

Physical Function Testing Apparatus for Rhesus Monkeys

Biomedical Engineering Design 301

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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 that has been used for research is the motor function of these animals. Research has been done to compare basic motor function to neurological stimuli [2] and to evaluate basic grip strength [Bury]. Although these efforts have been effective, there currently is no method for testing the strength for any large muscle group. 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. Due to this, there is a need for an apparatus that is capable of evaluating these major muscle groups maximum strength in a safe and effective way.

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Introduction

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 has 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.

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].

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

Original Design

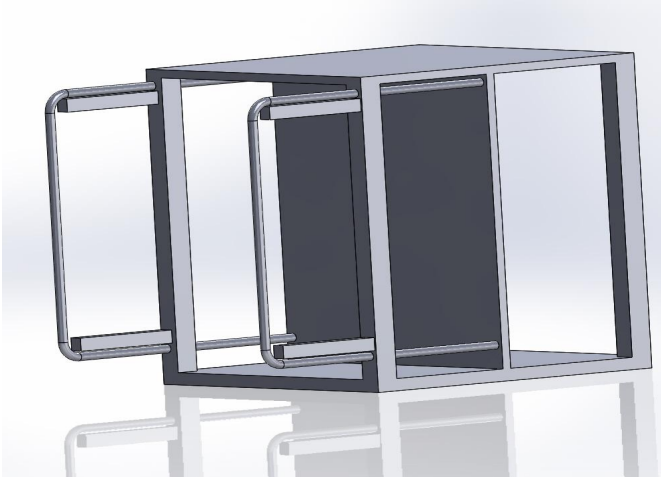


Figure 2: Model of monkey cage drawn in SolidWorks

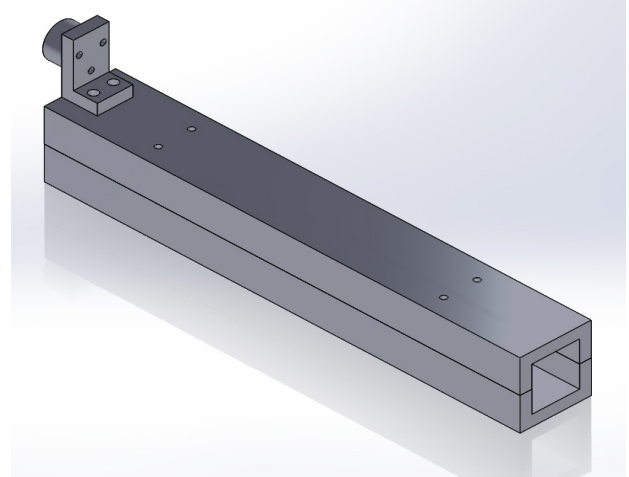


Figure 1: Original clamp design drawn in SolidWorks

The original design involved attaching force gauges to the bars connected to the squeeze plate. 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: Original clamp design depicted attached to the monkey cage

The final fabricated device is shown above attached to the squeeze plate on the exterior of the cage. Results from testing show that the 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, the load cell was relatively accurate. 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.

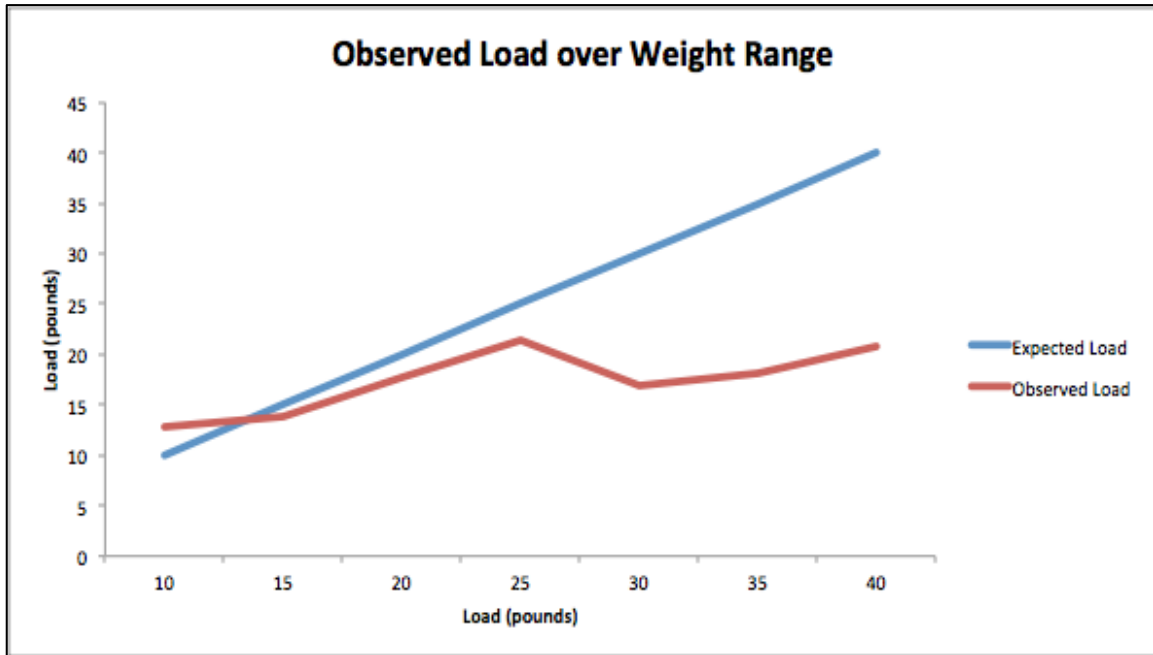


Figure 4: Graph of observed load applied on a scale and on the apparatus vs. actual load applied

Considered Designs

I. Hinged Design

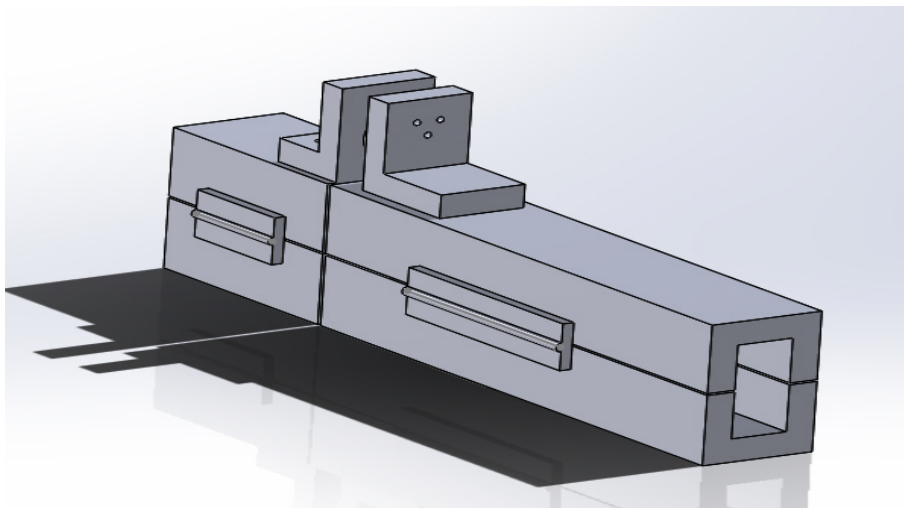


Figure 5: SolidWorks drawing of the Hinged Design

The hinged design was intended to make the device easier to attach for the researcher as well as reduce the size and weight of the overall design. This design features the same L shaped piece on the top of the device for load cell attachment that was featured on the original design. One difference between this design and the original design is that this design has a smaller width of the clamp. This was done so that the interior walls of the device make contact with the bar on all sides. This will increase the frictional force generated as the monkey pushes on the squeeze plate. The new hinge and lock system on the outside of the device allows the design to be attached easily by the researcher. The hinge on one side keeps the pieces attached when not in use and allows for easy alignment of the device on the bars. The main issue with the hinges and locks is that they isolate the majority of the force to individual points creating likely fail points.

The addition of a second piece can be seen in the figure above. This new feature is not isolated to the hinged design, and will be incorporated with all possible designs. This piece is much smaller than the main design at a length of 2 in. compared to 5 in. This piece is being added to produce a flat, consistent surface for the load cell to pin against and register forces. The inside of this piece will not be lined with the foam used in the main device. This is to minimize frictional forces in the small piece, so that only the main device acts to pin the squeeze plate.

II. One Piece Screwed Clamp

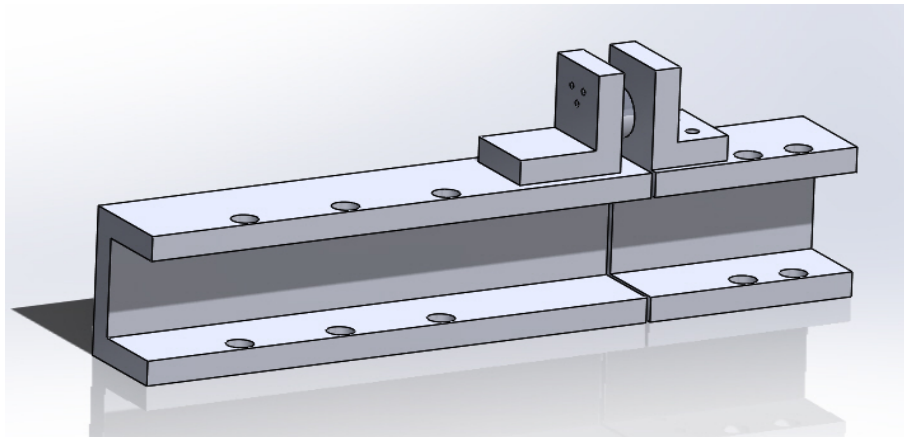


Figure 6: SolidWorks drawing of the One Piece Screwed Clamp design

This design utilizes screws and bolts to generate the clamping method. With the foam inserts lining the inner walls of the device the squeeze plate bars can be slid into the devices C shape and screwed into place on the open side. This allows for bar/device contact on three sides, increasing the frictional force

from the original design. This device reduces the difficulty of fabrication significantly by only having to remove a side of the square pipe used. The open side reduces the difficulty of attachment from the original design because the researcher can see the screw and bar locations inside the device. The original device was enclosed and had no visibility. As prior stated, this design also utilizes a second, smaller piece to create a flat consistent surface for the load cell.

Dimensions

Drawings with specific dimensions are found in Appendix E.

Circuit Designs

Since the new designs contain four load cells, the original circuit must also be adjusted to account for this changed. Two options were considered to replace the circuit. The first design uses four separate circuits, one for each load cell, and combines the data in the code. This design, though it is considered safer because there is less wiring for the monkeys to possibly break, is also significantly more expensive. The second circuit design, which will be implemented into our prototype, uses a combinator load device that is attached to all four load cells. This then sends one signal to the op amp, which further sends a signal to the Arduino. The combinator load cell only costs \$2, saving a significant amount of money in comparison to the other design.

Design Matrices

There were three independent aspects of the design that were evaluated separately. First and foremost, the three clamp designs were evaluated. Next to be assessed were three different possibilities for creating the electrical circuit. Finally, aluminum and stainless steel were compared in the materials matrix. Although each matrix holds different criteria, it was the safest, most convenient and most accurate designs that were chosen to be realized.

Clamp Design Matrix

	Original Clamp		Hinged Clamp		One Piece Screwed Clamp	
Safety (25)	4	20	3	15	4	20
Durability (20)	5	20	3	12	4	16
Ease of Fabrication (20)	4	16	3	12	4	16
Ease of Use (Researcher) (20)	2	10	5	20	4	16
Measurement Accuracy (10)	5	10	5	10	5	10
Cost (5)	5	5	4	4	5	5
Total (100)		81		73		83

Figure 7: Clamp design matrix

Safety

Safety is by far the most important aspect of this design because the monkeys will touch, pull, and bite this device it must be completely safe and not cause any harm to the animals. The Original Design is fairly safe because it has very few moving parts and the only way the monkeys could injure themselves is getting pinched on the sides of the plate. In the hinge design, the lock could possibly be released by the monkey which could lead to the monkey pinching himself or herself in the clamp. The Screw Design has the least moving parts and the only chance of injury to the monkey would be if he or she were to get pinched by the screw and nut. All of the designs run this risk though. Also, none of the design pose a significant risk of injury to the researcher.

Durability

Durability is very important to this project because our client's research lasts years and she must be able to test the same muscle force in the same way

over her experiments. The Original design has the fewest moving parts and the fewest screw holes, both of which act as possible points of failure. The Hinged Clamp has the most moving parts with the lock and hinge, along with some drill holes to screw the hinge in. The main risk of the One Piece Screwed Clamp is the screw holes which would most likely have to be drilled toward the edge of the metal piece which increases its chance of failure.

Ease of Fabrication

Ease of fabrication is very important, considering at least four devices will be created. Additionally, if the fabrication process was simple, it would be easier to make modifications if necessary. Primarily, only a strip of rectangular metal piping will need to be cut, and a few holes drilled for each of the designs. Having to fit the hinges and locks onto the Hinge Clamp adds another factor for its fabrication, which is why it was rated lower than the others.

Ease of Use- Researcher

Ease of use was weighted moderately heavily 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. The Original Clamp required the researcher to match up the two plates in order to screw them together and this task proved to be tedious. The Hinge Clamp would be the simplest to use, as it would only need to be closed and locked into place. Finally, the Screwed Clamp would be relatively easy to use because the screw holes are already aligned and only one piece needs to be held up as the screws are tightened.

Measurement Accuracy

Accuracy of Measurement is important because without accurate measurement of muscle force the device does not perform its purpose. All of the designs were rated equally because, if fabricated well, they would all apply enough friction to the cage bars so that they would hold in place, and the load cell would be pushing against a flat surface. If all four bars are fitted with one of the clamps, it would remove the moment forces that altered the test results in the previous semester.

Cost

Cost was weighted as 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. Every design incorporates a similar amount and type of bulk material (either stainless steel or aluminum) so the scores are similar. However, the Hinge Clamp requires the extra hinges and locks which would increase cost.

Circuit Matrix

	Original Circuit		Quadruple Circuit		Combined Circuit	
Cost (30)	5	30	2	12	4	24
Accuracy (30)	1	6	5	30	5	30
Ease of Fabrication (20)	4	16	3	12	5	20
Safety (10)	1	2	5	10	4	8
Ease of Use (Researcher) (10)	1	2	5	10	5	10
Total (100)		56		74		92

Figure 8: Circuit design decision matrix

Cost

The original circuit was the cheapest option (5) because it was already purchased along with all of the supplies necessary for a working circuit. The combined circuit was ranked a 4 because it only requires the purchasing of more wiring along with the combinator board which costs \$2. The quadruple circuit was rated a 2 because it would require 3 more Arduinos, 3 more op amps, and more wiring. This would cost hundreds dollars.

Accuracy

The quadruple circuit and the combined circuit were both ranked 5 because it would accurately measure the total load the monkey places on the squeeze plate. The load is divided among the four corners of the device, and the four load cells in these circuits would measure all four of those forces. The current device was given a 1 because it only measures one force on the exterior of the cage. It has already been shown through testing this isn't accurate above loads of 20 pounds.

Ease of Fabrication

The combined circuit was rated highest for ease of fabrication (5) because it simply adds the four load cells together using the combinatory, making the circuit design very organized. The current circuit was given a 4 because although it is already fabricated, the wires detach from the Arduino board and the overall fabrication was done somewhat poorly. The quadruple circuit was given a score of 3 because it would require fabricating four separate circuits, which would complicate the code design for all four load cells.

Safety

The quadruple circuit was given a score of 5 because it is completely out of reach from the rhesus monkeys. The wires are completely covered in boxes and will not harm the monkeys. The combined circuit was given a score of 4 because the wires should be out of reach from the monkeys, but they will not be completely covered in a box. The current circuit was given a score of 1 because the wires are not only uncovered, but they can also be reached by the monkeys. This could potentially harm both the monkey and the lab staff operating the device.

Ease of Use- Researcher

The combined circuit and the quadruple circuit were given a score of 5 because the user simply has to connect the four load cells to the clamps and turn on the code in order to gather data. The current circuit was given a 1 because some of the wiring has to be connected, and the device has to be connected to a computer. The two new designs take advantage of Bluetooth.

Materials Matrix

	Stainless Steel 304		Aluminum 2024	
Strength (25)	5	25	4	20
Ease of Fabrication (25)	2	10	4	20
Weight (20)	2	8	4	16
Cost (15)	4	12	5	15
Durability/ Corrosion Resistance (15)	5	15	4	12
Total (100)		72		83

Figure 9: Material decision matrix

Strength

Rhesus monkeys are deceptively powerful and a material that can withstand high compressive forces and has a high yield stress is required. Strength was rated highly because a device which fails would need to be re-fabricated and also poses a risk to injure the monkeys. Both stainless steel and aluminum have very high compressive strength, and with four devices on the cage, pose a very low risk of failure due to lack of strength. However, stainless steel is slightly stronger.

Ease of Fabrication

Ease of fabrication is vital both for the fabrication team and for maintaining the device during use. A material that can be fabricated in a timely manner would make the device more convenient for the client and the fabrication team, especially if changes need to be made to the design. Since we are making a device for each of the four bars, a material that can be manufactured quickly would be very beneficial. Aluminum is praised for its manufacturability while stainless steel takes a significantly longer time to fabricate.

Weight

The client requested that the new version of the device be lighter for the convenience of the researchers using the device. However, our design team does not want to sacrifice convenience of the client for functionality of the device which is why the weight is not the highest priority in the matrix. Aluminum is several times less dense than stainless steel.

Cost

Although there hasn't been a budget prescribed by the client, it is necessary to make sure that the price of the material doesn't drive up the overall cost of product. Aluminum 2024 and stainless steel 304 are both very similar in price range, although stainless steel is slightly more expensive by volume.

Durability/Corrosion Resistance

The devices are meant to withstand many tests over a long period of time without failing and should be resistant to rusting. Both of these materials will confidently be able to meet this requirement for a significant time period so the category was not weighted highly. However, stainless steel is extremely resistant to corrosion, and aluminum is a softer metal. Therefore, stainless steel ranked higher, although aluminum alloy is durable and resistant to corrosion.

Fabrication

Materials

A detailed list of materials used and cost can be found in section F of the Appendix. Hollow aluminum tubing was used for clamping device as a means of reducing cost and weight while still meeting the clients requirements. For the small bar clamps, $\frac{1}{8}$ " thick, by $1\frac{1}{2}$ " high by $\frac{3}{4}$ " wide alloy 6063 aluminum was used. The large bar clamps were fabricated from $\frac{1}{4}$ " thick by 2" high by 3" wide aluminum of the same 6063 alloy. This particular alloy is noted for its corrosion resistance, low density (2.69 g/cm^3) and high tensile strength (186 MPa). Preferably, the clamps would have both been made from $\frac{1}{8}$ " thick aluminum, but the specific dimensions needed to fit on the bars limited the thickness availability. Gasket rubber was adhered with outdoor, water-resistant mounting tape to the aluminum in order to increase friction on the bars. Gasket rubber was chosen due to its ability to withstand high frictional stress and its corrosion resistance. This allows it to be sanitized with the stainless steel. The circuit included a four single-strain 50 kg load cells, a combinator board, a HX711 op amp, an Arduino Red Board, and a computer. The load cells, combinator board, and op amp, together allowed force to be converted to resistance which could then be read by

the Arduino. The computer was used to program the Arduino and as a power source.

Methods

Clamp

A SolidWorks drawing can be found in Appendix E, which further details the dimensions of the clamps. All fabrication was done in the UW-Madison Student Shop. Measurements were made with digital calipers and marked using a metal ruler and a Sharpie. The aluminum tube for the large clamps was first cut using the drop saw to a length of 5", and then cut in half lengthwise using a band saw so that there were two U-shaped halves. Using a drill press, three equidistant $\frac{1}{4}$ " diameter holes were drilled $\frac{1}{2}$ " from the open side of each half. The first hole was drilled $1\frac{1}{2}$ " away from one side in order to leave room for the L piece to be attached on top (the L piece was used for attaching the force sensor). For attaching the L piece, two more $\frac{1}{8}$ " holes were drilled $\frac{1}{2}$ " from this same side.

The same procedure was used for drilling into the small bar clamps, but the holes were drilled $\frac{3}{4}$ " from the open side of the channel. The smaller aluminum piping was not large enough to make two clamps with a single lengthwise cut. As a result, the drop saw was used to cut two 5" pipes and the bandsaw was used to cut $\frac{1}{4}$ " off lengthwise, leaving a $\frac{3}{4}$ " by $1\frac{1}{4}$ " a U shape.

Another U-channel was cut from the smaller aluminum using the same technique and then cut two more times using the bandsaw in order to create four L-shaped pieces with the same width as the clamps. The drill press was again used to create two $\frac{1}{8}$ " holes in the short side of the L for bolting them to the clamps, and three more holes were made in the long part of the L for bolting the load cells. These holes needed to be in specific locations to match the load cells, so a center punch was used to align them correctly.

Bolts and nuts were used to attach the force sensors to the clamps permanently. Three bolts are inserted into each clamp to attach them to the bars of the monkey cage after the clamps are positioned.

All sharp edges of the aluminum were sanded down to avoid harm to any user or monkey. Strips of gasket rubber were measured to cover the three inner sides of the clamps. The rubber was then adhered to the inside of each half of the clamp using water-resistant mounting tape.

Circuit

The circuit was constructed using supplies bought from the Sparkfun website. The circuit consisted of four single strain load cells, which were attached to the front of the connecting bar by screws. The load cell was soldered to a combinator board, which created a connection between the four cells and combined the outputs together. The combinator load output was then sent to a 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 cells in order for them to run. The Red Board also grounded the entire circuit. A laptop was connected to the Red Board and used as a voltage source.

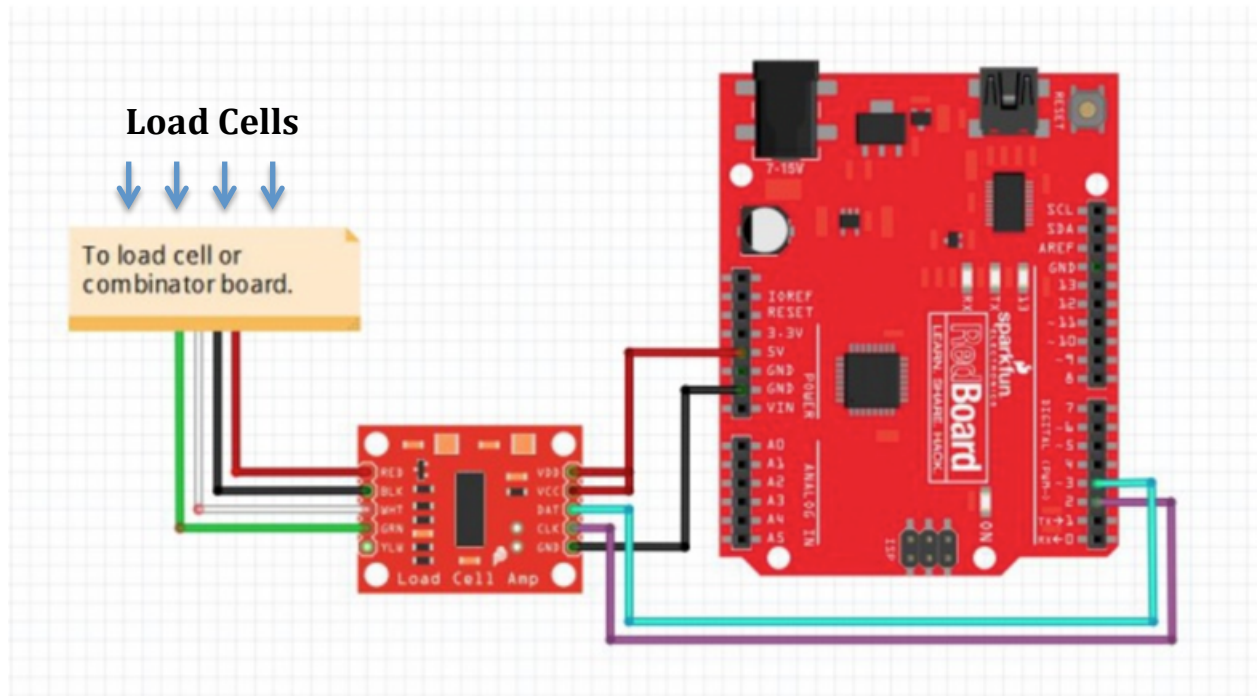


Figure 10: Circuit design figure. The load cells were connected to the combinator and further to the Red Board

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 11: Final clamp design attached to monkey cage

Figure 11 above shows the final clamp integrated onto the squeeze plate of the monkey cage. The load cell is attached to the front of the clamp so that it is pressed against the cage. The back side of the clamp is open such that the client can attach screws going through the three holes seen above, clamping the device to the squeeze plate.

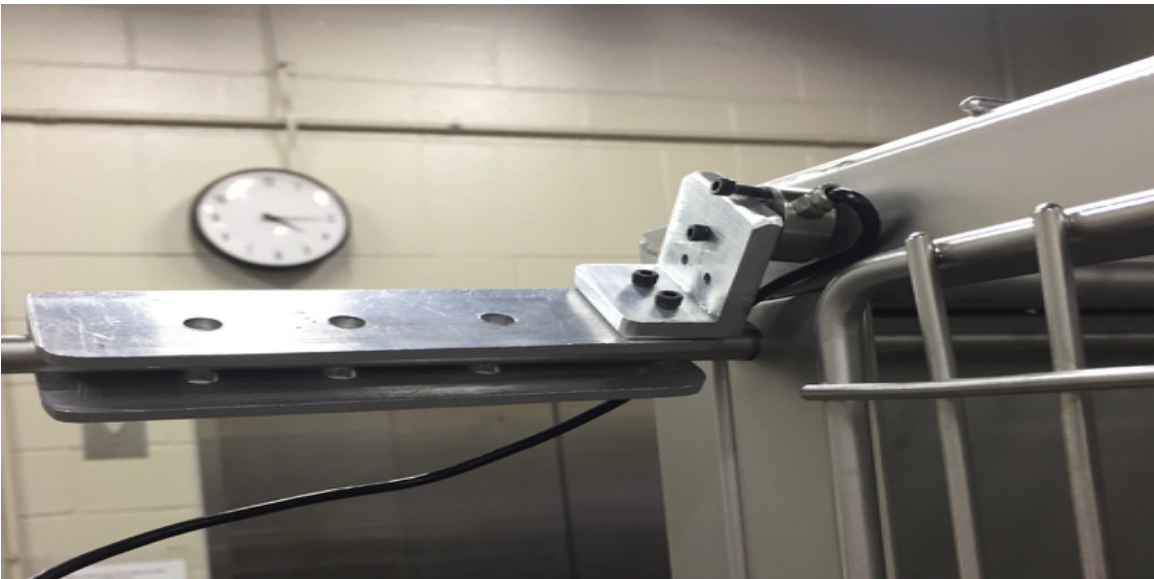


Figure 12: Top clamp attached to monkey cage in testing

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.

Clamp Testing

To ensure that the devices would clamp properly and strongly to the various squeeze plate bars of the cage, the devices were all attached to the appropriate bar size. The devices all attached easily and effectively. The devices were then removed and reattached to another cage to ensure that they would be reusable and attach effectively to multiple cages.

Device Testing Against Cage

Testing was completed by measuring a force in one isolated load cell due to a malfunction with the load combinator. While data was gathered in a similar fashion to the previous semester, a significant amount of the error was removed by attaching the devices in all four corners of the cage to pin the cage equally across its entire face. A bathroom scale was used to push against the back wall of the cage, and this represented the applied force. The force was incremented by 5 pounds, starting at 5 pounds and ending at 100 pounds. For the given applied force, the value sensed by the load cell was recorded. This experiment was run twice and the results were averaged.

Failure points were also documented by pushing on the back of the cage until one or more of the clamps slipped. The force displayed by the bathroom scale and load cell at the time of failure was recorded.

Results

Since only one load cell was available for testing due to issues with the combinator load board, the theoretical load would only be 25% of the applied load to the back of the cage with all four corners clamped. Data was collected from a range of five to one hundred pounds at increments of five pounds. The device showed that it does in fact work properly with one load cell based on the results that were collected (Figure 13). Using a statistical two-sided t-test, the slope of the data was tested against the ideal observed output (Figure 14). The slope values were determined to be statistically insignificant at an alpha = 0.05, where the p-value = 0.987. At a p-value this high, it can be strongly concluded that the observed output is not significant from the expected output, and the data does accurately reflected the expected output load.

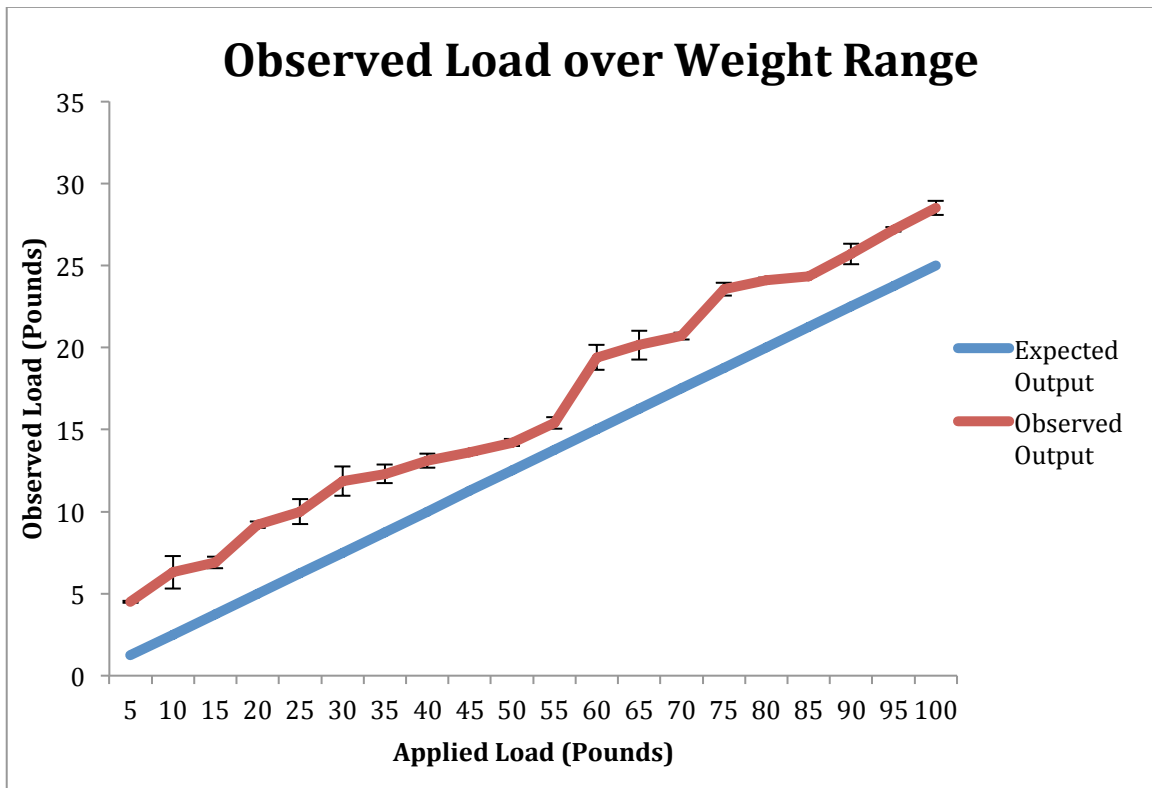


Figure 13: Observed load output by apparatus and expected value vs. applied load

A linear regression was run on the observed output as well to assess its accuracy. The line of best fit was $y = 1.2457x + 3.48$ with an R-squared value of 0.984. The expected slope would be equal to 1, and thus the linear regression further verifies the accuracy of the load cell when compared to the expected output.

$$H_0: \beta_1 = \beta_2 \text{ i.e. } \beta_1 - \beta_2 = 0$$

$$H_1: \beta_1 \neq \beta_2 \text{ i.e. } \beta_1 - \beta_2 \neq 0$$

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

$$\beta_1 - \beta_2 \sim N(0, s_{b_1 - b_2})$$

where

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

Figure 14: Statistical testing

Figure 14 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].

Failure Points as Detected by Load Cell (lbs)	Failure Point as Detected by Scale (lbs)	Place of Failure
38.4	138.5	Both left clamps
40.7	142.3	Both left clamps
40.1	142.8	Bottom left clamp

Figure 15: Table of failure points detected by the load cells, by the scale, and the location of failure

Further, the failure points were analyzed to determine at what points there was a slip between the clamp and the squeeze plate bars. This occurred when the friction force was less than the applied force on the clamp. Three trials were

run to determine the failure points detected by the load cell and also by the scale (Figure 15). The failure point detected by the load cells averaged at 39.73 with a standard deviation of 1.19. The failure point detected by the scale averaged at 141.2 with a standard deviation of 2.35. The primary point of failure was the bottom left clamp; however, both of the clamps on the left side of the cage failed in at least one of the trials.

Discussion

The fabrication of all four of the clamp devices was simple and efficient. In total, it took roughly 7 hours to completely fabricate all four devices to the appropriate dimensions and grind the corners and edges for safety purposes. The process mostly relied on a drop saw and drill press. The tolerance of these machines led to small variances between the actual dimensions of the fabricated devices and the desired dimensions. This was most noticeable with one hole that was drilled into one of the smaller devices. While possible to use for clamping, it was drilled too close to the cage bar's location, so it made it extremely difficult to attach and detach the nut and bolt that went through this hole. For more finite dimensions, it would be beneficial to use a mill so that dimensions are automated and not measured by hand. The devices were noticeably easier to attach and were considerably lighter. They also did not cause any large moments due to their weight. The front clamping piece, originally included in the considered designs and SolidWorks (Appendix E) was removed from the final prototype because it added unnecessary weight and complexity based on the geometry of the strain gages and the cage. The rubber material used for friction was also much more effective than the foam used last semester. The only problem with the rubber was that it was difficult to adhere to the aluminum, and the double-sided tape began to lose its adhesive purposes after some time. The circuit was also easy to fabricate due to the layout and code provided and explained directly on the SparkFun website. The main problem that affected both the project's timeline and fabrication was a broken combinator load board. Due to the internal circuitry of this board, it was difficult to troubleshoot the circuit. This was solved by first using a voltage multimeter to test the wire resistances and ensure proper placement. Then the combinator load board was detached, and an individual load cell was attached directly to the load cell amplifier. This load cell was then tested and found to be working, so it was determined that the load combinator board was broken. This was then confirmed after purchasing a new load combinator board and finding that it worked right away with all four of the strain gauges attached.

Testing was completed by pressing a bathroom scale against the back of

the squeeze plate from five to one hundred pounds at intervals of five pounds. This test was accurate in the lower range of the applied load; however, at the higher loads, some errors occurred. It was difficult to align and hold the bathroom scale steady against the back mesh of the cage, particularly because the four corners of the bathroom scale had to be pressed against the mesh. There is also a bend in the back wall of the cage, which forced the scale to be pressed off-center. This would create an uneven distribution in the load against the four corners, which would result in some error in the data. However, in the case that the monkeys are being tested, it is highly unlikely that they would push at the exact center. This reason for error is corrected by the use of the four load cells in each corner. Unfortunately, testing only used one load cell.

Even with these reasons for error, the results to the testing are promising. With a p -value = 0.987, it is clear that the expected output aligns well with the observed output. The implementation of the four clamps to the four corners of the device effectively eliminated the generation of moments about the single clamp, which drastically lowered the error. The p -value last semester was equal to 0.14 for comparison. The new prototype also showed improvements in failure point in comparison to last year. The device was not accurate above an applied force of 25 pounds last semester, but the new device was able to withstand forces up to 141.2 pounds with a standard deviation of 2.35. Clearly, the new prototype has made improvements over the old one.

Ethical Considerations

In order to ensure the new device works accurately, it needs to be tested with all four load cells. The combinator board was unfortunately broken, but a new one was ordered, and the new circuit was built. This circuit was also tested to ensure it worked properly. This same test should be run with all four load cells attached to the squeeze plate, and the data should be analyzed in a similar fashion. If these results are still accurate, then the device can be moved in the next phase where it is tested with actual rhesus monkeys. 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.

Conclusions

The lack of an existing device to measure the strength of Rhesus monkeys motivates the development 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 four extended bars of the squeeze plate feature on the monkeys' current cages. This design utilized a gripping substance to generate enough friction to resist the forces generated against the squeeze plate. The device registered these forces using four load cells as the only contact point to the cage so that as the monkeys push back on the plate the load cell registers the force. The four load cells are connected through a combinator circuit board and their signal is amplified and then output to the client. Only preliminary testing was completed on this device, and further testing would allow for better analysis on the accuracy of the device and how it can be improved.

Future Work

The biggest strides from the original design to the final prototype this semester were improving the quality of the clamp and implementing four load sensors and clamps as opposed to a single one. After testing, it is clear that the new clamp prototype fixes a majority of the problems with the older one. The new circuit also theoretically fixes the issues with measuring the appropriate force generated by the monkey. However, since there was little testing done with the new circuit, the most important next step would be to analyze and evaluate how accurate the new circuit is with all four strain gauges attached. This would also reveal any possible problems with the clamping mechanism. After further evaluation, there are other key implementations that would further improve the device. In order to train the monkeys to use the device, an automatic food reward system can be implemented into the circuit. This is the primary means of teaching the monkeys to use the device as it would implement a threshold system that the monkeys must reach to receive a reward. It would also be beneficial for the client if the device was wireless, and therefore implementing a Bluetooth system would allow her to access the data away from the device. Finally, the prototype could be improved by designing a container that protects the circuit and organizes it. This would make the device easier to handle, while also keeping the wiring away from the rhesus monkeys. Using PVC piping to contain the wiring and a box of some sort to contain the circuit elements would protect the device and the monkeys.

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Appendix

A. PDS

Physical Testing Apparatus for Monkeys PDS

Client: Dr. Ricki Colman

Advisor: Dr. Beth Meyerand

Team: Naren Chaudhry, Benjamin Myers, Benjamin Ratliff, Eli Stanek

Problem Statement:

In studying the effects of diet on the rhesus 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.

Preliminary Product Design Specifications

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 operating factor are 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 hindlimb 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:*

Our client's most significant concern is the safety of the device, as aforementioned. In their perspective, our 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). Our 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:

Our 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.

B. Testing Protocol

Testing Protocol for Monkey Strength Test

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 $a = 9.8$. Using this series of weights, the load cell was calibrated and was

ready for further testing.
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 any moment generated would be measured by the sensors. 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.

Test with Monkeys

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 Diagram

Load Cell Software Diagram

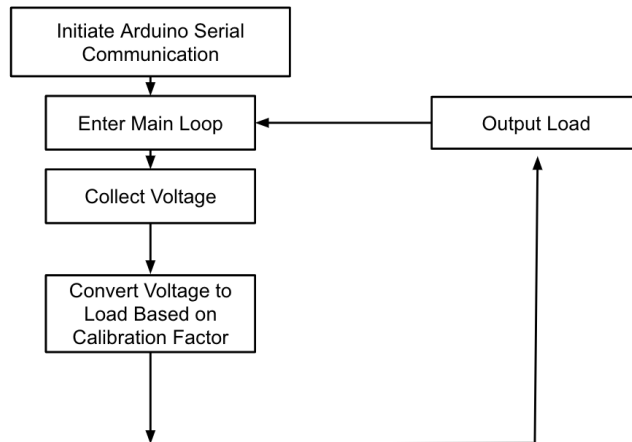


Figure 16: Software and Hardware Diagrams

Figure 16 above is 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.

E. Hardware Diagram and SolidWorks Images

Figure 17 shows 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.

Hinged Clamp

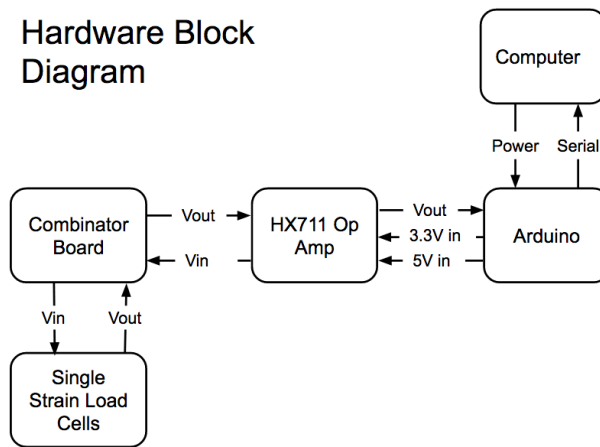


Figure 17: Hardware diagram

Open Side Screwed Clamp

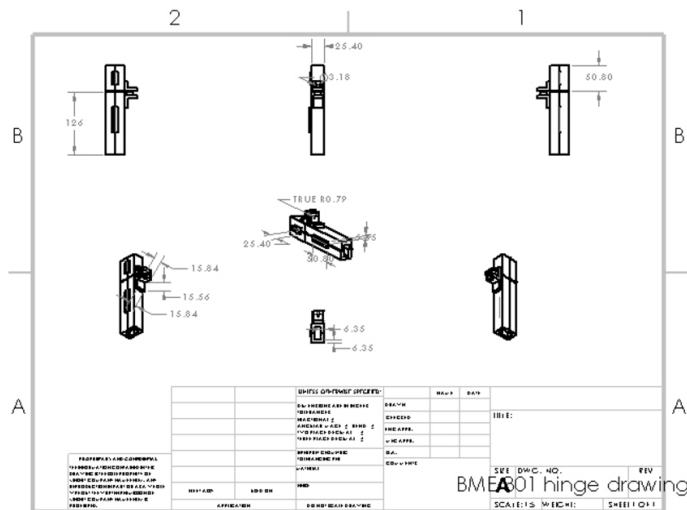


Figure 18: Hinged clamp design

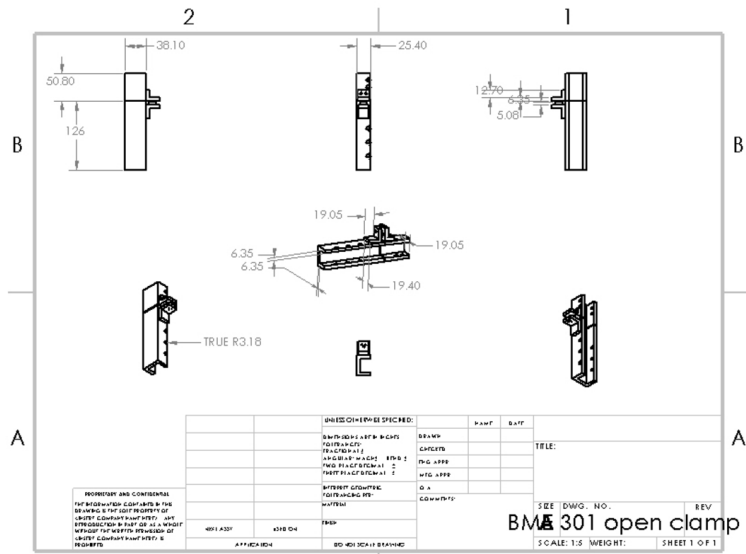


Figure 19: Open sided screw clamp design

Original Design

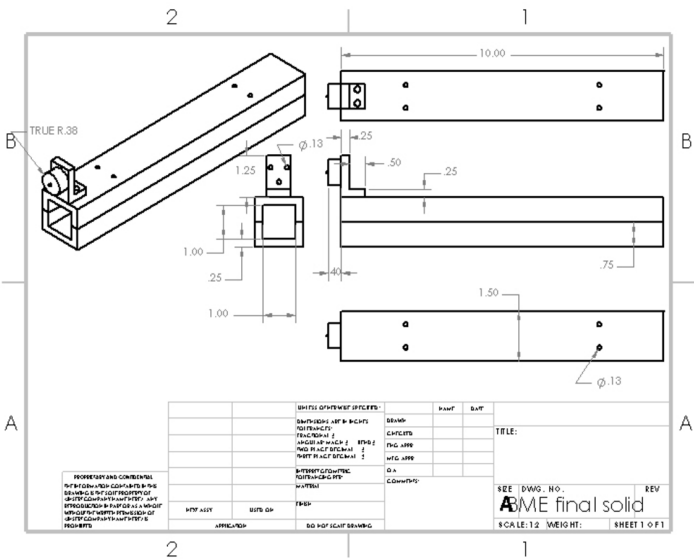


Figure 20: Original clamp design

F. Cost Analysis

Product Name	Product Number	Product URL	Cost	Amount
50 kg Load Cell		https://www.sparkfun.com/products/13331	\$56	3
Combinator Board		https://www.sparkfun.com/products/13878?_ga=1.209711511.401291228.1484597366	\$4	2
Bluetooth Mate Silver		https://www.sparkfun.com/products/12576	\$24	1
RedBoard		https://www.sparkfun.com/products/12757	\$0 (already have)	1
Load Cell Op Amp		https://www.sparkfun.com/products/13879	\$0 (already have)	1
6061 Aluminum Rectangular Tube, 1/4" Wall Thickness, 2" x 3	6546K28	https://www.mcmaster.com/#standard-aluminum-hollow-tubing/=16giro7	\$48.83	2 Feet
6061 Aluminum Rectagular Piping	6546K54	https://www.mcmaster.com/#standard-aluminum-hollow-tubing/=16i0ted	\$18.72	3 Feet
Single Strain Load Cells		https://www.sparkfun.com/products/10245	\$10.00	4

Figure 21: Cost spreadsheet