

Physical Function Testing Apparatus for Monkeys

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Abstract

Rhesus monkeys have long been used as models for scientific research due to their similar anatomy to humans [1]. One similarity utilized in research is their motor function. Dr. Colman's research on muscle retention with varying long-term diets proves that health benefits from caloric restriction throughout the aging process. Research has been done to compare basic motor function to neurological stimuli [2] and to evaluate basic grip strength [Bury]; however current methods for testing the threshold of muscle loss do not provide quantitative data on physical function. Large muscle groups, such as those on the arms and legs, are more effective to test, as they are most often the muscle groups that are biopsied by researchers. Therefore, there is a need for an apparatus capable of evaluating these major muscle groups' maximum strengths in a safe and effective way. A prototype that has the capability of testing the maximum strength of the subject's entire lower body has been fabricated, but improvements are necessary before the device can be used on any animal participants. The design will be fabricated and human-tested before being implemented in an experimental group of Rhesus monkeys.

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Introduction

Competing Designs

In assessing monkey strength, numerous competing devices follow two common practices: a reward, often in the form of food, is provided upon completion of a specific motion against a certain resistance, and resistance behind that motion is increased per trial to reach maximum strength. Motions utilized by these devices typically include gripping and pulling a weighted-sled. Once a maximum force is observed, it is divided by the monkey's weight to normalize measurements among separate individuals. While applicable to and optimal for many studies, these devices are not ideal in light of Dr. Colman's preferences for this project.

The first competing design, implemented by Bury SD et al. in a study to understand grip-behavior by normal and neurologically impaired squirrel monkeys, is a small force transducer within a bisected aluminum cylinder. As a monkey squeezes the cylinder, surfaces of the two aluminum halves contact each other and allow the force transducer to collect data. The grip-cylinder is mounted to a three-axis, sliding frame by a universal joint, which prevents normal and moment forces imparted by body-parts other than the hands from altering force data. Monkeys are provided a reward upon each squeeze at a specified force. This design is advantageous in its simplicity and intuitiveness to the monkeys. However, it is not ideal for Dr. Colman's research, which aims to assess leg strength rather than forearm strength [1].

The second competing design, implemented by Bozek et al. in a study to understand the evolutionary divergence of human, chimpanzee, and macaque monkey strength, is a sled with adjustable weight that is dragged against an even surface by a rope. Between the sled and rope is a linear force gauge, which measures the maximum force produced while pulling the sled during a specific trial. Using its entire body, a chimpanzee or macaque monkey pulls the sled towards its enclosure to receive an attached reward. This design is advantageous in its simplicity, intuitive use, and cost-effectiveness. However, it does not encourage a standard motion to produce a force -- allowing for many pulling strategies -- and therefore does not produce accurate data. It is not ideal for this project in that it does not isolate leg movement [2].

Problem Statement

In studying the muscular effects of calorie-restricting diets and their impact on aging, Rhesus monkeys must be assessed for muscle strength. Current methods simply

accurately measure muscle mass, which only loosely correlates with muscular function. The Wisconsin National Primate Research Center (WNPRC) requires an apparatus that intuitively allows monkeys to complete a range of motion under resistance and delivers quantitative feedback on leg strength. The goal of this project is to develop a safe, durable, and easily sanitizable device that meets this goal.

Background

Rhesus Monkey Physiology

Due to their similar anatomy to humans, data from Rhesus macaque medical studies can be extrapolated to human health [3]. Rhesus macaques are quadrupedal with opposable toes, enabling them to grip with their feet as well as hands. This increased range of motion provides more possibilities for muscle movements, but offers more challenges in finding ways to isolate the muscle groups. Despite their small size, averaging around 15 pounds, their high strength-to-weight ratio allows them to produce surprisingly large forces [3]. To obtain muscle mass data, biopsies are often taken from the quadriceps because of the muscle group's large amount of tissue and quick recovery time. According to Dr. Colman, scientists choose to avoid the core when taking biopsies because this would have more complications and further inhibit the animal's recovery.

Animal Testing Regulation

The majority of medical advances have been founded on animal research. This trend lessens the risk of transitioning new practices to human application. Discoveries ranging from vaccine breakthroughs to behavioral disorders are outcomes of non-human primate tests [4]. To ensure humane research and optimal results, animal-testing protocols are observed. Conditions corresponding to the transfer of animals, materials used, husbandry and colony management, pain experience, surgery, sanitation and safety, among others, are all regulated to minimize unnatural stressors to adaptable levels [5].

The Wisconsin National Primate Research Center exhibits high standards in humane animal care. A device measuring primate strength must adhere to its policies.

The Animal Welfare Act (AWA) and Health Research Extension Act determine primate maintenance protocol [5]. Safety hazards such as exposed wires, sharp edges, and breakable parts pose safety risks to animals and must be prevented.

Client Information

Dr. Colman's research at the Wisconsin National Primate Research Center concentrates on variation in muscular function and chronic disease rates due to caloric restriction. With age comes higher susceptibility to chronic diseases rooted in metabolic abnormalities. Dr. Colman's research indicates that caloric restriction may stave off these diseases, including cancer, obesity, and diabetes [6]. With aging, rhesus monkeys and humans experience natural muscle loss, a condition called sarcopenia [7]. Although incapable of full prevention, long-term dietary alterations can slow sarcopenia. Testing this theory on rhesus monkeys may someday provide a valid human treatment.

Motivation

While muscle mass data is accurately obtainable through methods such as x-ray imaging, aging studies, lean body mass calculations, and quadricep analyses during necropsies [6], physical function and strength of individual muscle groups cannot yet be quantitatively measured. A device to generate these measurements would provide the missing link for Dr. Colman's research in examining the long-term effects of caloric reduction on muscle composition.

Design Specifications

An apparatus that tests rhesus monkey strength must be fully functional, safe, and durable before animal exposure. Due to strict animal-testing regulations, the device must be safe in all possible scenarios of usage. There cannot be any exposed wires or sharp edges and animal escape must be made impossible during setup and testing. The device must be easily sanitized and rust resistant. It must be weighted and shaped so that one person is able to attach the device to varying cage designs. Lastly, a reward system must be in place to positively reinforce the animal. This system, coupled with

training that the client will provide, should ensure maximum effort from the monkey and the most accurate results. The apparatus must be intuitive enough to require minimal animal training (Appendix A).

Design

Considered Designs

Stationary Deadlift

The first considered design consisted of a box that has a force gauge on the inside that is attached to a handle, which is located on top. The apparatus would be attached to the bottom of the cage. While the device is being set up, the monkey would need to be moved to a temporary cage. This device would test the monkey's strength by having the monkey pull upwards on the handle. In order to test maximum strength, the minimum force threshold required to get a reward would be gradually increased. This would motivate the monkey to pull with maximum strength. Due to the motion of movement by the monkey, the apparatus would test both upper and lower body strength. Although the primary focus is lower body, we believe that if the minimum forces required for a reward were great enough, the monkey would incorporate its lower body as much as possible. This would still allow for the testing of the maximum strength of the lower body.

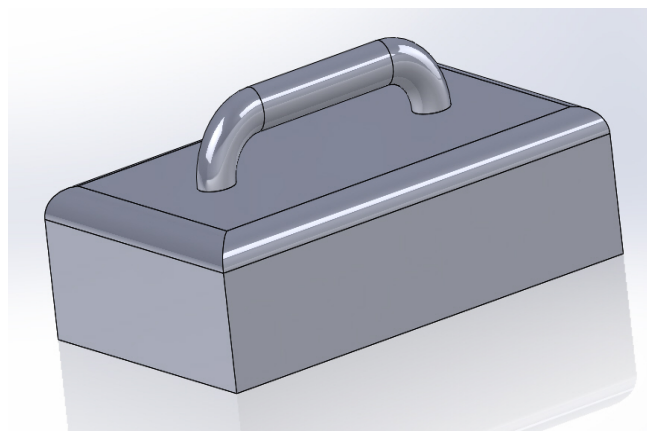


Figure 1: SolidWorks of the Stationary Deadlift design.

Push Plate

A second design would utilize a feature of the cage called a squeeze plate. The squeeze plate involves a plate located at the back of the cage, which is attached to bars that come out past the front of the cage. When the bars are pulled outwards, the squeeze plate moves towards the front of the cage. This forces the monkey towards the front of the cage as well, and allows the researcher to more easily take various samples from the monkey. For this design, the squeeze plate would be pulled up towards the front of the cage and the monkey would be on the bottom of the cage with its back against the squeeze plate. The monkey would then place its hands on handles on either side, and use its legs to push on a plate that contains a force gauge. This design would be able to test the monkey's legs independently, as the handles would contain sensors that need to be activated by the monkey's hands in order to activate the push plate. Like the "Stationary Deadlift" design, the monkey would need to continually need to increase its force on the plate in order to continue to obtain a reward. In this manner, a maximum strength of the monkey could be obtained. This apparatus would be attached to both the front and bottom of the cage while the monkey was in a temporary cage.

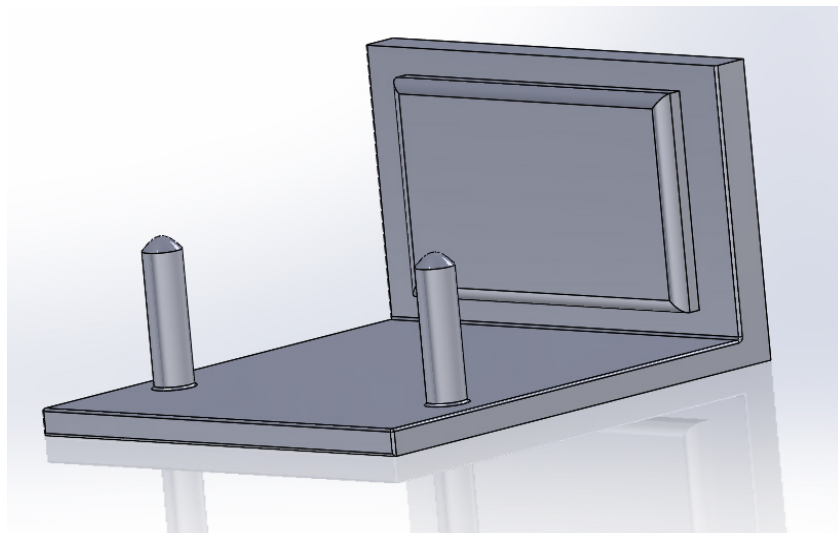


Figure 2: SolidWorks image of the Push Plate design.

Sliding Cage

Another design considered involved attaching force gauges to the bars connected to the squeeze plate. Like the "Push Plate" design, the squeeze plate would be brought towards the front of the cage. The force gauges would then be attached to

the bars, which are now extended past the front of the cage. These gauges would prevent the monkey from pushing the squeeze plate back, while measuring the force placed upon the squeeze plate as the monkey pushes on it. The monkey would push back against the squeeze plate with their legs, as it is natural behavior to do so according to the client. This natural behavior would be reinforced with a reward system similar to the other designs, allowing the apparatus to acquire the maximum strength of the monkey's legs.

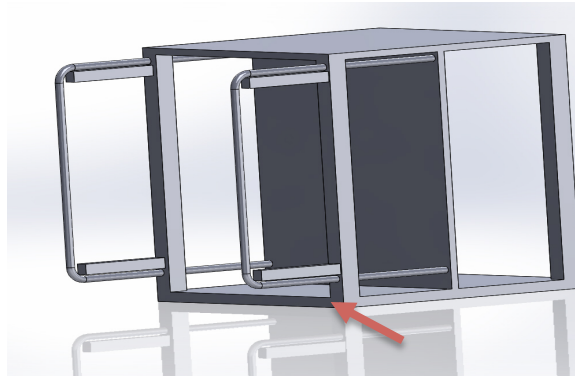


Figure 3: SolidWorks design of a cage including the Sliding Cage device that is indicated by the arrow. Identical devices appear in each corner. Also shown is the cage's squeeze plate.

Design Matrix

The designs were critiqued on seven categories in a design matrix. The design with the best outcome in the areas of safety, durability, difficulty of training, ease of fabrication, ease of use for the researcher, measurement accuracy, and cost was chosen as the final design that we will be moving forward with.

	Push Plate		Stationary Deadlift		Sliding Cage	
Safety (25)	4	20	4	20	5	25
Durability (20)	5	20	4	16	5	20
Difficulty of Training (Subject) (15)	3	9	4	12	5	15

Ease of Fabrication (15)	3	9	3	9	4	12
Ease of Use (Researcher) (10)	4	8	3	6	5	10
Measurement Accuracy (10)	5	10	3	6	4	8
Cost (5)	5	5	4	4	3	3
Total (100)		81		73		93

Figure 4: Shown is the design matrix that compares each of the preliminary designs. Each criterion in the left column was given a percentage indicating its importance in the overall rating. The number on the left under each preliminary design is the rating that was awarded in each category. The product of this number and the percentage is in the right side under each design. These were then totaled and compared to find that the Sliding Cage device was the best option.

Safety

Safety was the most important aspect of this design because the monkeys will manipulate the device however possible. Due to this it must be completely safe and not cause any harm to the animals. The Stationary Deadlift design was extremely safe since it has little movement and all parts of the device are enclosed inside the shell. The Push Plate design was fairly safe although one area that could harm the monkey would be the small handles. The Sliding Cage design was very safe due to the fact that it is not even placed in the cage and does not make contact with the monkeys. This is why it received a 5/5 while the other designs received 4/5.

Durability

Durability was very important to this project because the client's research lasts years and she must be able to test the same muscle force in the same way over her experiments. The Push Plate design was very durable because it uses a very small amount of movement in a set pathway to test the force. The Stationary Deadlift design was slightly less durable because the pressure on the sensor would have no resistance to support it, and the sensor would be at risk of being damaged over time with repeated use. The Sliding Cage design was very durable because the force exerted by the monkeys would be distributed between four sensors placed on the corners of the cage.

Due to the distribution of forces in the Push Plate and Sliding Cage designs they both received 5/5 in durability while the Stationary Deadlift only received a 4/5.

Difficulty of Training - Subject

The difficulty of training was defined as the difficulty of teaching the subject how to use the design as intended. This category was seen as relatively important, as an important consideration was the length of time it would take to train the monkey to use the device. All designs would incorporate motivation through positive feedback received through food. The difference between the designs involves the complexity of movement that the monkey has to perform. Based on this, the Stationary Deadlift design scored high with a 4/5, as the motion is a basic pulling motion, something that should be easy to train. The Push Plate was rated slightly lower at 3/5, as this design incorporated a more complex movement that involved the monkey using both its arms and legs. The Sliding Cage design received the highest score with a 5/5 because the monkeys have already used the squeeze plate feature of their cages before, and naturally push back.

Ease of Fabrication

Ease of fabrication was an important consideration, as multiple iterations may have to be made in the future. Additionally, if the fabrication process was simple, it would be easier to make modifications if necessary. The Push Plate and Stationary Deadlift were rated 3/5 due to the need to make enclosed cases for inside the cage as well as adjusting attachment features. The Sliding Cage Design was rated a 4/5 because the monkeys don't make direct contact with the devices, so they can have less complex casings and attachment systems.

Ease of Use - Researcher

Ease of use was relatively important because for any of the designs to be feasible, the researcher must be able to install the device and motivate the monkey to use it properly. After installation, the Push Plate is the most easily used device because the researcher can use the back wall of the cage to pull the monkey towards the device and insure they use it, so it earned a 4/5. The Stationary Deadlift required the monkey to choose to use it instead of being prompted to use it, so it only earned a 3/5. The Sliding Cage design earned a 5/5 because it utilizes the squeeze plate to insure use, just as the Push Plate does. However, the Sliding Cage design does not require the researcher to take the monkey out of the cage to install the device, which must be done in either of the other designs.

Accuracy of Measurement

Accuracy of Measurement was important, as without accurate measurement of muscle force, the device does not perform its purpose. The Push Plate design would perform this the best and receives a 5/5 because it isolates the leg muscles. Also, since the design has handles, which occupy the hands, it has the lowest chance for the monkey to cheat the test. The Stationary Deadlift receives the lowest score at 3/5 because the monkey has multiple ways to cheat. They can use their body weight to lean back and create a force, or they can use other muscle groups such as their arms, back, and core to lift the handle instead of only their legs. The Sliding Cage design received a 4/5 because the monkey can cheat by using their arms. Besides this there could also be material bending on the cage wall distributing force away from the sensors.

Cost

Cost was weighted as one of the least important criteria because there was no strict limit on the budget as long as the design was functional and reasonably priced. However, this category was included to guarantee that the designs were cost effective. Since every design incorporated roughly the same materials, mainly stainless steel, the variations in scores were due to the amount of material needed. The Push Plate and Stationary Deadlift were rated relatively high because they only require one force gauge, which is the most expensive aspect of the designs. The Sliding Cage design requires four separate force gauges to compile the full force exerted by the monkeys, so it scored the lowest with only a 3/5.

Proposed Final Design

Based on the design matrix the Sliding Cage design was the clear choice to move forward. It scored well in all categories except for cost, which the client agrees is the least important criteria. It achieved the best score in safety, durability, difficulty of training, ease of fabrication, and ease of use for the researcher. The ability to implement the design without the monkey having to be removed from the cage or being in physical contact with the device were the design characteristics that made the Sliding Cage design the best choice moving forward.

Fabrication

Materials

A detailed list of materials used and cost can be found in section E of the Appendix. Hollow stainless steel tubing was used for clamping device since it is the safest material for the animals. Seven $\frac{1}{8}$ " and two $\frac{3}{16}$ " screws were used to attach various pieces of the device. Closed cell polyethylene foam was used as padding between the clamp and the bar. This was chosen due to its ability to withstand high frictional stress, and that it does not absorb water. This allows it to be sanitized with the stainless steel. The circuit included a 50 kg load cell disc, HX711 op amp, an Arduino Red Board, and a computer. The load cell and op amp allowed force to be converted to resistance, which then could be read by the Arduino. The computer was used to program the Arduino and as a power source.

Methods

Clamp

A SolidWorks image and drawing can be found in Appendix E. The clamp was fabricated from square stainless steel hollow tubing provided by the Wisconsin National Primate Research Center. All fabrication was done in the UW-Madison Student Shop. The steel tube was first cut to a length of 10", and then cut in half lengthwise so that there were two U-shaped halves. Four $\frac{1}{8}$ " holes were drilled into each half, with two holes being drilled at a distance 2" from each end and 0.4" from each side. Screws were put through these holes and tightened by nuts, allowing the device to be clamped around the bar. To attach the load cell, an L-shaped piece was cut from the stainless steel. This piece was 0.75" on the bottom, and 1.25" in height. On the bottom, two $\frac{3}{16}$ " holes were drilled 0.5" from each side. Complementary holes were drilled in one of the U-shaped pieces, 1" from the end. Three $\frac{1}{8}$ " holes were drilled into the other wall of the L-piece, which matched up with holes on the load cell. Screws were then placed through each set of holes, allowing the load cell to be attached to the clamp. All sharp edges of the stainless steel were sanded down to avoid harm to any user. Strips of polyethylene were adhered to the inside of each half of the clamp using the adhesive backing that was present on the material.

Circuit

The circuit was constructed using supplies bought from the Sparkfun website. The circuit consisted of a 50 kg load cell disc, which was attached to the front of the connecting bar by screws. The load cell was soldered to an HX711 op amp by four wires (V_{cc} , GND, S+, S-), where V_{cc} was the 5 V input, GND was the ground, and S+ and S- controlled the signal from the load cell. The HX711 op amp is a Wheatstone bridge op amp that contains two series-parallel arrangements of resistors and is used to measure unknown resistance values [9]. The op amp was further connected to an Arduino Red Board, which supplied 5 V to the op amp and further the load cell in order for it to run. The Red Board also grounded the entire circuit. A laptop was connected to the Red Board and used as a voltage source.

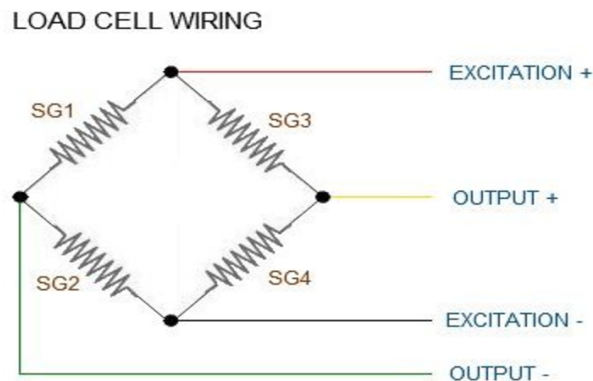


Figure 5: Circuit information for the HX711 op amp device used. The HX711 op amp is a wheatstone bridge op amp consisting of two series-parallel resistors. It is used to solve for an unknown resistance [8].

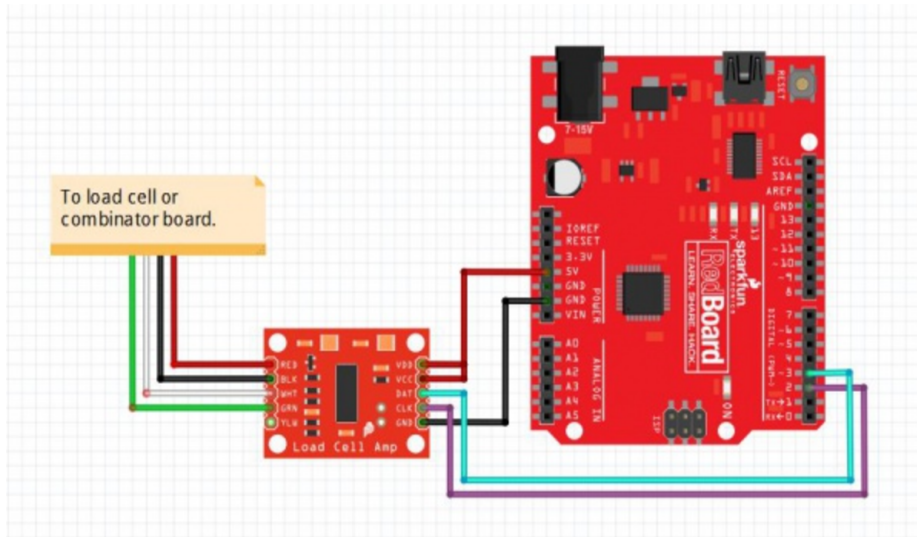


Figure 6: Overall layout of our circuitry. The load cell was connected to the HX711 op amp, which was further connected to our Red Board [8].

Code

The Arduino code used can be found in Appendix C. The first portion of the code was used to calibrate the device and determine the calibration factor. The calibration factor could be adjusted in real time until the appropriate loads were read. From here, the calibration value was moved to the load testing code, which was used to analyze unknown loads in our testing on the series of loads and also the cage load.

Final Prototype



Figure 7: Above is an image of the final prototype facing the cage. The polyethylene foam can be seen forming to the squeeze plate bar, increasing frictional forces and keeping the device in place.



Figure 8: Shown is a side image of the attached final prototype. In this image the clamping mechanism can be seen. The four screws on the surface protrude out the bottom of the device and are held in place by firmly tightened bolts. On the cage side of this image the load cell can be seen attached to the device.



Figure 9: Shown is another image of the final prototype facing the cage from further away. This image shows the relative size of the device relative to the cage. Only the bottom right quarter of the cage is pictured.



Figure 10: This image displays the testing setup of the device. The load cell's black wire is pictured running from the device to the Arduino circuitry on the desk. The circuitry is then connected to the computer, which is running the testing program.

Testing

Calibration Testing

In order to ensure the load cell would be able to respond to a load accurately, it first had to be calibrated. Using a series of known weights from 5 to 15 pounds, the device was continually adjusted using the calibration code (Appendix C) to determine an appropriate calibration value. Once the calibration value was determined, the device was checked again to ensure it was working properly.

Load Cell Reading Over Time Testing

The second test run was to analyze the load cell's ability to read different forces over a time period. The load cell was placed and pushed up against a scale to determine the load it was experiencing. The device was subjected to a series of forces, starting with

5 pounds and continually increased by 5-pound increments until 25 pounds. The data was graphed over time and can be found in the results (Figure 11).

Clamp Testing

The third test analyzed the device's ability to connect to the cage at all four corners. Since each corner of the cage has a different geometry, the device must have the adjustability to fit and grip to each of the bars. The device was attached at each corner successfully; however, the amount of polyethylene foam had to be adjusted to ensure a stronger grip against the narrower bars. Regardless, the device can clamp to each corner orientation with a sufficient polyethylene foam matrix.

Device Testing Against Cage

The final test analyzed the device's ability to read forces while clamped to one corner of the cage. The device was clamped in the bottom right corner about one of the larger geometries of the cage. Using a scale, a known force was applied to the squeeze plate of the cage. A load was applied starting at 10 pounds, increasing by 5 pounds increments until 40 pounds. This force was read by the load cell, which was isolated and pinned against the exterior of the cage. The data was graphed versus the expected load and can be found in the results (Figure 12).

Results

The load cell test over a time period showed that the load cell does in fact accurately read isolated forces at a high precision level. The device was able to respond to the range of loads effectively, and each load also remained independent from the others. The device was not tested over its entire load range (up to 50 kg) because these forces were not plausible on the scale that was used. However, this data shows promise that the load cell would accurately read the entire load range it has. The image below (Figure 11) shows the graphical results to the experiment.

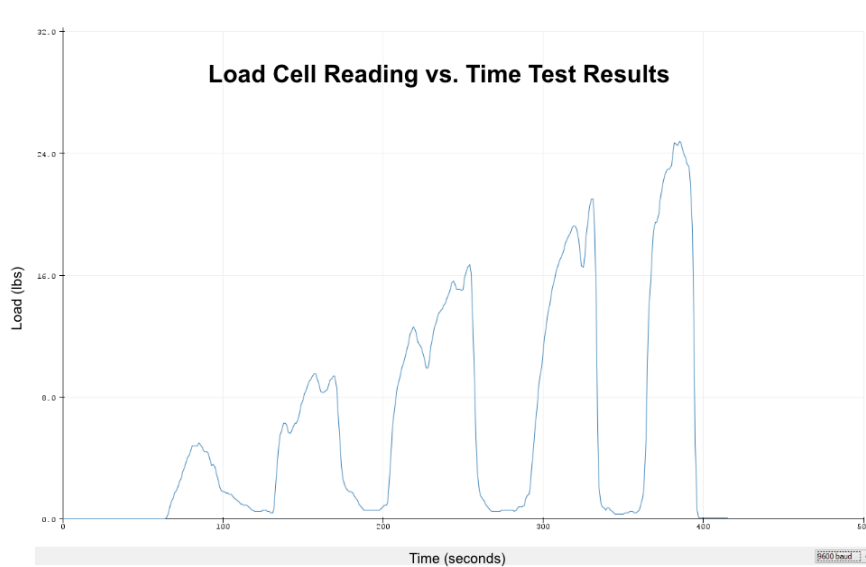


Figure 11: The graph above represents the force read by the force sensory over time. The peaks are not clear because the force could not be maintained due to human error. The tester pushed against a scale beginning with 5 pounds and incrementing by 5 pounds. The tester could not maintain the exact pressure, which is why the fluctuations occur.

When clamped to the corner of the cage, the device continued to show some promise of working accurately. In the image below (Figure 12), the observed data from the load cell is graphed against the expected load values. Using a statistical test that compares the slopes of two samples (Figure 13), the slopes were determined to be statistically significant from one another, with a p-value = 0.0245, where alpha = 0.05. However, in considering only the data up to the 25 pound cut-off, the two slopes were determined to be statistically insignificant with a p-value = 0.147, where alpha = 0.05. This means that the slope of the observed data accurately portrays the expected results for loads less than 25 pounds. However, when the load data over 25 pounds is included, the load cell data is no longer accurate.

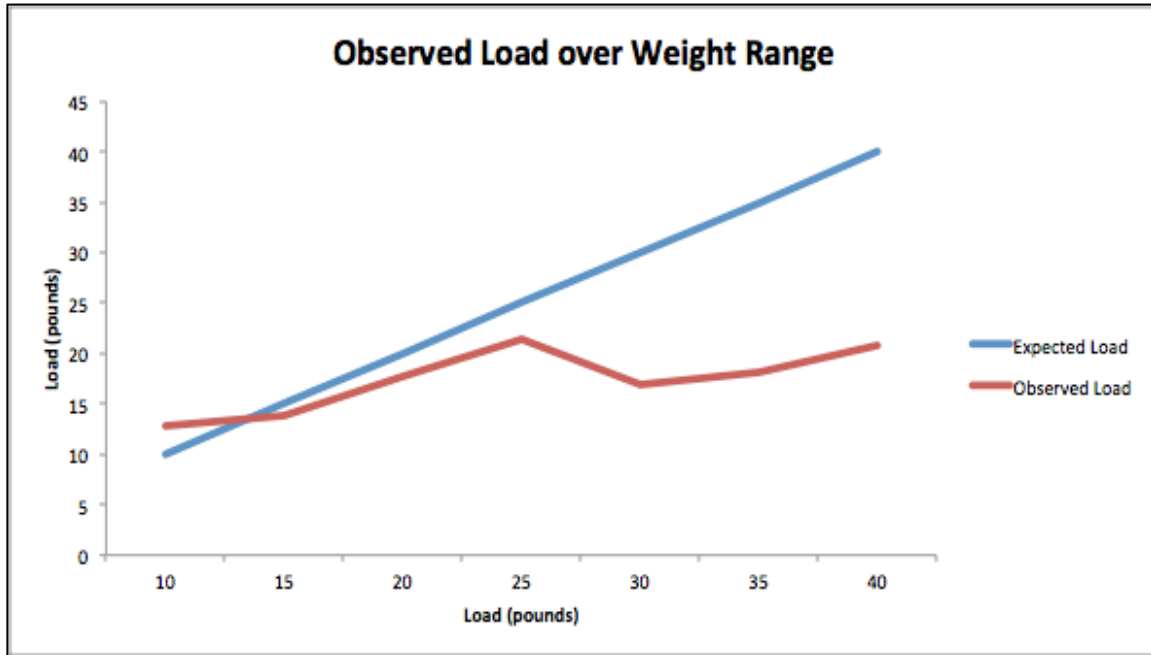


Figure 12: The graph above compares the expected load read by the load cell to the observed load from pushing the back of the cage at varying forces beginning with 10 pounds and increasing by 5 pounds. The x-axis represents the force shown on the scale; the y-axis measures the force read by the force sensor.

$H_0: \beta_1 = \beta_2$ i.e. $\beta_1 - \beta_2 = 0$
 $H_1: \beta_1 \neq \beta_2$ i.e. $\beta_1 - \beta_2 \neq 0$

The test statistic is

$$t = \frac{b_1 - b_2}{\sqrt{s_{b_1}^2 + s_{b_2}^2}} \sim T(n_1 + n_2 - 4)$$

If the null hypothesis is true then

$$\beta_1 - \beta_2 \sim N(0, s_{\beta_1 - \beta_2})$$

where

$$s_{\beta_1 - \beta_2} = \sqrt{s_{b_1}^2 + s_{b_2}^2}$$

Figure 13: The image above shows the statistical test used to determine if there was significance between the expected load readings and the actual load readings. The t-value calculated was used in a two-sided t-test to determine the p-value for the statistical test [10].

Discussion

The clamp of the device was fairly simple to fabricate. This process took less than six hours to complete and was done by only using saws and press drills. Although this led to minor inconsistencies between our design dimensions and our final prototype, the device was assembled with ease. In future prototypes, using a mill for the majority of the fabrication would help to meet exact dimensions. Building the circuit was also simple since a diagram was provided on the Sparkfun website as seen in Figure 6. To make the circuit more stable, wires that were attached to the op amp were soldered. The code was also available on the Sparkfun website, making this process easier as well. One issue that we ran into with the code was the requirement that a Windows processor must be used. Multiple times files were transferred from a Macintosh computer to a Windows computer, only to be corrupted; however, we eventually were able to implement the code. The code had a process where it could be calibrated based on a predetermined calibration value already implemented in the code. There was a separate portion of code solely used to calibrate the device (Appendix C). This code allowed for the calibration value to be adjusted in real time until the device was accurately reading the proper loads. From here, the calibration value was placed in the testing code in order to produce an accurate response from the load cell during testing (Appendix C).

Results from our tests show that our device was able to measure forces correctly within a range. Calibration of the device was effective and easy to accomplish. Since calibration could be done in real time, our load cell was relatively accurate. This is seen in Figure 11, as a person was able to accurately increase the force read by the load cell in increments close to 5 lbs. Testing done directly on the cage however, less successful results. During this test, shown in Figure 12, the device was accurately able to measure the expected force up to 25 lbs.; however, above 25 lbs. this accuracy decreased significantly. This error is most likely due to a moment being created since the device is pinning only one of the four bars. A moment would create multiple points of contact instead of the load cell being the only one. These points of contact would have forces acting upon them, rather than all of the force being directed through the load cell. This error would be able to be corrected by having devices on each corner, leading to all forces being applied only to the load cells.

When implemented, the device could be attached to either of the bottom bars. However, the device could not be attached to the top bars due to the different geometries between the top and bottom bars. The bottom bars had ridges (Figures 7-10) while the top bars did not have these. The device could have been attached to the top bars; however, multiple layers of polyethylene would need to be attached on top of the single

one that we already had. We thought that this would waste materials and increase cost unnecessarily, so the device was only tested on the bottom two bars.

Ethical Considerations

The primary ethical consideration with regards to this research is the comfort and safety of the primates. Since this design utilizes the squeeze plate, the monkeys will be subjected to tight spaces during the course of the data collection. Due to this physical restriction, the device should not be used for extended periods of time. The device should also be placed with a reasonable amount of distance between the squeeze plate and the monkey to avoid harming or severely discomforting the animal.

Conclusion

The lack of an existing device to measure the strength of Rhesus monkeys motivates the development of a safe and accurate method to gauge the maximum muscle force that adult Rhesus monkeys are capable of generating. To accomplish this goal, we developed a clamping device to attach to the extended bars of the squeeze plate feature on the monkeys' current cages. This design utilized polyethylene gripping to generate enough friction to resist the forces generated against the squeeze plate. The device registered these forces using a load cell as the only contact point to the cage so that as the monkeys push back on the plate the load cell registers the force. Through our testing of one device on the lower right bar of the squeeze plate we found our design to be relatively accurate from 5 lbs. of force up to 25 lbs. of force. The device's failure at 25 lbs. seemed to be caused by the moments generated due to only one of the bars being pinned against the cage. This can be fixed by fabricating four devices to register the forces on each of the bars. By pinning all four of the bars the moments will be reduced and the forces generated at each of the load cells will decrease allowing for greater total forces to be generated against the squeeze plate and more accurate testing to be completed.

Future Work

For the design to become more effective and efficient, it must be made smaller and lighter. This means less space between the device's clamp mechanism and the squeeze plate's extended bar. By reducing the unnecessary material, the induced moment will decrease allowing the squeeze plate to slide smoothly. This serves to isolate the monkey's force better into the load cell by reducing the amount of force lost to friction. An even smaller design must be created for the top two bars of the squeeze plate due to the significant decrease in vertical length of these bars. The new designs should simplify the clamping mechanism of the device. A hinge or similar design would greatly increase the ease of use for the researcher. A containment system for the electronics must be incorporated. After all design adjustments are completed, four devices must be fabricated so that the devices can be effectively tested. Fabricating all four devices instead of one will remove the testing error generated by the moment about the one pinned bar.

The code should eventually include a threshold system for increasing force goals. To accomplish this a Boolean loop system should be used with a recommended increase of 2.5 lbs. per attempt. This simplifies and aids the training process for the researcher.

With regards to electronics, a wireless adapter for the Arduino should be purchased and connected so that all four devices can be connected wirelessly to each other and to the computer testing code. This increases animal safety as well as ease of setup for the researchers. Also, the automatic food delivery system that the Wisconsin National Primate Center currently possess should be evaluated to determine if it can be successfully linked with the system to reward the primates for reaching the implemented thresholds.

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Appendix

A. Product Design Specifications

Problem Statement:

In studying the effects of diet on the macaque monkey, muscle function and strength give important data to the aging of the test subjects. Currently, only muscle mass can be measured; however, information on the animal's' muscle strength lacks. An apparatus to motivate the monkeys to test their strength, exercise their upper and lower body, and give feedback, isn't available in the primate center on the UW campus. The goal of this project is to develop a method for testing the physical function of the hind and forelimbs of a macaque monkey that will be durable, able to be sanitized, and safe for the animals.

Client Requirements:

- 1) The device must be able to measure the strength of a rhesus monkey.
- 2) The device must be sanitizable.
- 3) The device must not be harmful to the monkey.
- 4) The device must be durable enough to withstand long-term abuse from a monkey.
- 5) The device must be resistant to rust.
- 6) The device must be able to be operated by a monkey after training.
- 7) The device must be able to give feedback to the client in real time.
- 8) The device must be able to measure the strength of the monkey's arms and legs separately.
- 9) The device must be able to be moved by a single person.
- 10) The device must have a way to reward the monkey with food.

Physical and Operational Characteristics:

a. Performance Requirements:

The physical testing apparatus for rhesus monkeys should be wear-and-tear resistant with long-term durability. The apparatus must be able to test rhesus monkey upper body and lower body strength separately, while providing feedback to the user. The rhesus monkeys are very strong, so the device must be able to withstand large forces from the monkeys.

b. Safety:

The device should meet all of the regulations for animal testing established by the Institutional Animal Care and Use Committee (IACUC). The device cannot harm the animals in any way, and we must be careful to design a device that is still safe even if used incorrectly. The device also must be made using a metal that cannot rust, likely stainless steel.

c. Accuracy and Reliability:

The device must be able to accurately and reliably relay data to the client on the strength of the animals. Ideally, the device returns leg strength and arm strength as two separate sets of data.

d. Life in Service:

The client did not give any specific description into life in service; however, the device will be used several times a day and should be able to last at least a year. The device will be under constant stress while in use, so it must be able to withstand high forces from the animals.

e. Shelf Life:

The device should be able to maintain the wear and tear damage while in use with the monkeys. The client stressed the strength of the monkeys and their ability to break devices easily.

f. Operating Environment:

The device will primarily be used in the cages that the rhesus monkeys are currently kept in. As a result, the biggest factor of the operation is the monkeys themselves. The device also must remain rust free over time.

g. *Ergonomics:*

The testing apparatus must be able to withstand the full strength of the monkeys. It must be easy to use for the monkeys and motivate them to use their full strength.

h. *Size:*

The product should be able to work on different sized cages. It must be detachable so that it can be fully sterilized. It should be portable enough to move from one cage to another. It should have a maximum weight of 40lbs.

i. *Power Source:*

The product can be outlet or battery powered.

j. *Weight:*

The strength testing device should not exceed 40lbs.

k. *Materials:*

All parts that are open to the monkeys should be made from metal or plexiglass so the monkeys can not destroy the equipment or hurt themselves with parts. The apparatus must be rust resistant too.

l. *Aesthetics, Appearance, and Finish:*

This product should have no sharp corners or edges that the monkeys could injure themselves on. It should be smooth enough that the monkeys cannot grab and destroy it. It must be rust resistant.

Production Characteristics:

a. *Quantity:*

The product may be produced on a larger scale, but a working prototype must be created first.

b. *Target Product Cost:*

The current product cost is \$500.

Miscellaneous:

a. *Standard and Specification:*

The strength testing apparatus must be able to gauge force produced by macaque monkeys during specific forelimb and hind limb movements and export readings to a data collection interface. It must be attached to and functioned within monkey cages, easily detached and transported, resistant to animal-abuse, dishwasher-safe, and operated without mechanical, electrical, chemical, or biological hazards to the animals. Properties and usage of the device must fall under AWA (Animal Welfare Act) regulations.

b. Patient-Related Concerns:

The client’s most significant concern is the safety of the device, as aforementioned. In their perspective, the greatest challenge will be creating an apparatus that the monkeys will use properly and consistently. Preferences include minimal requirement of animal and human training to use, reinforcing monkey compliance with an automated reward system, not using physical restraints, and using washable, corrosion and oxidation-resistant materials (such as plexiglass and stainless steel). The client is in favor of operating the device in environments familiar to the monkeys, such as individual cages, to maximize the subjects’ comfortability.

c. Competition:

Several monkey-strength testing devices built for individual studies exist. Each mechanism is used with increasing resistance over trial number, and supplies a reward after each successful trial as positive reinforcement. For example, a device utilized by Katarzyna Bozek et al. consists of a sliding shelf attached to a handle on one side, and suspended adjustable weights on the other. Sufficient displacement of the shelf brings food within the subject’s reach. Another example is a device utilized by Bury SD et al. that measures grip strength through the squeezing of two halves of an aluminum cylinder against an internal force transducer. If sufficient force is provided, food is dispensed as a reward.

d. Customer:

The client is Dr. Ricki Colman, PhD, an expert on primate aging, caloric restriction, and primate models as well as an associate scientist at the Wisconsin National Primate Research Center.

Description	Supplier	Part/Model #	Link to Part	#	Date	Price	Total
RedBoard - Programmed with Arduino	SparkFun	DEV-12757	https://www.sparkfun.com/products/12757	1	11/12/16	19.95	19.95
SparkFun Load Cell Amplifier - HX711	SparkFun	SEN-13879	https://www.sparkfun.com/products/13879	1	11/12/16	9.95	9.95
Load Cell - 50 kg, disc	SparkFun	TAS606	https://www.sparkfun.com/products/13331	1	11/18/16	56.95	56.95
54" x 1/8" Polyethylene Foam Rubber Sheet	MSC	31941735	http://www.mscdirect.com/product/details/31941735	1 ft	11/18/16	8.11/ft	8.11
UW-Madison Shop Fee	UW-Madison	N/A	https://emu.engr.wisc.edu/emu/users/milestone_tracker.php	1	12/05/16	50	50
Scale Taylor OPP Body Fat	Target	64190342	http://www.target.com/p/-/A-16334331	1	12/07/16	27.42	27.42
Poster Printing	College Library Posters	N/A	N/A	1	12/08/16	57.78	57.78
						TOTAL:	230.16

Table 1: In this spreadsheet are listed all of the expenses accumulated throughout the design process.

B. Testing Protocol

Calibration Testing for Product

In order to calibrate the load cell and MatLab code, the device was subject to a series of known weights that were placed on top of the sensor. These weights ranged from 5 to 15 pounds with a 5-pound incremental increase. The expected forces for the weights are $F = ma$, where m is the mass of the weight and $a = 9.8 \text{ m/s}^2$. Using this series of weights, the load cell was calibrated and was ready for further testing.

Testing Load Cell Over Time

In order to test the load cells accuracy over time, it was subjected to a series of loads over a time period. The load test began with 5 pounds and ended at 25 pounds with 5 pound increasing increments. The device should continue to measure the various loads over time, without the prior loads affecting the results of more recent ones.

Test with Monkey Cage

The device was connected to the squeeze plate in one of the four corners on the exterior of the cage - the same location that will be used by the client. Using an empty cage, a measured force was applied to the back of the squeeze plate in order to test whether the device was functioning correctly. The force at the back of the squeeze plate will range from 10 to 40 pounds at 5-pound increments. The force will be read by pushing on the squeeze plate with a scale. Ideally, the single force sensor reads the entire force applied because the squeeze is on a track, preventing moments from occurring. However, this is not a perfect system, and a moment could possibly be generated. Using four force sensors, the force would be distributed among them, and the sensors would measure any moment generated. The load cell was tested in all four corners to ensure that it can be attached on the various bars on the exterior of the cage.

Further Testing

In the future, the device will be implemented onto a cage with a rhesus monkey inside. Four devices will need to be attached on the four corners of the cage. The circuit must be expanded to include an automated food dispenser that provides motivation to the monkey as they continue to generate forces. By this time, the device will already be calibrated, and our client should be able to begin generating some data.

C. Code

Calibration

/*

Example using the Sparkfun HX711 breakout board with a scale

By: Nathan Seidle

Sparkfun Electronics

Date: November 19th, 2014

License: This code is public domain but you buy me a beer if you use this and we meet someday (Beerware license).

This is the calibration sketch. Use it to determine the calibration factor that the main example uses. It also outputs the zero factor useful for projects that have a permanent mass on the scale in between power cycles.

Setup your scale and start the sketch WITHOUT a weight on the scale

Once readings are displayed place the weight on the scale

Press +/- or a/z to adjust the calibration factor until the output readings match the known weight

Use this calibration factor on the example sketch

This example assumes pounds (lbs.). If you prefer kilograms, change the `Serial.print("lbs");` line to `kg`. The calibration factor will be significantly different but it will be linearly related to lbs (1 lbs = 0.453592 kg).

Your calibration factor may be very positive or very negative. It all depends on the setup of your scale system

and the direction the sensors deflect from zero state

This example code uses bogde's excellent library: <https://github.com/bogde/HX711>

bogde's library is released under a GNU GENERAL PUBLIC LICENSE

Arduino pin 2 -> HX711 CLK

3 -> DOUT

5V -> VCC

GND -> GND

Most any pin on the Arduino Uno will be compatible with DOUT/CLK.

The HX711 board can be powered from 2.7V to 5V so the Arduino 5V power should be fine.

```
*/  
  
#include "HX711.h"  
  
#define DOUT 3  
#define CLK 2  
  
HX711 scale(DOUT, CLK);  
  
float calibration_factor = -7050; //-7050 worked for my 440lb max scale setup  
  
void setup() {  
  Serial.begin(9600);  
  Serial.println("HX711 calibration sketch");  
  Serial.println("Remove all weight from scale");  
  Serial.println("After readings begin, place known weight on scale");  
  Serial.println("Press + or a to increase calibration factor");  
  Serial.println("Press - or z to decrease calibration factor");  
  scale.set_scale();  
  scale.tare(); //Reset the scale to 0  
  long zero_factor = scale.read_average(); //Get a baseline reading  
  Serial.print("Zero factor: "); //This can be used to remove the need to tare the scale.  
  Useful in permanent scale projects.  
  Serial.println(zero_factor);  
}  
  
void loop() {  
  
  scale.set_scale(calibration_factor); //Adjust to this calibration factor  
  Serial.print("Reading: ");  
  Serial.print(scale.get_units(), 1);  
  Serial.print(" lbs"); //Change this to kg and re-adjust the calibration factor if you follow SI  
  units like a sane person  
  Serial.print(" calibration_factor: ");  
  Serial.print(calibration_factor);  
  Serial.println();  
  if(Serial.available()){
```

```
char temp = Serial.read();
if(temp == '+' || temp == 'a')
  calibration_factor += 10;
else if(temp == '-' || temp == 'z')
  calibration_factor -= 10;
}
}
```

Load Cell

```
/*
```

Example using the Sparkfun HX711 breakout board with a scale

By: Nathan Seidle

Sparkfun Electronics

Date: November 19th, 2014

License: This code is public domain but you buy me a beer if you use this and we meet someday (Beerware license).

This example demonstrates basic scale output. See the calibration sketch to get the calibration_factor for your specific load cell setup.

This example code uses bogde's excellent library: <https://github.com/bogde/HX711>
bogde's library is released under a GNU GENERAL PUBLIC LICENSE

The HX711 does one thing well: read load cells. The breakout board is compatible with any wheat-stone bridge based load cell which should allow a user to measure everything from a few grams to tens of tons.

Arduino pin 2 -> HX711 CLK

3 -> DAT

5V -> VCC

GND -> GND

The HX711 board can be powered from 2.7V to 5V so the Arduino 5V power should be fine.

```
*/
```

```
#include "HX711.h"
```

```
#define calibration_factor -7050.0 //This value is obtained using the
SparkFun_HX711_Calibration sketch

#define DOUT 3
#define CLK 2

HX711 scale(DOUT, CLK);

void setup() {
  Serial.begin(9600);
  Serial.println("HX711 scale demo");

  scale.set_scale(calibration_factor); //This value is obtained by using the
SparkFun_HX711_Calibration sketch
  scale.tare(); //Assuming there is no weight on the scale at start up, reset the scale to 0

  Serial.println("Readings:");
}

void loop() {
  Serial.print("Reading: ");
  Serial.print(scale.get_units(), 1); //scale.get_units() returns a float
  Serial.print(" lbs"); //You can change this to kg but you'll need to refactor the
calibration_factor
  Serial.println();
}
```


D. Software and Hardware Diagrams

Load Cell Software Diagram

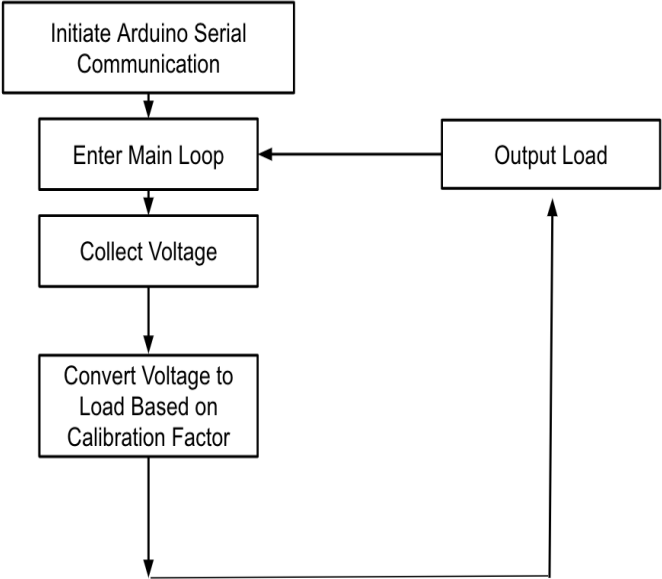


Figure 14: This figure is of the software diagram associated with the load cell readings. It depicts the loop statement that initially takes in the Arduino serial communication and converts the registered voltage to loading force data.

Hardware Block Diagram

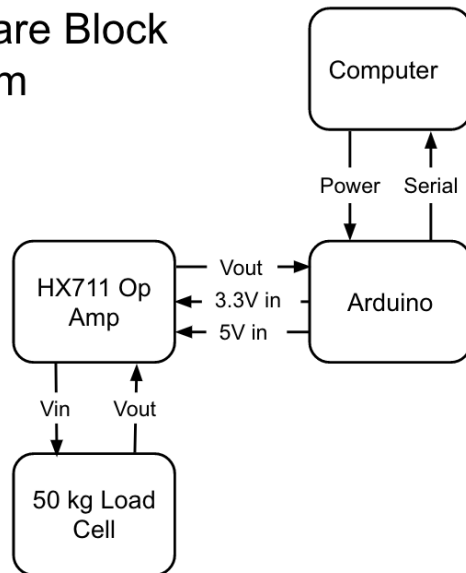


Figure 15: This figure is of the hardware diagram associated with the load cell to computer circuitry. The computer powers the Arduino, which passes voltage to the op amp to read in voltages from the load cell and return this data to the computer.

E. Final Prototype SolidWorks and Drawing Depicting Dimensions

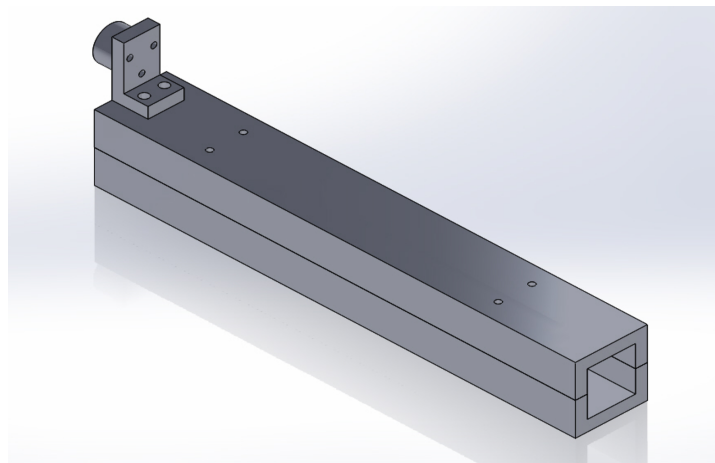


Figure 16: This image is a SolidWorks depiction of our final prototype.

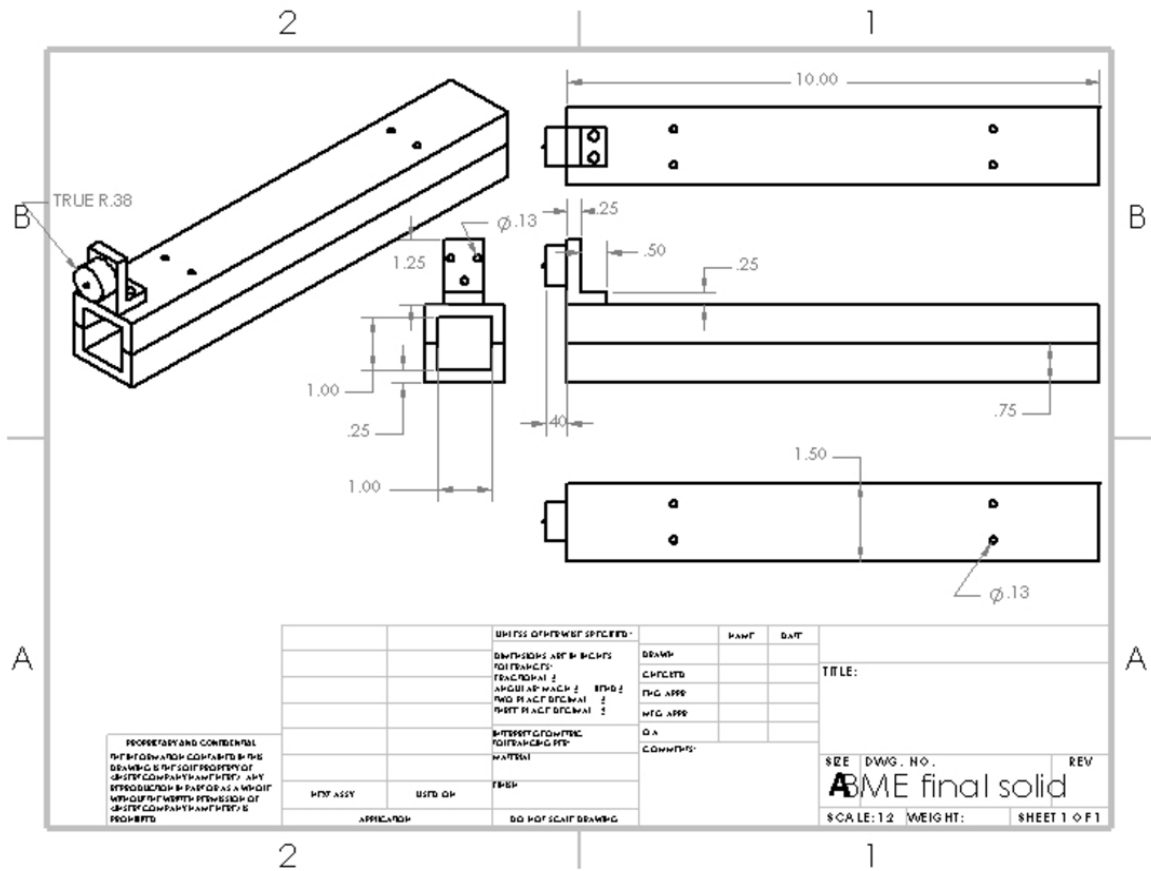


Figure 17: Shown is a SolidWorks drawing of our final prototype design along with all applicable dimensions.