of the insert requires a 3/16" hex Allen key. These inserts are custom-manufactured components and aren't available for direct purchase. For guidance on manufacturing a replacement, refer to the manufacturing guide in Appendix F of the Spring Rate Measurement of a Pneumatic Mountain Bike Tire's critical design review (CDR) report.

Certain components are produced using additive manufacturing processes. The only 3-D printed part prone to failure is the tire contactor. If it experiences issues like cracking or permanent deformation, the user must ensure no loads are applied before attempting to replace it. Removing the tire contactor involves accessing and unscrewing the shallow hex nut attaching it to the load cell, after which the damaged contactor can be replaced. Replacement parts can be obtained from CAD files provided with the project documentation, ensuring a minimum infill setting of 80% for strength for the new 3-D printed part.

Another potential failure mode involves the load cell, which, due to its compact size, may buckle or experience cantilever failure. Like the tire contactor, it's imperative to ensure no loads are applied before attempting removal. Following the procedure outlined for the tire contactor, the load cell can be unthreaded from the lower bearing adapter. Wired connections to the electronic housing must be carefully disconnected. Replacement load cells, such as the FUTEK LCM200 with a 500 lb force capacity, are available from the manufacturer, but note that they constitute a significant expense. For further assistance or additional troubleshooting, users are advised to directly contact the project team.

Appendix B – Risk Assessment

designsafe Report

Application:	Tire Spring Rate Device		Analyst Name(s):	Joseph, Alex, Luki, Duncan
Description:			Company:	F33
Product Identifier:	SRTM		Facility Location:	Locker 101
Assessment Type:	Detailed			
Limits:				
Sources:				
Risk Scoring System:	ANSI B11.0 Two Factor			

Guide sentence: When doing [task], the [user] could be injured by the [hazard] due to the [failure mode].

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
1-1-1	operator normal operation	mechanical : pinch point	Moderate Unlikely	Low		Moderate		
1-1-2	operator normal operation	mechanical : break up during operation	Moderate Remote	Negligible		Moderate		
1-1-3	operator normal operation	mechanical : machine instability	Minor Likely	Low		Minor		
1-1-4	operator normal operation	electrical / electronic : energized equipment / live parts	Moderate Unlikely	Low		Moderate		
1-1-5	operator normal operation	electrical / electronic : lack of grounding (earthing or neutral)	Moderate Unlikely	Low		Moderate		
1-1-6	operator normal operation	electrical / electronic : shorts / arcing / sparking	Moderate Unlikely	Low		Moderate		
1-1-7	operator normal operation	electrical / electronic : water / wet locations	Minor Unlikely	Negligible		Minor		

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
1-1-8	operator normal operation	slips / trips / falls : falling material / object	Minor Likely	Low		Minor		
1-1-9	operator normal operation	ergonomics / human factors : posture	Minor Likely	Low		Minor		
1-1-10	operator normal operation	noise / vibration : fatigue / material strength	Minor Unlikely	Negligible		Minor		
1-1-11	operator normal operation	material handling : instability	Minor Likely	Low		Minor		
1-2-1	operator basic trouble shooting / problem solving	mechanical : pinch point	Moderate Unlikely	Low		Moderate		
1-2-2	operator basic trouble shooting / problem solving	electrical / electronic : energized equipment / live parts	Moderate Unlikely	Low		Moderate		
1-2-3	operator basic trouble shooting / problem solving	electrical / electronic : lack of grounding (earthing or neutral)	Moderate Unlikely	Low		Moderate		
1-2-4	operator basic trouble shooting / problem solving	electrical / electronic : shorts / arcing / sparking	Moderate Unlikely	Low		Moderate		
1-2-5	operator basic trouble shooting / problem solving	ergonomics / human factors : posture	Minor Remote	Negligible		Minor		

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
1-3-1	operator misuse - (add description)	mechanical : pinch point	Moderate Unlikely	Low		Moderate		
1-3-2	operator misuse - (add description)	mechanical : break up during operation	Moderate Remote	Negligible		Moderate		
1-3-3	operator misuse - (add description)	electrical / electronic : energized equipment / live parts	Moderate Unlikely	Low		Moderate		
1-3-4	operator misuse - (add description)	electrical / electronic : lack of grounding (earthing or neutral)	Moderate Unlikely	Low		Moderate		
1-3-5	operator misuse - (add description)	electrical / electronic : shorts / arcing / sparking	Moderate Unlikely	Low		Moderate		
1-3-6	operator misuse - (add description)	electrical / electronic : water / wet locations	Minor Unlikely	Negligible		Minor		
1-3-7	operator misuse - (add description)	slips / trips / falls : falling material / object	Minor Unlikely	Negligible		Minor		
1-3-8	operator misuse - (add description)	ergonomics / human factors : posture	Minor Remote	Negligible		Minor		
1-3-9	operator misuse - (add description)	noise / vibration : fatigue / material strength	Minor Unlikely	Negligible		Minor		

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
1-3-10	operator misuse - (add description)	material handling : instability	Minor Likely	Low		Minor		
2-1-1	maintenance technician parts replacement	mechanical : pinch point	Moderate Unlikely	Low		Moderate		
2-1-2	maintenance technician parts replacement	mechanical : break up during operation	Moderate Remote	Negligible		Moderate		
2-1-3	maintenance technician parts replacement	noise / vibration : fatigue / material strength	Minor Unlikely	Negligible		Minor		
2-2-1	maintenance technician trouble-shooting / problem solving	mechanical : pinch point	Moderate Unlikely	Low		Moderate		
2-2-2	maintenance technician trouble-shooting / problem solving	mechanical : break up during operation	Moderate Remote	Negligible		Moderate		
2-2-3	maintenance technician trouble-shooting / problem solving	mechanical : machine instability	Minor Likely	Low		Minor		
3-1-1	electrician / controls technician repair / replace wiring / systems	electrical / electronic : energized equipment / live parts	Moderate Unlikely	Low		Moderate		
3-1-2	electrician / controls technician repair / replace wiring / systems	electrical / electronic : lack of grounding (earthing or neutral)	Moderate Unlikely	Low		Moderate		

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
3-1-3	electrician / controls technician repair / replace wiring / systems	electrical / electronic : shorts / arcing / sparking	Moderate Unlikely	Low		Moderate		
3-2-1	electrician / controls technician troubleshooting	electrical / electronic : energized equipment / live parts	Moderate Unlikely	Low		Moderate		
3-2-2	electrician / controls technician troubleshooting	electrical / electronic : lack of grounding (earthing or neutral)	Moderate Unlikely	Low		Moderate		
3-2-3	electrician / controls technician troubleshooting	electrical / electronic : shorts / arcing / sparking	Moderate Unlikely	Low		Moderate		
3-3-1	electrician / controls technician install / test / repair circuit	electrical / electronic : energized equipment / live parts	Moderate Unlikely	Low		Moderate		
3-3-2	electrician / controls technician install / test / repair circuit	electrical / electronic : lack of grounding (earthing or neutral)	Moderate Unlikely	Low		Moderate		
3-3-3	electrician / controls technician install / test / repair circuit	electrical / electronic : shorts / arcing / sparking	Moderate Unlikely	Low		Moderate		

Appendix C – Final Project Budget

Team Part #	Item Description	Vendor	Vendor's Part #	Item Cost	Shipping & Tax	Total Cost	Date Purchased	How Purchased	Who Purchased	Location
11100	1.5" x 1.5" Silver 80/20 T-Slot Rail, 4ft.	McMaster	47065T103	$ 49.29	$ 53.03	$102.32	18-Jan	Credit Card	Alex	Bonderson
11200	Silver Corner Surface Bracket for 1.5" Rail	McMaster	47065T271	$ 26.68	$ -	$ 26.68	18-Jan	Credit Card	Alex	Bonderson
	Carbon Steel Set Screw Collar for 14 mm Shaft Diameter	McMaster	6056N22	$ 3.43	$ -	$ 3.43	18-Jan	Credit Card	Alex	Bonderson
15000	End Feed Single Nut w/ 5/16"-18 Button Head Screw (4 pack)	McMaster	47065T215	$ 17.80	$ -	$ 17.80	18-Jan	Credit Card	Alex	Bonderson
11300	Beam Type Load Cell	Cal Poly		$ -	$ -	$ -				
	Comfort-Grip Plastic Three-Arm Knob with 1/4"-20 Thread 1/2" Long Stud, 1-3/4" Wide Head	McMaster	2776K19	$ 3.13	$ -	$ 3.13	18-Jan	Credit Card	Alex	Bonderson
12220	18-8 Stainless Steel Button Head Hex Screw 1/2"-20 2" Long	McMaster	92949A884	$ 3.11	$ -	$ 3.11	9-Feb	Credit Card	Alex	Bonderson
12230	18-8 Stainless Steel Threaded Rod 1/2"-20 1' Long	McMaster	98804A119	$ 15.34	$ -	$ 15.34	9-Feb	Credit Card	Alex	Bonderson
12300	Permatex Sleeve Retaining Compound	Napa	PTX 7651149	$ 9.99	$ -	$ 9.99	28-Feb	Credit Card	Alex	Bonderson
12400	1/2"-20 Steel Hex Nut	Miners-Ace		$ 8.97	$ 0.72	$ 9.69	28-Feb	Credit Card		Bonderson
	Nylon Four Arm Knob with 1/2"-13 Threaded Hole, Black	McMaster	7921K44	$ 4.05	$ -	$ 4.05	18-Jan	Credit Card	Alex	Bonderson
13200	1/2"-20 Steel Round Coupling Nut, 2" Long	McMaster	96177A520	$ 28.04	$ 11.40	$ 39.44	7-May	Credit Card	Alex	Bonderson
13300	3/8"-24 Steel Hex Nut	McMaster	94846A206	$ 5.12	$ 12.13	$ 17.25	19-May	Credit Card	Duncan	Bonderson
13400	Ball Bearing R8-2RS for 1/2" Shaft Diameter	McMaster	60355K691	$ 30.93	$ 12.52	$ 43.45	9-Feb	Credit Card	Alex & Duncan	Bonderson
13500	USB to DC Power Cable	Amazon		$ 6.99	$ 0.56	$ 7.55	24-Apr	Credit Card	Joseph	Bonderson
13600	9V Battery Holder	Amazon		$ 7.99	$ 0.64	$ 8.63	24-Apr	Credit Card	Joseph	Bonderson
13700	JBTek Acrylic Base	Amazon		$ 7.95	$ 0.64	$ 8.59	14-May	Credit Card	Joseph	Bonderson
14100	3M Double Side Foam Tape	Amazon		$ 5.40	$ 0.43	$ 5.83	23-May	Credit Card	Joseph	Bonderson
14200	Dupont Jumper Wires	RadioShack		$ 4.99	$ 0.40	$ 5.39	24-May	Credit Card	Luki	Bonderson
14300	Function Button	Digi-Key	2223-TS02-66-	$ 0.10	$ 0.01	$ 0.11	25-May	Credit Card	Luki	Bonderson
14400	10K Linear Potentiometer	Adafruit	562	$ 0.95	$ 0.08	$ 1.03	26-May	Credit Card	Luki	Bonderson
14500	20 Amp Single Pole Toggle Switch	Miners-Ace	3531266	$ 6.59	$ 0.53	$ 7.12	27-May	Credit Card	Luki	Bonderson
14600	Load Cell Amplifier	Amazon		$ 6.79	$ 0.54	$ 7.33	23-May	Credit Card	Luki	Bonderson
14700	Arduino Uno REV3	Amazon		$ 24.50	$ 1.96	$ 26.46	24-May	Credit Card	Luki	Bonderson
14800	LCD Screen	Digi-Key	3647-LCD1602	$ 3.03	$ 0.24	$ 3.27	25-May	Credit Card	Luki	Bonderson
14900	Rubber Grommet Kit	Amazon		$ 9.69	$ 0.76	$ 10.45	23-May	Credit Card	Joseph	Bonderson
					Total Cost:	$387.44				

Appendix D – Software

-- Calibration --

```
/*
   -------------------------------------------------------------------------------------
   HX711_ADC
   Arduino library for HX711 24-Bit Analog-to-Digital Converter for Weight Scales
   Created By: Olav Kallhovd sept2017
   Modified By: F33 – Spring Rate Team (Spring 24')
   -------------------------------------------------------------------------------------
*/

/*
   This example file shows how to calibrate the load cell and optionally store the calibration
   value in EEPROM, and also how to change the value manually.
   The result value can then later be included in your project sketch or fetched from EEPROM.

   To implement calibration in your project sketch the simplified procedure is as follow:
       LoadCell.tare();
       //place known mass
       LoadCell.refreshDataSet();
       float newCalibrationValue = LoadCell.getNewCalibration(known_mass);
*/

#include <HX711_ADC.h>
#if defined(ESP8266)|| defined(ESP32) || defined(AVR)
#include <EEPROM.h>
#endif

//pins:
const int HX711_dout = 4; //mcu > HX711 dout pin
const int HX711_sck = 5; //mcu > HX711 sck pin

//HX711 constructor:
HX711_ADC LoadCell(HX711_dout, HX711_sck);

const int calVal_eepromAdress = 0;
unsigned long t = 0;

void setup() {
  Serial.begin(57600); delay(10);
  Serial.println();
  Serial.println("Starting...");

  LoadCell.begin();
```

```
  //LoadCell.setReverseOutput(); //uncomment to turn a negative output
value to positive
  unsigned long stabilizingtime = 2000; // preciscion right after power-up
can be improved by adding a few seconds of stabilizing time
  boolean _tare = true; //set this to false if you don't want tare to be
performed in the next step
  LoadCell.start(stabilizingtime, _tare);
  if (LoadCell.getTareTimeoutFlag() || LoadCell.getSignalTimeoutFlag()) {
    Serial.println("Timeout, check MCU>HX711 wiring and pin
designations");
    while (1);
  }
  else {
    LoadCell.setCalFactor(1.0); // user set calibration value (float),
initial value 1.0 may be used for this sketch
    Serial.println("Startup is complete");
  }
  while (!LoadCell.update());
  calibrate(); //start calibration procedure
}

void loop() {
  static boolean newDataReady = 0;
  const int serialPrintInterval = 0; //increase value to slow down serial
print activity

  // check for new data/start next conversion:
  if (LoadCell.update()) newDataReady = true;

  // get smoothed value from the dataset:
  if (newDataReady) {
    if (millis() > t + serialPrintInterval) {
      float i = LoadCell.getData();
      Serial.print("Load_cell output val: ");
      Serial.println(i);
      newDataReady = 0;
      t = millis();
    }
  }

  // receive command from serial terminal
  if (Serial.available() > 0) {
    char inByte = Serial.read();
    if (inByte == 't') LoadCell.tareNoDelay(); //tare
    else if (inByte == 'r') calibrate(); //calibrate
    else if (inByte == 'c') changeSavedCalFactor(); //edit calibration
value manually
  }

  // check if last tare operation is complete
  if (LoadCell.getTareStatus() == true) {
    Serial.println("Tare complete");
  }
```

```
}

void calibrate() {
  Serial.println("***");
  Serial.println("Start calibration:");
  Serial.println("Place the load cell an a level stable surface.");
  Serial.println("Remove any load applied to the load cell.");
  Serial.println("Send 't' from serial monitor to set the tare offset.");

  boolean _resume = false;
  while (_resume == false) {
    LoadCell.update();
    if (Serial.available() > 0) {
      if (Serial.available() > 0) {
        char inByte = Serial.read();
        if (inByte == 't') LoadCell.tareNoDelay();
      }
    }
    if (LoadCell.getTareStatus() == true) {
      Serial.println("Tare complete");
      _resume = true;
    }
  }

  Serial.println("Now, place your known mass on the loadcell.");
  Serial.println("Then send the weight of this mass (i.e. 100.0) from
serial monitor.");

  float known_mass = 0;
  _resume = false;
  while (_resume == false) {
    LoadCell.update();
    if (Serial.available() > 0) {
      known_mass = Serial.parseFloat();
      if (known_mass != 0) {
        Serial.print("Known mass is: ");
        Serial.println(known_mass);
        _resume = true;
      }
    }
  }

  LoadCell.refreshDataSet(); //refresh the dataset to be sure that the
known mass is measured correct
  float newCalibrationValue = LoadCell.getNewCalibration(known_mass);
//get the new calibration value

  Serial.print("New calibration value has been set to: ");
  Serial.print(newCalibrationValue);
  Serial.println(", use this as calibration value (calFactor) in your
project sketch.");
  Serial.print("Save this value to EEPROM adress ");
  Serial.print(calVal_eepromAdress);
  Serial.println("? y/n");
```

```
  _resume = false;
  while (_resume == false) {
    if (Serial.available() > 0) {
      char inByte = Serial.read();
      if (inByte == 'y') {
#if defined(ESP8266)|| defined(ESP32)
        EEPROM.begin(512);
#endif
        EEPROM.put(calVal_eepromAdress, newCalibrationValue);
#if defined(ESP8266)|| defined(ESP32)
        EEPROM.commit();
#endif
        EEPROM.get(calVal_eepromAdress, newCalibrationValue);
        Serial.print("Value ");
        Serial.print(newCalibrationValue);
        Serial.print(" saved to EEPROM address: ");
        Serial.println(calVal_eepromAdress);
        _resume = true;

      }
      else if (inByte == 'n') {
        Serial.println("Value not saved to EEPROM");
        _resume = true;
      }
    }
  }

  Serial.println("End calibration");
  Serial.println("***");
  Serial.println("To re-calibrate, send 'r' from serial monitor.");
  Serial.println("For manual edit of the calibration value, send 'c' from
serial monitor.");
  Serial.println("***");
}

void changeSavedCalFactor() {
  float oldCalibrationValue = LoadCell.getCalFactor();
  boolean _resume = false;
  Serial.println("***");
  Serial.print("Current value is: ");
  Serial.println(oldCalibrationValue);
  Serial.println("Now, send the new value from serial monitor, i.e.
696.0");
  float newCalibrationValue;
  while (_resume == false) {
    if (Serial.available() > 0) {
      newCalibrationValue = Serial.parseFloat();
      if (newCalibrationValue != 0) {
        Serial.print("New calibration value is: ");
        Serial.println(newCalibrationValue);
        LoadCell.setCalFactor(newCalibrationValue);
        _resume = true;
      }
```

```
    }
  }
  _resume = false;
  Serial.print("Save this value to EEPROM adress ");
  Serial.print(calVal_eepromAdress);
  Serial.println("? y/n");
  while (_resume == false) {
    if (Serial.available() > 0) {
      char inByte = Serial.read();
      if (inByte == 'y') {
#if defined(ESP8266)|| defined(ESP32)
        EEPROM.begin(512);
#endif
        EEPROM.put(calVal_eepromAdress, newCalibrationValue);
#if defined(ESP8266)|| defined(ESP32)
        EEPROM.commit();
#endif
        EEPROM.get(calVal_eepromAdress, newCalibrationValue);
        Serial.print("Value ");
        Serial.print(newCalibrationValue);
        Serial.print(" saved to EEPROM address: ");
        Serial.println(calVal_eepromAdress);
        _resume = true;
      }
      else if (inByte == 'n') {
        Serial.println("Value not saved to EEPROM");
        _resume = true;
      }
    }
  }
  Serial.println("End change calibration value");
  Serial.println("***");


}
```

--- Read_1x_load_cell ---

```
/*
   ----------------------------------------------------------------------
--------------
   HX711_ADC
   Arduino library for HX711 24-Bit Analog-to-Digital Converter for Weight
Scales
   Created By: Olav Kallhovd sept2017
   Modified By: F33 – Spring Rate Team (Spring 24')
   ----------------------------------------------------------------------
--------------
*/

/*
   Settling time (number of samples) and data filtering can be adjusted in
the config.h file
```

```
   For calibration and storing the calibration value in eeprom, see
example file "Calibration.ino"

   The update() function checks for new data and starts the next
conversion. In order to acheive maximum effective
   sample rate, update() should be called at least as often as the HX711
sample rate; >10Hz@10SPS, >80Hz@80SPS.
   If you have other time consuming code running (i.e. a graphical LCD),
consider calling update() from an interrupt routine,
   see example file "Read_1x_load_cell_interrupt_driven.ino".

   This is an example sketch on how to use this library
*/

#include <LiquidCrystal.h>
#include <HX711_ADC.h>
#if defined(ESP8266) || defined(ESP32) || defined(AVR)
#include <EEPROM.h>
#endif

// Pins:
const int HX711_dout = 4; // MCU > HX711 dout pin
const int HX711_sck = 5;  // MCU > HX711 sck pin
const int buttonPin = 2;  // the number of the pushbutton pin

// HX711 constructor:
HX711_ADC LoadCell(HX711_dout, HX711_sck);

const int calVal_eepromAdress = 0;
unsigned long t = 0;

// initialize the library by associating any needed LCD interface pin
// with the Arduino pin number it is connected to
LiquidCrystal lcd_1(12, 11, 10, 9, 8, 7);

void setup() {
  // Set up LCD
  lcd_1.begin(16, 2);
  lcd_1.print("Starting...");

  // Set up serial communication
  Serial.begin(57600);
  delay(10);
  Serial.println();
  Serial.println("Starting...");

  // Set up HX711
  LoadCell.begin();
  float calibrationValue;
  calibrationValue = 696.0;

#if defined(ESP8266) || defined(ESP32)
  // EEPROM.begin(512);
#endif
```

```
  EEPROM.get(calVal_eepromAdress, calibrationValue);

  unsigned long stabilizingtime = 2000;
  boolean _tare = true;
  LoadCell.start(stabilizingtime, _tare);
  if (LoadCell.getTareTimeoutFlag()) {
    Serial.println("Timeout, check MCU > HX711 wiring and pin
designations");
    while (1);
  } else {
    LoadCell.setCalFactor(calibrationValue);
    Serial.println("Startup is complete");
  }

  // Set up button pin
  pinMode(buttonPin, INPUT);
}

bool collectData = true;
bool maxReached = false;
float maxOutput = 0.0;
float lastOutput = 0.0;
unsigned long startTime = 0;
unsigned long stopTime = 0;
const unsigned long maxRunTime = 30000;  // 30 seconds in milliseconds
const float minDifference = 100.0;
const float decreaseThreshold = 50.0;
unsigned long dataCollectionStartTime = 0;  // Store the time when data
collection starts

void loop() {
  // LCD display loop
  static boolean newDataReady = false;
  const int serialPrintInterval = 0; // Increase value to slow down serial
print activity

  // Start recording data collection time
  if (collectData && !dataCollectionStartTime) {
    dataCollectionStartTime = millis();
  }

  // Check if 1 minute has passed and return the maximum value
  if (millis() - dataCollectionStartTime >= maxRunTime && maxReached) {
    lcd_1.clear();
    lcd_1.setCursor(0, 0);
    lcd_1.print("SRV (lb/in):");
    lcd_1.setCursor(0, 1);
    lcd_1.print(maxOutput * 0.0022053861 / 0.5); // Apply conversion
factor to final output
    Serial.print("Maximum output value recorded: ");
    Serial.println(maxOutput * 0.0022053861 / 0.5); // Apply conversion
factor to final output
    while (true); // Stop simulation
  }
```

```
  // Check for new data/start next conversion if data collection is
enabled:
  if (collectData && LoadCell.update()) newDataReady = true;

  // Get smoothed value from the dataset if data collection is enabled:
  if (collectData && newDataReady) {
    if (millis() > t + serialPrintInterval) {
      float currentOutput = LoadCell.getData();
      currentOutput = abs(currentOutput); // Take the absolute value of
the current output
      lcd_1.clear();
      lcd_1.setCursor(0, 0);
      lcd_1.print("Load cell val:");
      lcd_1.setCursor(0, 1);
      lcd_1.print(currentOutput);

      if (!maxReached && (millis() - dataCollectionStartTime >= maxRunTime
|| abs(currentOutput - lastOutput) >= minDifference)) {
        maxOutput = currentOutput; // Update maximum value
        dataCollectionStartTime = millis(); // Reset start time
        maxReached = true;
      } else if (maxReached && currentOutput > maxOutput) {
        maxOutput = currentOutput; // Update maximum value if the current
output is larger
      }

      newDataReady = false;
      t = millis();
      lastOutput = currentOutput;
    }
  }

  // Check if the button is pressed to restart data collection
  if (digitalRead(buttonPin) == HIGH) {
    restartDataCollection();
  }

  // Receive command from the serial terminal:
  if (Serial.available() > 0) {
    char inByte = Serial.read();
    if (inByte == 't') {
      LoadCell.tareNoDelay(); // Initiate tare operation
    } else if (inByte == 's') {
      // Toggle data collection
      collectData = !collectData;
      if (collectData) {
        Serial.println("Data collection resumed.");
      } else {
        Serial.println("Data collection paused.");
      }
    }
  }
```

```
  // Check if the last tare operation is complete:
  if (LoadCell.getTareStatus() == true) {
    Serial.println("Tare complete");
  }
}

// Function to restart data collection process
void restartDataCollection() {
  collectData = true;
  maxReached = false;
  maxOutput = 0.0;
  lastOutput = 0.0;
  dataCollectionStartTime = 0;
}
```

Appendix E – Design Verification Plan & Report (DVPR)

DVP&R - Design Verification Plan (& Report)											
Project:	F33 - Pnuematic Tire Spring Rate		Sponsor:	Andrew Kean					Edit Date:	6/7/2024	
TEST PLAN										TEST RESULTS	
Test #	Specification	Test Description	Measurements	Acceptance Criteria	Required Facilities/Equipment	Parts Needed	Responsibility	TIMING Start date	TIMING Finish date	Numerical Results	Notes on Testing
	Weight	NOT A TEST - Use a digital bike scale to weigh the entire assembly	Weight in lbs	Design must weigh less than 15lbs	Digital Bike Scale	VP	Alex	5/31/2024	5/31/2024	7.54	Assembly got about 2 pounds lighter after switching to the FUTEK load cell.
	Cost of Production	NOT A TEST - Track cost of all components with budget	Dollar amounts	\$450 to \$550	Team budget spreadsheet and iBOM	VP	Alex	5/30/2024	5/30/2024	\$1204.88 from iBOM \$387.44 from Budget	iBOM value is much higher because of the load cell price being included. We technically met our criteria for Budget.
	Nice Appearance	NOT A TEST - Ask sponsor, coach and teammates their opinion	None	Pass/Fail	Notebook to record feedback	VP	Luki	5/30/2024	5/30/2024	N/A	Device was determined to be aesthetically pleasing.
	NOT A TEST - Time for user to get measurement	Wheel will already be mounted to device. Team member will power on device, apply the force with the lead screw and get a spring rate measurement. Another team member will time the process with a stopwatch.	Time in seconds	No longer than 2 minutes	Stopwatch (iPhone)	VP	Joseph	4/30/2024	4/30/2024	1-1/2 minutes to fully compress tire to the rim and get measurment	Data collection time was programmed into the electronics. After running our repeatability test we fine tuned the necessary time for the user to compress the tire and programmed it to match.
1	1 - Force Application Repeatability	Team will use device to measure a single tire's spring rate 10 times, recording each set of measurements. Perform percent difference calculations to determine variability.	Multiple spring rate curves	1 to 3% difference in measurements	Wheel/tire setup, notebook for hand calcs or spreadsheet for calculations	VP	Joseph	4/30/2024	4/30/2024	Average percent difference between measurements across all displacements was **1.5%**	Results were with old load cell. New Futek load cell should be even more precise.
2	2 - Force capability	Monitor force applied through lead screw force applicator using the load cell. Verify that the lead screw can apply the force required to fully compress the tire.	Force in lbf	Can reach 450 lbf	Wheel/tire setup, DAQ system to read load cell outputs, computer to see live readout from DAQ	SP	Luki	4/30/2024	4/30/2024	**296 lbf** to fully compress tire (bottomed out on rim)	Device was able to fully compress tire inflated to 23 psi. New limiting factor will be the smaller load cell rather than the device itself. Device can exceed 500 lbf limit of load cell.
	Number of buttons	NOT A TEST - Visually verify the design was achieved with less than 3 buttons	Numerical count	Less than 3	DAQ Subassembly of device	VP	Joseph	5/7/2024	5/7/2024	1 button 1 ON/OFF switch	It was determined that only one button was needed along with an on/off switch to acheive the desired operation.
	Size	NOT A TEST - Measure largest length, width and depth of completed device	Inches or centimeters	Max values of L: 30in W: 10in D: 8in	Tape measure or ruler	SP	Duncan	5/2/2024	5/2/2024	L: 29 in W: 18 in D: 7 in	Width was over spec due to mountain bike handlebar that was used for the force application handle.

Appendix F – Test Procedures

F33 Test Procedure for Uncertainty Analysis

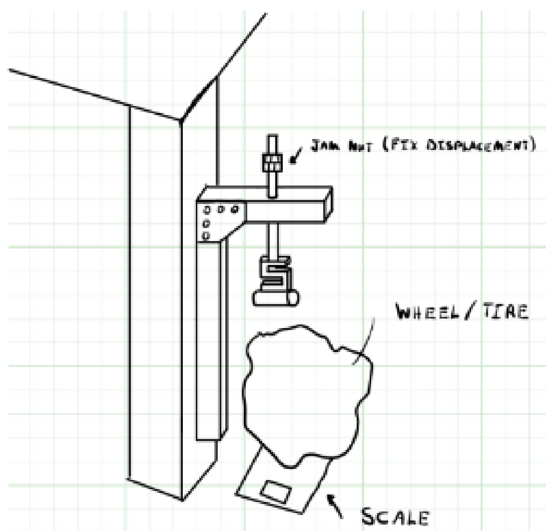
Test Name: Force Application Repeatability

Purpose: This test will be somewhat dual purpose. The main purpose of this test is to test the repeatability of the force application subsystem of the device. The team wants to ensure the force can be applied to the tire in an easy and repeatable way that will produce good results. This test will also serve as a good way to test the force capability of the force application subsystem.

Scope: This test is designed to verify the overall functionality of the force application subsystem as well as the repeatability of the data that the system yields.

Equipment:

1. Structural prototype with functioning force application subsystem
2. Analog scale
3. Wheel/tire assembly
4. Tire pump
5. Calipers
6. ¾" Wrench for jam nuts
7. C-clamps for clamping device to table leg



Hazards:

1. C-clamps fail, and device falls onto someone's foot
2. Finger pinching between tire and scale
3. Finger pinching between device and table leg

PPE Requirements: Safety glasses, closed toe shoes

Facility: Cal Poly Hangar

Procedure:

1. Analog scale placed on ground near where device will be clamped
2. Team member will weigh themselves on the analog scale 5 times
3. Other team member will record these readings to verify scale is operating
4. Wheel/tire assembly placed on analog scale
5. Analog scale is zeroed manually by team member
6. Device is C-clamped to table leg
7. Jam nuts set to initial baseline test displacement with wrench and calipers (TBD)
8. Apply force to take sample measurement
9. Apply force to tire 5 times at baseline displacement
10. Team member records readings in excel table
11. Jam nuts set to first testable displacement
12. Sample measurement taken
13. Apply force to tire 5 times
14. Team member records readings in excel table
15. Repeat Steps 11 – 14 for the 3 other displacement values

Results:

For each tested displacement, a percent difference will be calculated between the highest and lowest values. Initially up to 10% difference will be passing, above 10% is failing. Reading uncertainty will be calculated for the caliper measurements, analog scale readings, and tire pressure reading.

Tested Pressure (psi)	23				
Displacement	__(in)	__(in)	__(in)	__(in)	__(in)
Sample					
1					
2					
3					
4					
5					
Perfect Difference					
Uncertainty					
Pass/Fail					

Test Date(s): TBD

Test Results:

Filled out excel table and plots of results of each displacement test will go here.

Performed By:

Joseph Balderama, Alex Kachlakev, Luki Rosen, Duncan Wyke

Test Procedure for Size Constraints

Team: F33 Tire Spring Rate

Test Name: Size

Purpose: This test will be performed to determine whether the overall dimension(s) of the design meets the requirements specified maximum values in the design verification plan. The device must not exceed the specified dimensions in order to maintain the portability aspect of the design.

Scope: This test is targeting the assembly of the four main subsystems together. The assembly will include any fasteners or brackets that join the systems together and be evaluated connected to meet the design size criteria.

Equipment:

1. Tape measure
2. Ruler
3. Calipers
4. Writing tools (pen or pencil)
5. Paper or electronic notepad
6. Four subsystems of the device
7. 3/16 SAE inch Hex-L Key allen wrench

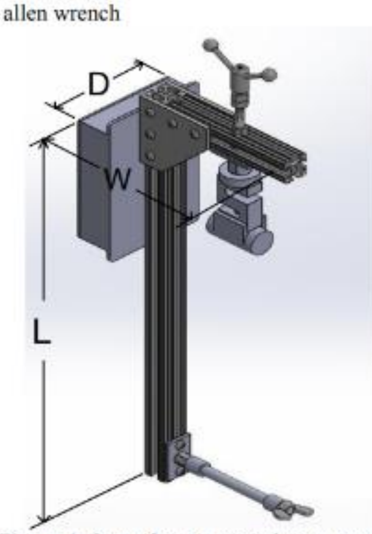


Figure 1: Setup for test procedure apparatus.

Hazards:

1. Users drop the device onto their foot or other extremity.
2. Users pinch their fingers while assembling the device.
3. Users hand slips while tightening fasteners and impact device.
4. Users drop and/or release tools/measurement devices that smack their body.

PPE Requirements:

1. Safety glasses
2. Closed toed shoes

Facility: The test will occur in the Cal Poly Aero Hangar or Bonderson (Mustang 60), where measurement tools will be available.

Procedure:

1) Verify that all users have safety glasses and closed toe shoes.
2) Ensure all measurement tools are calibrated and/or zeroed out if applicable.
3) Assemble device with necessary fasteners and brackets using allen key.
4) Attach remaining components using hand threading or inserting.
5) Choose the measurement tool of choice and use it for all measurements for consistency.
6) Hold device up right for measurement procedure.
7) Measure the device from the bottom of the long vertical member of the frame to the top of the handle attached to the lead screw and record the data in the table under the length column.
8) Measure the device from the front the short horizontal member to the front face of the electronic housing and record the data in the table under the width column.
9) Measure the device from one side of the electronic housing to the other side and/or the separation of the furthest points on the handlebar, (depending on which measurement is longer), and record the data in the table under the depth column.
10) Repeat steps 6-9 for a total of 5 trials to output more consistent measurement values for the test procedure.
11) Evaluate the tests results on a pass/fail criteria.

Results: The following table will be filled out to interpret the results.

Specifications to be met:

- Length will not exceed 30 inches.
- Width will not exceed 10 inches.
- Depth will not exceed 8 inches.

Table 1: Data table for the measurements gathered from experimental procedure.

Test no.	Length (in)	Width (in)	Depth (in)	Pass/Fail (Y/N)
1				
2				
3				
4				
5				

Test Date(s): TBD

Test Results: The filled-out table will be evaluated upon a pass or fail criteria, where the device must pass all three size constraints.

Performed By: Joseph Balderama, Luki Rosen, Alex Kachlakev, and Duncan Wyke

F33 Test Procedure for Force Capability

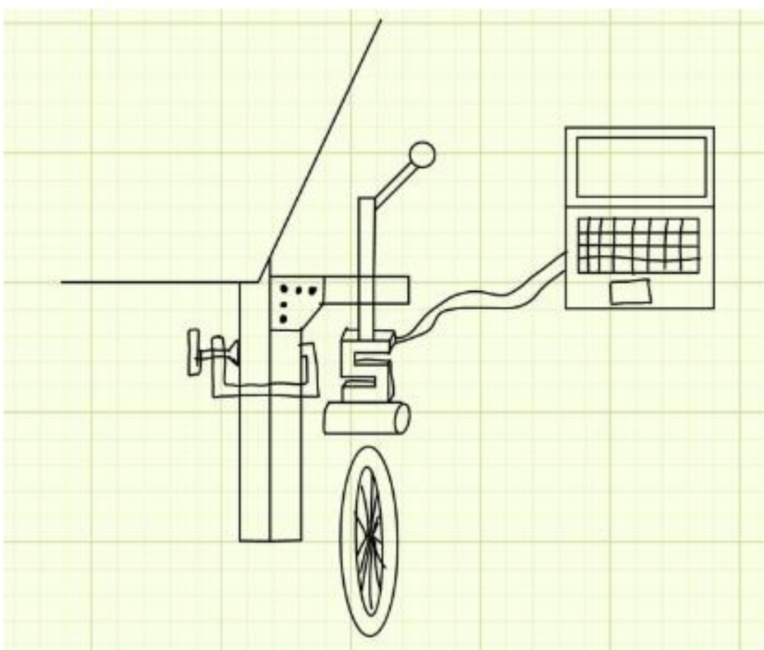
Test Name: Force Capability

Purpose: This test will be performed to determine the force capability of the force application subsystem of the device. The device needs to be able to apply enough force to fully compress the tire to the rim of the wheel, potentially up to 450 lbs.

Scope: This test is designed to verify the force capability of the device which will inform the team of any potential redesigning needed. The jam nuts will be set high enough to allow for max force to be achieved.

Equipment:

1. Verification prototype with functioning force application subsystem and load cell
2. Wheel/tire assembly
3. Tire pump
4. Calipers
5. ¾" Wrench for jam nuts
6. C-clamps
7. Laptop to read load cell readings
8. Arduino uno
9. Load cell amplifier



Hazards:

1. Device falls onto someone's foot
2. Finger pinching between tire and tire contactor
3. Finger pinching between device force application handle

PPE Requirements: Safety glasses, closed toe shoes

Facility: Cal Poly Hangar

Procedure:

1. Device gets clamped to table leg
2. Laptop hooked up to load cell
3. Wheel/tire assembly placed under tire contactor by team member
4. A few sample force application readings will be taken to ensure load cell is reading correctly
5. Ensure the laptop is connected and getting readings
6. Team member holds wheel/tire assembly in place for force application
7. Other team member applies force to tire by advancing the lead screw
8. Lead screw advanced until tire is almost bottomed out on the wheel
9. Reading monitored by team member & recorded in excel table
10. Force value should not exceed 450lbs and will tell team member to stop advancing lead screw if so
11. Repeat 9 more times for 10 total data points

Results:

For each force application, the value will be recorded in the table below. Reading uncertainty of the load cell value will be accounted for as well. A Pass/Fail criteria will be applied to this test based on the devices ability to fully compress the tire.

Tire Pressure (psi)	23
Run	Force (lb)
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	

Test Date(s): TBD

Test Results:

Filled out excel table and plots of results for each run will go here.

Performed By:

Joseph Balderama, Alex Kachlakev, Luki Rosen, Duncan Wyke