Final Report: Force Sensor for Rowing Biomechanics

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BME 300/200

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Abstract

Elite rowers that engage in a high volume of training can suffer from a variety of injuries, the most common occurring in the lumbar spine [1]. As rowing is a full-body movement, perfecting technique and maintaining proper form is essential to preventing such injuries and improving performance overall [2]. The UW-Madison women's rowing team is seeking a way to measure real-time biomechanical data in the form of approximate foot force in order to determine the presence of any lower extremity asymmetries and correct athletes' form. Existing products such as the BioRow Force Plates, are far too expensive and cannot be implemented in different rowing configurations [3]. In an effort to reach a more affordable solution, a working prototype was developed using a load cell, HDPE plates, and Arduino-coded circuitry, and secured to a Concept2 RowErg [4]. The signal from the load cell is sent through an amplifier to the Arduino, a reading in pounds is calculated and stored in the EEPROM [5]. Through use of a serial plotter, a user-friendly graph depicting force exertion over time is then displayed on a connected laptop. Testing of the device revealed that our subject did not display consistent asymmetry throughout a 30-40 second long interval, though more trials are necessary to determine whether these results are as a result of device error or subject form. Selecting a different load cell shape and implementing multiple load cells to measure data simultaneously from both feet are areas for future improvement of the device.

Table of Contents

Abstract 1
Table of Contents 2
I. Introduction 4
Motivation 4
Current Methods and Existing Devices 4
Problem Statement 5
II. Background 6
Relevant Physiology and Biology 6
Relevant Design Information 7
Client Information 10
Design Specifications 11
III. Preliminary Designs 11
Force-Sensitive Resistor 11
Silicone-Magnetic Force Sensor 14
Miniature Compression Load Cells 15
IV. Preliminary Design Evaluation 16
Design Matrix 16
Design Evaluations 17
Proposed Final Design 21
V. Fabrication/Development Process 21
Materials 21
Methods 22
Final Prototype 24
Testing 27
VI. Results 29
VII. Discussion 32
Implications of Results 32
Sources of Error 33
Ethical Considerations 34
Future Work 35
VIII. Conclusions 36
IX. References 36
X. Appendix 40
Appendix A: Product Design Specifications 40
Appendix B: Materials and Expenses 50
Appendix C: Fabrication Protocol 51

Appendix D: Load Cell Calibration Protocol 52
Appendix E: Testing Protocol 53
Appendix F: Arduino Code 54

I. Introduction

Motivation

Many members of the University of Wisconsin Women's Rowing team have been dealing with lower back pain and other injuries, possibly due to asymmetric force output while rowing. Rotational twisting at the hips and torso are the lead causes for back pain in rowers, but is currently only qualitatively studied by the University of Wisconsin personal trainers [6]. Many rowers experience back injury due to various reasons: consistently exerting force when the back is flexed, repetition of the rowing movement, and not properly adapting to the size of the ergometer or boat [7]. However, current methods do not involve a way to quantitatively assess asymmetry in rowers. The Women's Rowing coaching staff is looking for a device to measure the force output female collegiate athletes produce while rowing. With this device, the athletic training staff hopes to be able to interpret differences in symmetry of a rower's force output, fix their form, and potentially reduce the risk of lower back injury by looking at quantitative values, rather than one-on-one observations.

Current Methods and Existing Devices

The University of Wisconsin Women's Rowing team currently uses an ergometer and one-on-one visual coaching and analysis to critique form and look for potential injury risks. Their current data is all qualitative, and uses the judgment of a trainer or coach to make observations and correct form. The ergometer is a symmetrical rowing device, and is very different from the natural rowing movement on water, which can be asymmetrical. The combination of only qualitative data and a machine that does not accurately represent actual rowing creates the need for a new device that can quantitatively measure rowing performance and asymmetry in a location where a more natural rowing movement is used.

The Concept2 RowErg, which is the ergometer used by the UW Rowing Team, displays a Force Curve that is used by rowers to track their force throughout a stroke. This design uses an ergometer that displays a live force-time curve and provides feedback by showing certain graph shapes. However, this design focuses on force output through the handle, not the lower extremities [8]. This device helps athletes compare their real time force output to reference graphs which help understand the flaws in their form.

To track lower extremity forces, the BioRow 2D Force Stretcher, produced by BioRow Ltd., is a plate affixed to the foot stretcher of an ergometer. The plate has load cells attached to it with strain gauges that measure force in horizontal and vertical directions. The plate contains four load cells, two for each foot, placed on the heel and the toe locations [3]. These load cells are capable of measuring high force outputs in rowers, and can assist personal trainers and coaches with critiquing a rower's form. However, this device is well over the client's budget and cannot be integrated with the Concept2 RowErg.

The Bertec Force Plates are also capable of sensing forces from lower extremities; specifically, they sense ground reaction forces during gait, balance, and performance analysis. They contain load cells that sample at a rate of 100 Hz, and can sense force in three directions. These force plates have large load capacities ranging from around 4500 N to 17,800 N, and come in a permanent model which can be fixed to the floor, or a portable model. Bertec also produces custom electronics and software which are both used to process the raw data from the force plates [9]. Though they are the lab and industry standard, these force plates cannot be modified in any way in terms of size or configuration to fit an ergometer.

Problem Statement

Many college rowing athletes, particularly women, are susceptible to lifelong lower back or hip injuries due to disparate weight distributions on each leg while rowing. This issue can be addressed through gathering real-time data on athlete biomechanics, but this data is often difficult to obtain. Collection and analysis of biomechanical data will enable athletes to adapt their technique towards better performance, and will assist coaches and trainers in preventing injury. The client, Dr. Jill Thein-Nissenbaum, has tasked the team with creating a force plate system that can collect biomechanical data from rowers' lower extremities. The team's goal is to create a wireless sensor system in the rowboat that will capture load distribution during time of use and will assess lower extremity asymmetry to establish risk stratification. Additionally, the team aims to translate the force plate system into a user-friendly interface that will enable coaches and athletes to understand essential biofeedback information, thereby improving both performance and safeguarding against potential injuries.

II. Background

Relevant Physiology and Biology

Rowing is a very high impact, fast-paced, and technical sport. Without extreme care, it is easy to get injured. Rowing requires a high magnitude of force from the entire body, but especially from the legs. As shown in Figure 1, there are four phases of the rowing stroke: the catch, the drive, the finish, and the recovery. During the catch phase, the rower's oars are fully in water, and their hips, knees, and ankles are in full flexion. The rower then moves into the drive phase, the rower extends their hips, knees, and ankles forcefully to propel the oar. During this phase, the upper body is braced so force can be transferred from the legs to the oars. During the finish, the rower is in full extension in their lower extremities and their elbows are in full flexion as they have completed the full range of motion required to move the oar. The recovery phase is the return to full flexion as the rower prepares to start the cycle of catch, drive, finish and recovery again [1].

The forces involved in the upper body can cause the spine to rotate as rowers typically only hold one oar on one side of their body in sweep rowing. This creates torque in the upper body as the spine twists to help pull and the push oar. The lumbar spine only allows for about 1.2 to 1.7 degrees of rotational movement, but most rotation happens in the mid-spine causing stress on the lumbar spine leading to back pain [10]. As a result, the most commonly cited injuries in rowers are those of the lumbar spine [11].

Figure 1. Phases of the rowing stroke [1].

Relevant Design Information

Rowing involves precise movements of the entire body. As a result, there are multiple forms of rowing. The two main forms of rowing are sculling and sweeping. Sculling is symmetric as rowers hold onto one handle of the oar in each hand directly in front of them and are able to pull straight back without having to twist. This form is mimicked in an ergometer. The second form, sweeping, is done on one side of the body and each rower has only one oar to manipulate. This is an asymmetric form of rowing that causes rowers to twist their upper body as they row. This form of rowing is done in a boat or tank. Boats have several configurations, and are known as “shells” for competitive racing. There is a four-person shell that allows for each rower to have control over two oars, mimicking sculling. There are two configurations for sweeping; one is in a four-person shell and the other is in an eight-person shell. These configurations are pictured in Figure 2.

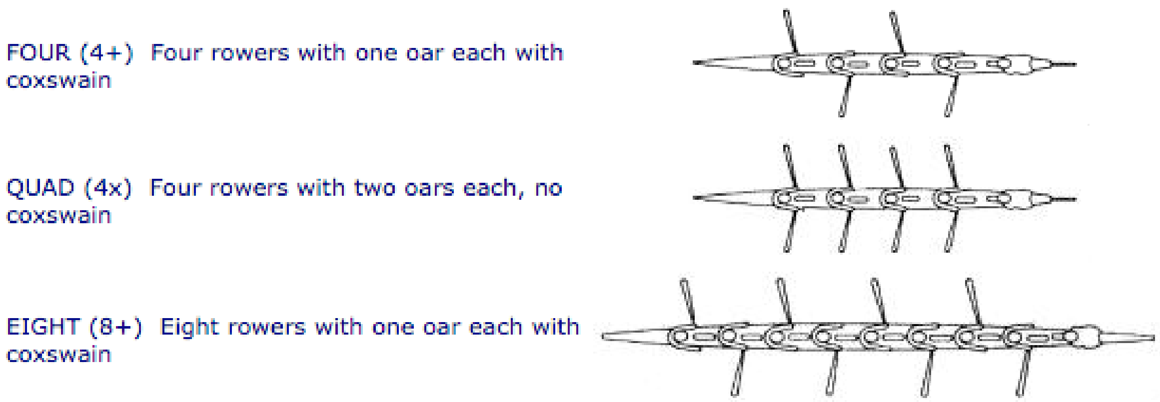


Figure 2. Configurations of boats for competition rowing.

The prospective design must be installed into a device or environment that closely mimics that of rowing on the water. Understanding a rower's movement is crucial to understanding the design ideas and constraints to ensure that the device does not impede a rower's technique. The UW Boathouse has a rowing tank, which is able to mimic the current of water as well as provide rower's with seating, oars, and overall environment similar to rowing while still being a controlled environment where conditions cannot change very quickly and suddenly. Coaches and rowers generally use this tank for form and technique correction. The tank houses 12 bases of the Concept2 RowErg lined up in a row to simulate a boat configuration, as shown in Figure 3. Figure 4 shows the footplate on the ergometer and its dimensions, which features a detachable heel portion called the Flexfoot that allows for rowers' heels to disconnect from the footplate and gain momentum when pulling back on the oar. Additionally, foot straps keep the rower's forefoot attached to the foot plate allowing the rower to pull back in using force generated from the front of the foot. The seat can freely move up and down along a bar, permitting the rower full extension of their legs.

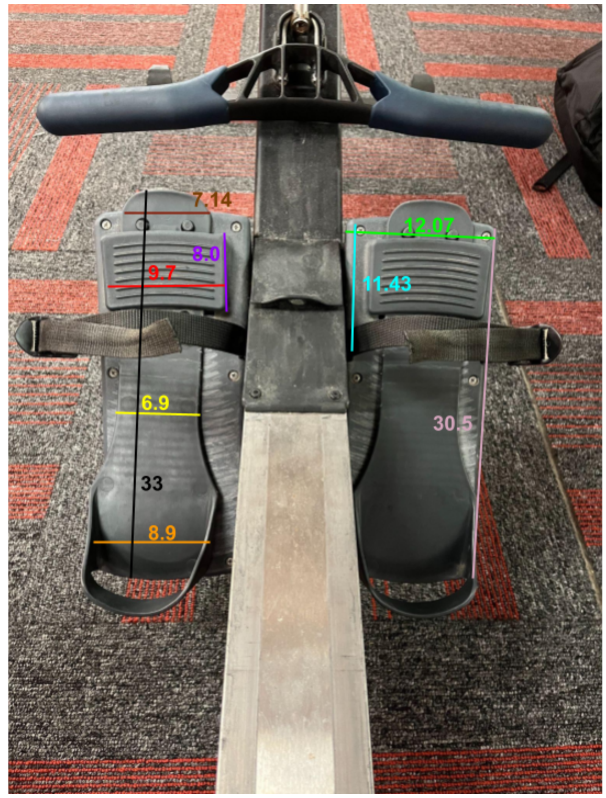


Figure 3 (left). Tank in the UW Porter Boathouse with Concept2 RowErg bases.

Figure 4 (right). Concept2 RowErg dimensions in cm.

Client Information

The clients that the team is working with include Dr. Jill Thein-Nissenbaum, Ms. Tricia De Souza, and Ms. Sarah Navin. All three work with and are representing the University of Wisconsin-Madison (UW-Madison) Women's Rowing Team. Dr. Jill Thein-Nissenbaum is a professor in the UW Madison Physical Therapy Program, and is the staff physical therapist for Badger Sports Medicine. She provides consultation and rehabilitation services for all UW Madison sports and works in the Badger Athletic Performance Center analyzing athletic testing performed on UW Madison athletes [12]. Ms. De Souza is a UW-Madison Athletic Trainer; in particular, she provides athletic training services for both the Badgers Men's and Women's Rowing Teams [13]. Finally, Ms. Sarah Navin is a UW Madison Physical Therapy student. She attended UW Madison for undergraduate school and was previously on the Badger Women's Rowing team.

Design Specifications

This product has several specifications that will determine how fabrication and design is approached. Most importantly, the product must be compatible with the Concept2 RowErg, as this is the ergometer used by the rowing team during indoor practices. This will entail taking certain dimensions into consideration, such as the ergometer's 61 cm overall width and footplate dimensions [4]. The device must not impede normal rowing motions, so it should not noticeably affect the shape of the ergometer. The main goal of the design is to provide real-time, relatively accurate measurements of rowers' magnitude of force so that any asymmetries can be corrected in the moment. As such, the force magnitude must be measured within a limited margin of error of 5% [14]. The product should be engineered to last a service life of around 10-12 years, approximately the length of an average rower's career [15]. Due to the year-round practice season for UW Madison rowers, as well as the wide temperature range experienced in Madison, Wisconsin, the product must withstand temperatures from around 8.3 degrees Celsius to 22.2 degrees Celsius [16]. The product should also be reproducible, with the end goal of interpreting data from 8 rowers in a boat at once. The full Product Design Specifications are outlined in Appendix A.

III. Preliminary Designs

Force-Sensitive Resistor

The Force-Sensitive Resistor design utilizes a Force-Sensitive Resistor (FSR), which decreases in resistance when compression is applied. As the resistor is compressed, more conductive elements within the FSR make contact with wires, which increases the electrical output. FSRs have a simple construction which makes them a cost-effective and accurate way to measure force magnitude [17]. The FSR design consists of four FSRs, with two mounted on each footplate of the ergometer to measure toe and heel forces throughout a stroke, as shown in Figure

5. The exact configuration of the FSR circuit is yet to be determined in testing; however, the team aims to begin with a voltage divider circuit as shown in Figure 6. The analog output voltage from the voltage divider will be processed by an Arduino. From an output voltage, the Arduino can calculate the resistance in the FSR using Equation 1, which can be correlated to the force applied to the FSR by using a Force-Resistance curve provided by the manufacturer of the FSR in use. The Force-Resistance curve will resemble that of Figure 7. A laptop connected to the Arduino will display the force magnitude in real-time as it is calculated.

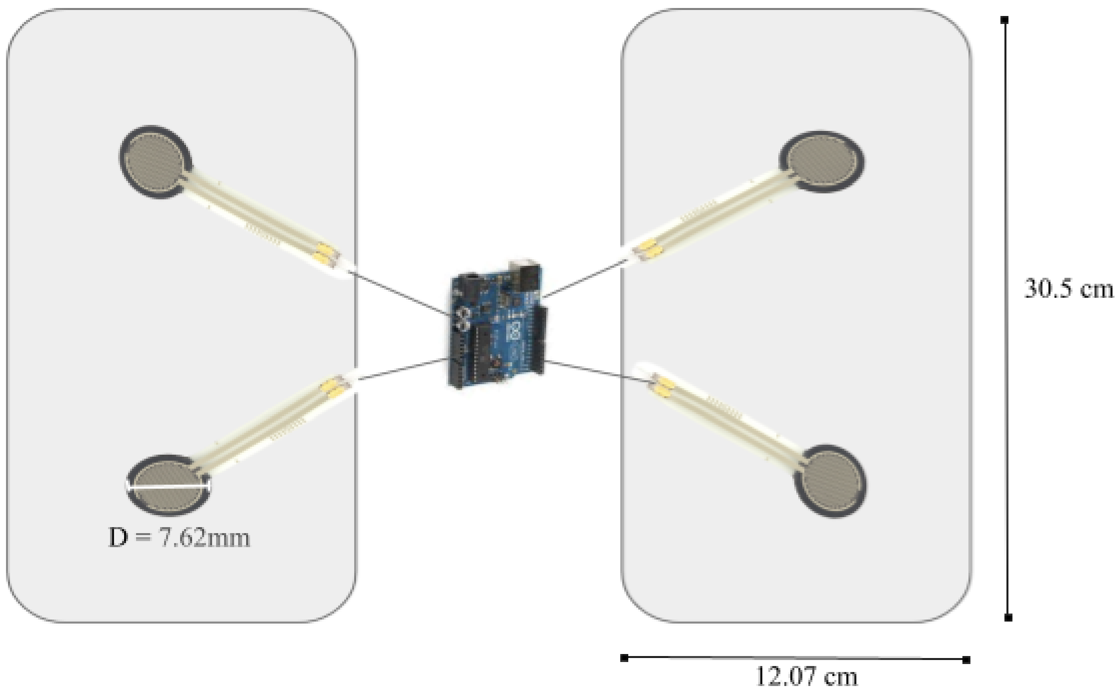


Figure 5. A schematic of the Force-Sensitive Resistor Design.

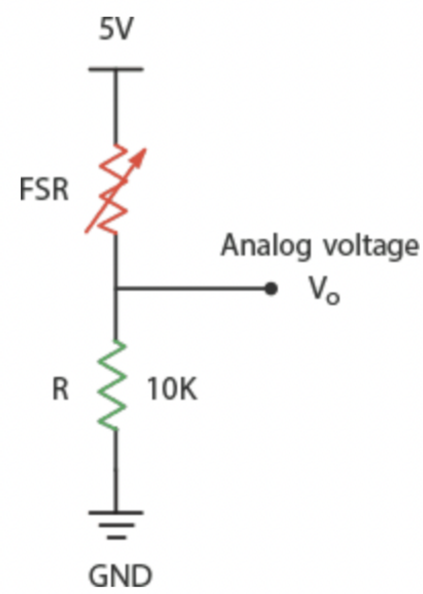


Figure 6. Example voltage divider circuit containing FSR [18].

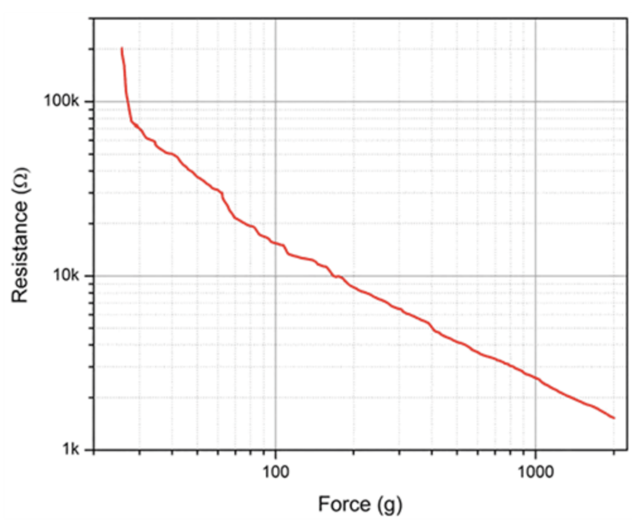


Figure 7. Example Force-Resistance Curve for an FSR [18].

$$V_O = V_{CC}(R \div (R + FSR) \quad (1)$$

Silicone-Magnetic Force Sensor

The Silicone-Magnetic Force Sensor preliminary design is centered around a set of handmade force sensors; that is, fabrication of said sensors would be completed by the team. These small sensors would gather data through the Hall effect, by both generating a magnetic field and an electric current [19]. Once the devices' magnetic field is disturbed, the electric current would be disrupted and the sensors would generate a reading to be processed by an Arduino and subsequently pictured on a display screen for rowing athletes. Given the ability of Hall-effect chips and sensors to measure compressive force, these sensors would hypothetically present accurate, helpful data [20]. The fabrication process would include 3D printing a PDMS silicone and rubber mold, filling the mold with a silicone and magnetic powder mixture that comprises the magnet upon setting, and aligning the constructed magnet via existing permanent magnets [21]. Once formed, the force sensors would be adhered to the ergometer's footplates – one on each corner of each footplate – and likewise connected to the processing Arduino through wires or a similar creation, as shown in Figure 8.

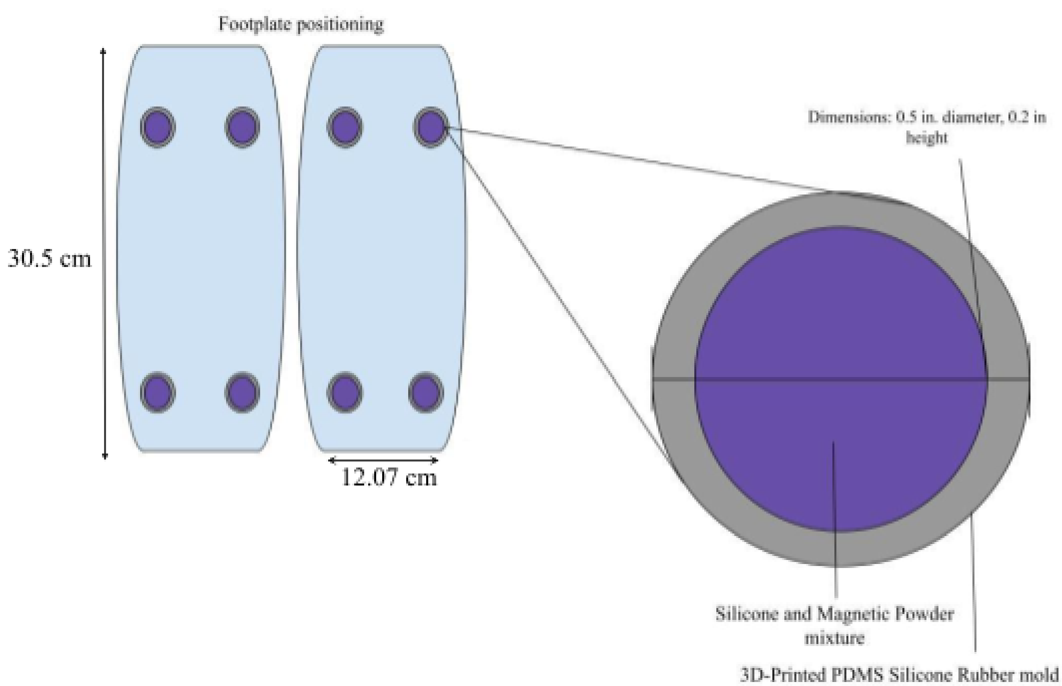


Figure 8. A schematic of the Silicone-Magnetic Force Sensor design.

Miniature Compression Load Cells

The third design is made up of miniature compression load cells, with one located on the heel of each foot pad. Load cells convert an input mechanical force such as weight or compression into an output, such as a resistance value. As the force applied to the force sensor increases, the electrical signal changes proportionally [22]. Individual load cells were chosen over a force plate as they are more cost efficient. The compression cells have a measuring capacity of 5000N and a sensitivity of 2.0±10%mV/V [23]. Each miniature load cell will be placed on a rectangular thin pad 3D printed out of PLA. The pads will then be screwed beneath the rowers foot pad in order to measure the rowers' load distribution in an uninhibited manner. The load cells will be wired to an Arduino that is connected to a digital panel meter or display monitor system.

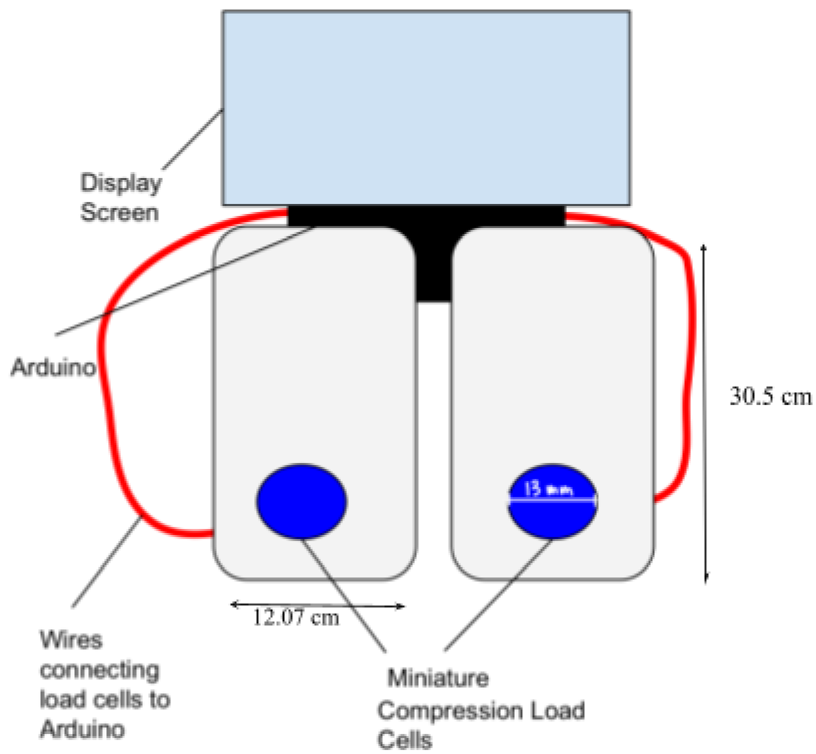


Figure 9: A schematic of the Miniature Compression Load Cell Design.

IV. Preliminary Design Evaluation

Design Matrix

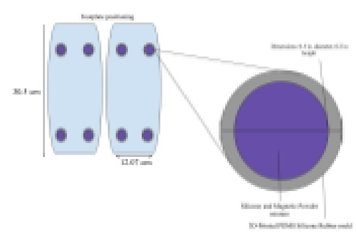
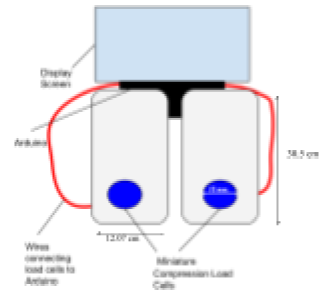
Force Sensor Location Decision Matrix:

Table 1: Design matrix used to rank the three location design ideas. Each category is rated by importance and is used to determine an overall score for each location.

		Ergometer 		**Boat** 		**Tank** 	
Criteria	**Weight**	Score (5 max)	Weighted Score	Score (5 max)	Weighted Score	Score (5 max)	Weighted Score
Safety	15	5	15	4	12	4	12
Compatibility	25	1	5	3	15	4	20
Resemblance	30	0	0	5	30	5	30
Complexity	20	3	12	2	8	4	16
Cost	10	3	6	3	6	3	6
Sum	**100**	**Sum**	**38**	**Sum**	**71**	**Sum**	**84**

Force Sensor Design Matrix:

Table 2: Design matrix used to rank the preliminary force sensor design ideas. Each category is rated by importance and is used to determine an overall score for each design.

		Force-Sensitive Resistor 		**Silicone-Magnetic Force Sensor** 		**Miniature Compression Load Cells** 	
Criteria	**Weight**	Score (5 max)	Weighted Score	Score (5 max)	Weighted Score	Score (5 max)	Weighted Score
Cost	15	5	15	3	9	2	6
Safety	15	3	9	3	9	4	12
Ease of Use	20	4	16	4	16	5	20
Compatibility	15	5	15	4	12	4	12
Functionality	25	4	20	4	20	5	25
Reproducibility	10	4	8	3	6	3	6
Sum	**100**	**Sum**	**83**	**Sum**	**72**	**Sum**	**81**

Design Evaluations

Location Matrix Category Descriptions and Evaluations:

The design matrix to determine the best location to install our device includes the following criteria: safety, compatibility, resemblance, complexity, and cost. Safety is to measure the degree of risk to the user in each location. Compatibility is to determine which location will best fit the device and how transferable to other locations the device can be based on the original location. Resemblance is to consider how similar the location will be to actual rowing. The next criterion, Complexity, is to decide how many outside considerations, based on environment and use, we will have to take when implementing our design. Cost is a criterion to ensure that we are taking into account the budget constraints before moving forward with a design and location.

Location Score Distributions:

The ergometer came in last place between the three locations, with a total of 32. A score of 5/5 for safety was given because the ergometer should be in dry conditions, and therefore electronics or cords near water is not a concern. It is also the simplest location, with a very straightforward rowing mechanism that the device should not interfere with. The ergometer scored a 1/5 for compatibility because the design would have to modify the ergometer greatly in order to represent real rowing. A score of 0/5 for resemblance was given for the ergometer because it poorly represents the true asymmetrical rowing motion. Athletes are able to be much more symmetrical on the ergometer because they pull straight back, with near even force distribution. However, this poorly represents the full rowing motion in water. In terms of complexity, this location was given a 3/5. Due to fewer environmental factors since the ergometer is indoors, a somewhat higher score for complexity is given. Waterproofing or being able to adapt to climates is not a consideration for the ergometer, giving it a better score. The cost for all three locations should remain similar, as they will all use a similar mechanism. A 3/5 was given for cost, as the design overall is somewhat expensive, but should not vary greatly from design to design.

The boat overall came in second place of the three locations, scoring a total of 71. Firstly, the boat was given a 4/5 in Safety. The design should hardly impact the crew in the boat, but will involve circuitry on open water. Next, the Boat received a 3/5 in Compatibility, as the design will be able to fit comfortably under the footplate in the boat, but will need to be waterproofed. This location scored a 5/5 in Resemblance, as the client's ultimate goal is to have the final design compatible for the boats. For Complexity, the boat scored the lowest again due to waterproofing, and the need for data to be collected portably. For the last category, Cost, the boat scored a 3 with thoughts that waterproofing the design may contribute to additional expenses.

The tank location received a total score of 84. The tank is located in the UW Boathouse, made up of lined up ergometer machines that sit next to a stationary tank of water with controllable current. The tank was given a 4/5 in Safety, as it is a controlled indoor machine. The location also received a 4/5 for Compatibility, as the tank is more similar to an actual boat than the ergometer; however, the footplates for the tank are more similar to the ergometer than in the shells. The tank scored complete marks in Resemblance, as it allows for sweeping and can emulate similar conditions to rowing on the water. The tank location was given the highest score for Complexity with a 4/5, as it does not require our force sensor to be waterproof. The Tank was also designed by UW Engineers, so we would be able to find their resources if needed for designs. Finally, the Cost of the tank received the same score as the others with a 3/5, as the materials needed to build our design would be very similar across all locations. With these scores, the tank location overall scored the highest of the three.

Force Sensor Design Matrix Category Descriptions and Evaluations:

The design matrix to determine the best design includes the following criteria: cost, safety, ease of use, compatibility, functionality, and reproducibility. Cost is a criterion to ensure that we are taking into account the budget constraints before moving forward with a design. Safety is to determine the degree of risk the device may pose to the user. Ease of Use is to ensure that the rower's technique is not impeded in any way and that any additions to the design are user-friendly. Compatibility is to consider how the device will fit into a location, how transferable it is between locations, and what alterations are necessary to the current setup or the design. Functionality considers the accuracy, reliability, and longevity of the device. Finally, reproducibility outlines how easy the device is to implement for multiple rowers or in a boat.

Force Sensor Design Explanations and Score Distributions:

The force-sensitive resistor design received an overall score of 83/100, making it the highest scored design. It received a 5/5 in the Cost category, because force sensitive resistors can be purchased within budget for roughly $200 [24], and the team already has access to accompanying circuitry at little to no cost. The design received a score of 3/5 in the Safety category because the resistor and accompanying circuitry will be connected to wall power, which poses a risk to the rower in case they come in contact with any of the elements or the circuit malfunctions. A 4/5 was awarded in the Ease of Use category because the computer display that accompanies the rower will not be mounted directly to the tank ergometer, so the rower and the coach may have difficulty viewing the real-time data. The design received a 5/5 in the Compatibility category because it will not require any modification of the current tank ergometer system. The design earned a 4/5 in the Functionality category because the sensors will be placed underneath the footplate, which will affect the accuracy of the magnitude of the forces applied. Finally, the design received a 4/5 in the Reproducibility category because the force-sensitive resistor can be easily damaged, so it may have to be replaced often.

The Silicone-Magnetic Force Sensor scored highest in Ease of Use, Compatibility, and Functionality. This device would be planted directly onto the footplates of the tank, erg, or boat; however, due to its projected smaller size, it would not be likely to interfere with the rowers' technique and would fit in and be transferred between all of the considered locations quite easily. Thus, it scored a 4/5 in both Ease of Use and Compatibility. It would also involve use of magnetic sensors and communicating results through a microcontroller to a display, which is a process that would not be overly complex, but may be difficult for rowers and coaches alike to view in real time. As such, this design scored a 4/5 in Functionality. It received middling scores, 3/5, in both Cost and Safety, as the current cost of production and logistics of installation and use are unknown. Finally, considering that this design would involve constructing new magnetic sensors out of magnetic powder and silicone, potentially indicating a long and complicated fabrication process, it received a 3/5 in Reproducibility. This design therefore scored the lowest of the three.

The Miniature Compression Load Cell design received an overall score of 81. The design scored full points in the Functionality and Ease of Use category. Load cells are very reliable and produce results with 5% accuracy and can be used over the long rowing practice times without wearing down [23]. The design can also be integrated easily into the foot plates due to their small size and won't impede on rowing technique. The load cell design received a 2/5 score in the Cost category because load cells can cost upwards of hundreds of dollars and this will exceed our budget. Additionally, the load cell design received a 4/5 in Safety due to the fact they will be connected to circuitry which can pose risks if it comes into contact with water; however, there are many methods to waterproof components in the circuitry including 3D-printing covers for the load cells. The design received a 4/5 in the Compatibility category because load cells will be embedded effectively within the footplate and won't require any drastic changes in the tank foot plates. Load cells can also directly measure force magnitude and won't require any conversion but they will require a lot more knowledge of coding and software than the other designs. Lastly, the design received a 3/5 in Reproducibility because of the high cost, reproducing will be difficult within our budget.

Proposed Final Design

The team decided to move forward with placing the force sensor in the tank in the final design, because it most accurately resembles the action of real rowing while remaining both cost-effective and easy to implement. This evaluation is reflected in the location matrix, in which the tank received the highest score. In addition, the rowing team already examines rowers' form in the tank, and placing the device there would accompany this practice well. Finally, since the tank uses the Concept2 RowErg base, the design can be transferred to the ergometer to test sculling as well. For the final design, the team proposed a load cell as the force sensing method despite it scoring slightly lower on the design matrix. The load cell has direct force reading capabilities; it does not require a complicated circuit and analysis of variable resistance, but rather comes with accompanying firmware that will do that processing automatically before interfacing with the display. This allowed production of the prototype to occur within the given timeframe. In addition, the FSR can exhibit some nonlinearity and is not always accurate throughout the entire sensing area, whereas a load cell is more reliable. Though a load cell may interfere with the geometry of the existing footplate, the team proposed 3D-printing or fabricating a housing for the load cell that can be adhered onto the footplate. For the display element, the Arduino's Serial Plotter tool will be utilized, as it can plot data from the Arduino in real time.

V. Fabrication/Development Process

Materials

The device consists of a load cell enclosed in a housing block fastened onto the footplate of an ergometer. The circuit is placed in a separate housing box that connects to a laptop for display. The full materials and cost list to fabricate the device can be found in Appendix B.

The load cell circuit consists of several key components and materials designed to measure and respond to varying levels of force or pressure. The device consists of a

200kg-capacity HX711 load cell that contains four strain gauges in a Wheatstone Bridge configuration. Applied force on the load cell causes changes in the resistance inside the load cell that are then read and interpreted through an Arduino Uno microprocessor.

The load cell is connected to an Arduino using its compatible HX711 amplifier to amplify the signal of the variable resistance of the load cell. The Arduino is a microcontroller board and analog-to-digital converter which will store and execute code written in the Arduino IDE [25]. A USB cable is used to connect the Arduino to a laptop which will function as the power source and will be used for viewing the real-time force vs time graphs produced during rowing.

To house the load cell on the footplate of the ergometer, a plate was fabricated using HDPE found in the TEAM Lab. A steel plate also from the TEAM lab was used to sit on top of the load cell to act as a rigid surface for the foot. Additional HDPE and metal plates were used to even the footplate's surface. Lastly, Velcro strips were used between the plates and the ergometer's footplate to attach the device such that it could be repositioned to different rowers' anatomical variations.

Methods

The fabrication of the load cell design consisted of two main processes: the circuit connecting the load cell to the Arduino, and physical embedding of the load cell into the ergometer. Building the circuit began with a 200kg-capacity HX711 load cell. The load cell was connected to its amplifier through four wires, each corresponding to a node of the Wheatstone bridge inside the load cell. The amplifier allows signals from the load cell to be read by the Arduino. Finally, the Serial Plotter tool on the Arduino creates a live feedback display of the change in force over time when loads are applied. The full circuit diagram is shown in Figure 10.

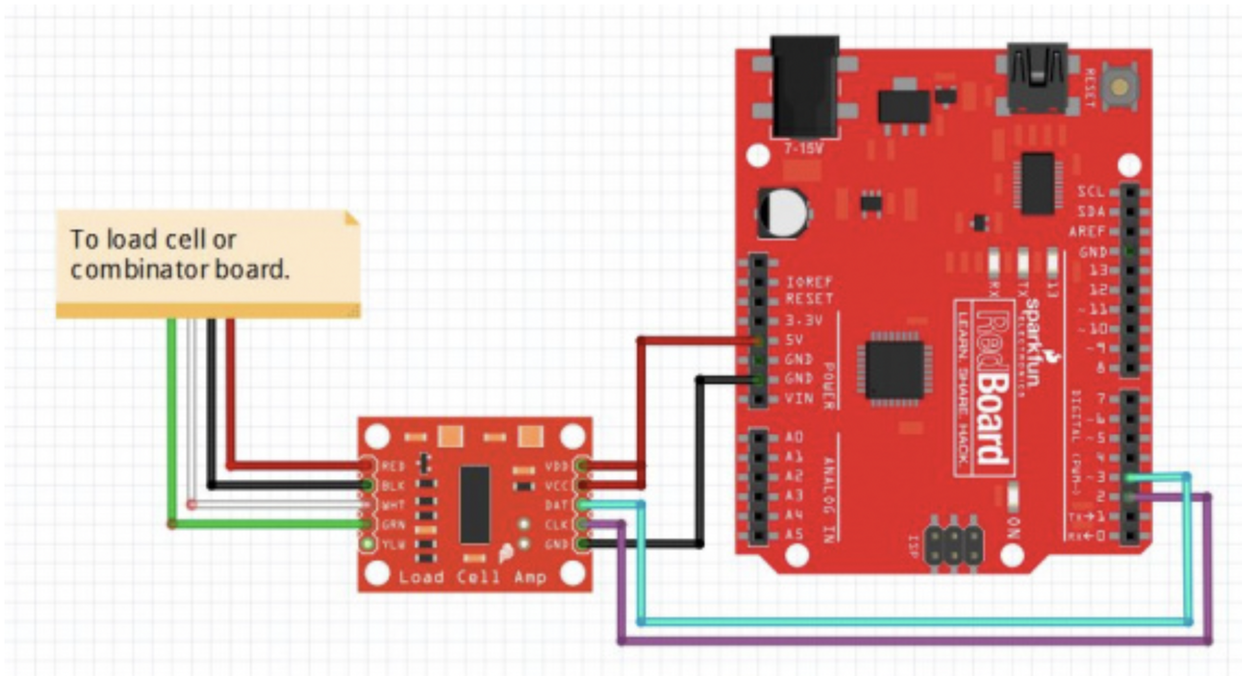


Figure 10. Circuit diagram for connecting the load cell to the Arduino board [26].

The final step of the fabrication process was to create a way for the load cell to be embedded into the ergometer without impeding a rower's natural movement. Two plates were created using HDPE found in the TEAM Lab. The first plate, to hold the load cell, was trimmed using a bandsaw, and then drilled with a 51/64" drill bit as shown in Figure 11. This created a space for the load cell to sit. A metal plate was placed on top of the HDPE plate and secured using velcro and duct tape. The entire load cell housing was placed on the ergometer using velcro at the approximate location of the rower's metatarsophalangeal joint. The second plate was trimmed with a bandsaw according to the dimensions in Figure 12, and placed at the heel of the ergometer using velcro. This plate was created to keep the full foot on an even surface while rowing. A full fabrication protocol is found in Appendix C.

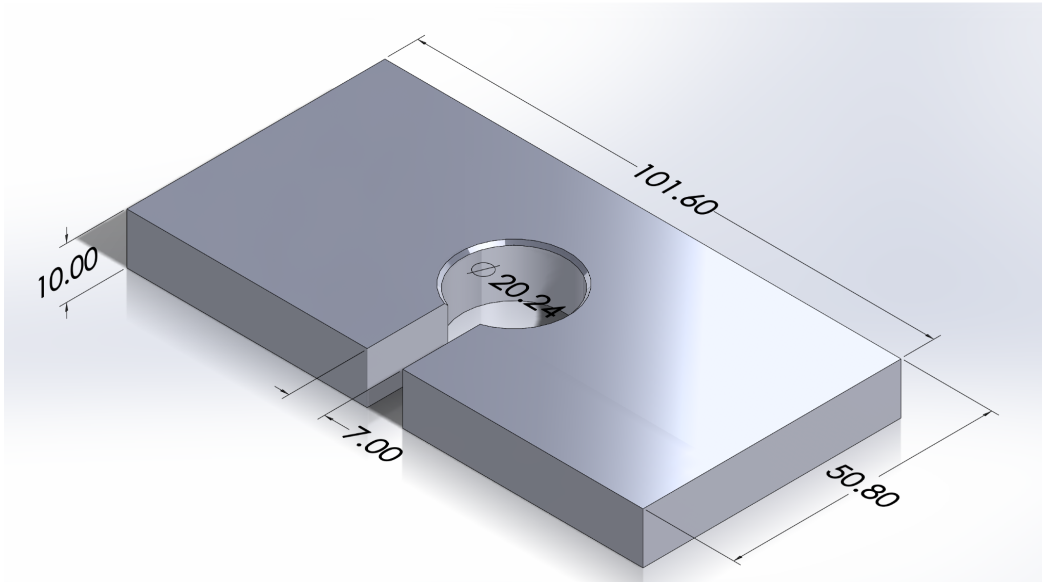


Figure 11. Load Cell Housing Plate. Dimensions are in mm.

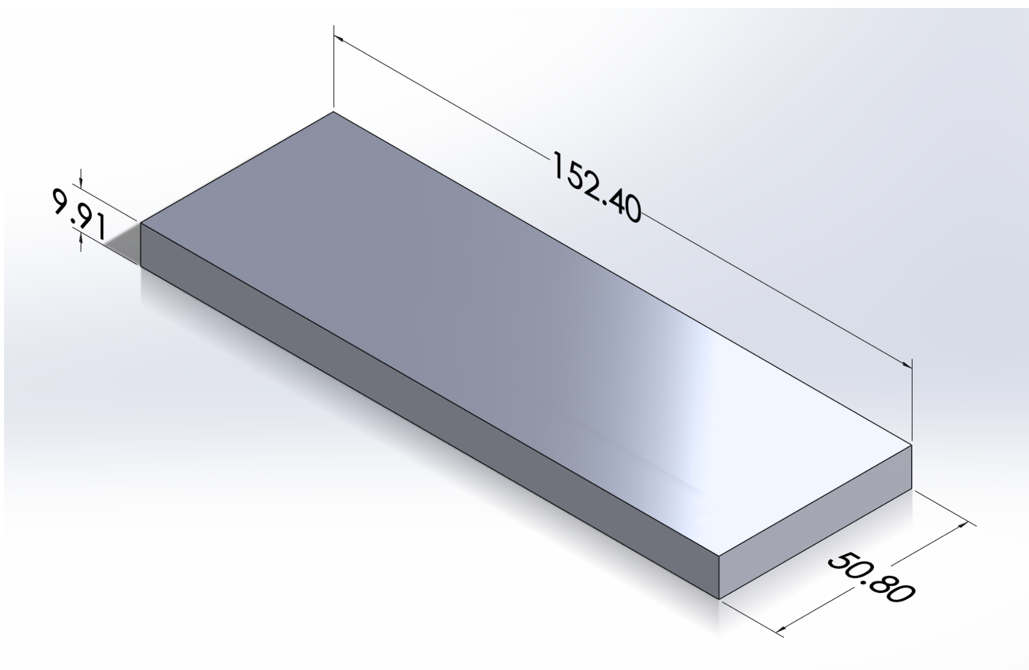


Figure 12. Heel Plate for the footplate. Dimensions are in mm.

Final Prototype

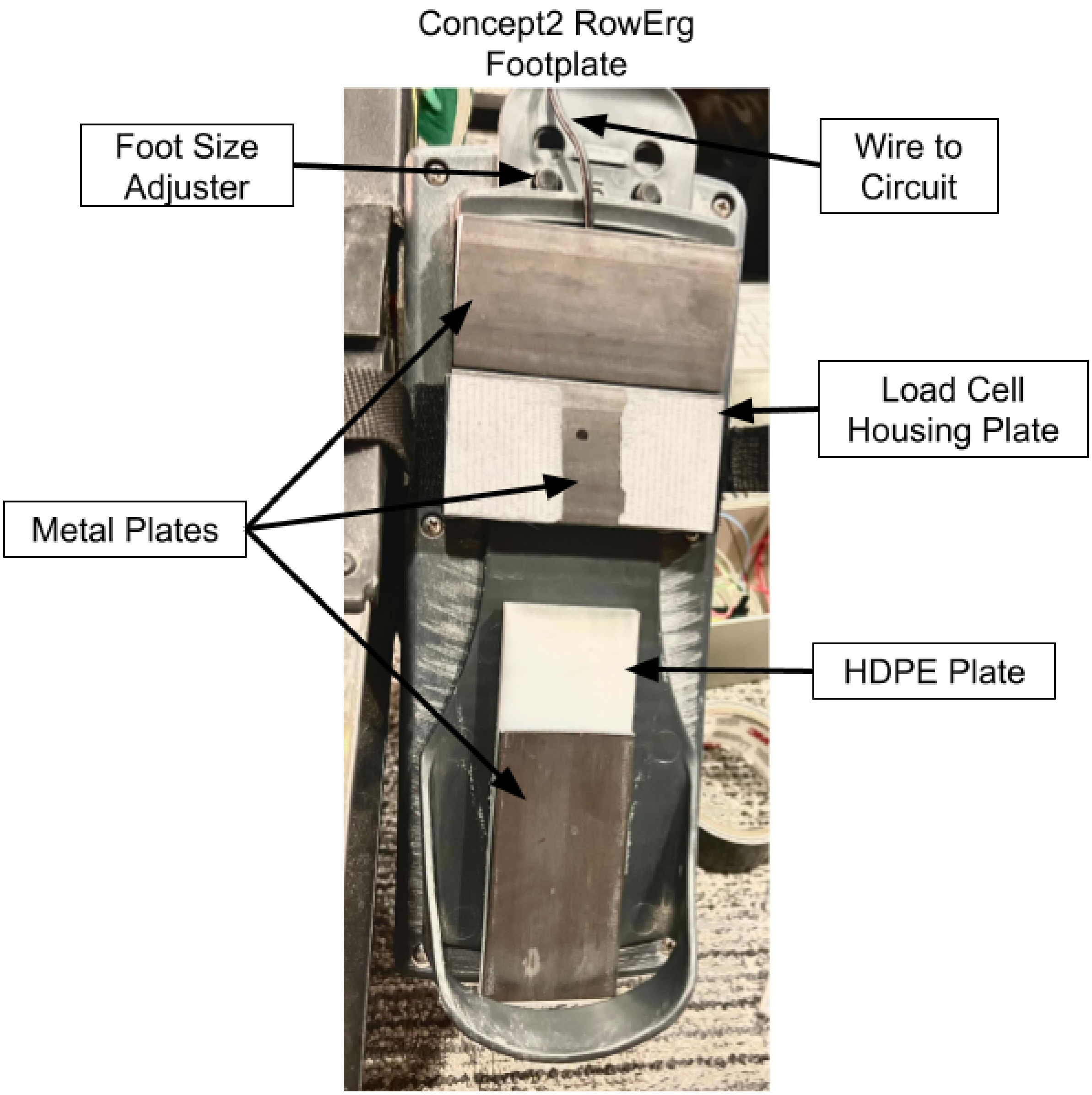


Figure 13: Final Prototype on the right footplate of the ergometer.

The final prototype consists of one load cell plate connected to a circuit and computer, and is transferable from one foot to the other. The load cell is housed in a HDPE plate, placed below the toe pad of the ergometer, in order to have the highest possible contact with the ball of the foot where the most pressure occurs during rowing. In order to adjust for the added height from the load cell plate, additional HDPE and metal plates were adhered to the heel of the footplate to level overall foot contact. A metal plate was also added to the toe of the footplate for additional leveling after receiving user feedback. All plates are adhered to the ergometer's footplate by 2 inch velcro strips, allowing for easy removal. The design is compatible with the ergometer's Flexfoot. As seen in Figure 10, the load cell housing block is located over the slider, allowing adjustment based on rowers' shoe size, which meets design requirements of the Customer section from the PDS, found in Appendix A.

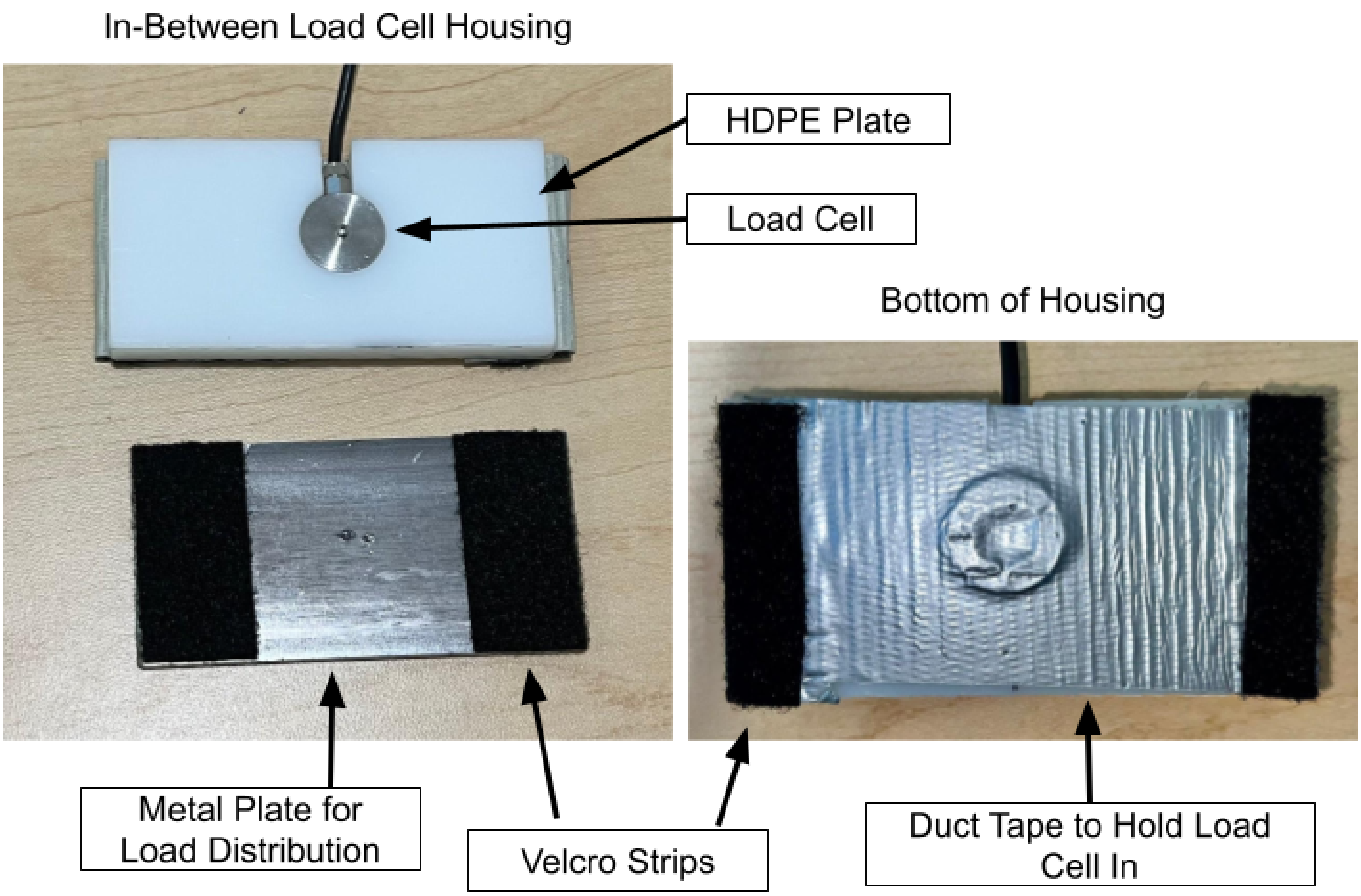


Figure 14: Deconstruction of the load cell housing plate.

A 10 mm hole was cut into the HDPE where the load cell rests and a slit for its wire to feed out from. The load cell's point extends above the HDPE housing block. A metal plate was fixed on top of the load cell, to better concentrate the applied force to the point load. Velcro strips were situated between the metal plate and plastic plate to counteract tilting and translation of the plate. Duct tape was used to assemble the plates, as well as to keep the load cell from falling out the bottom. Additional Velcro strips attach the housing to the footplate.

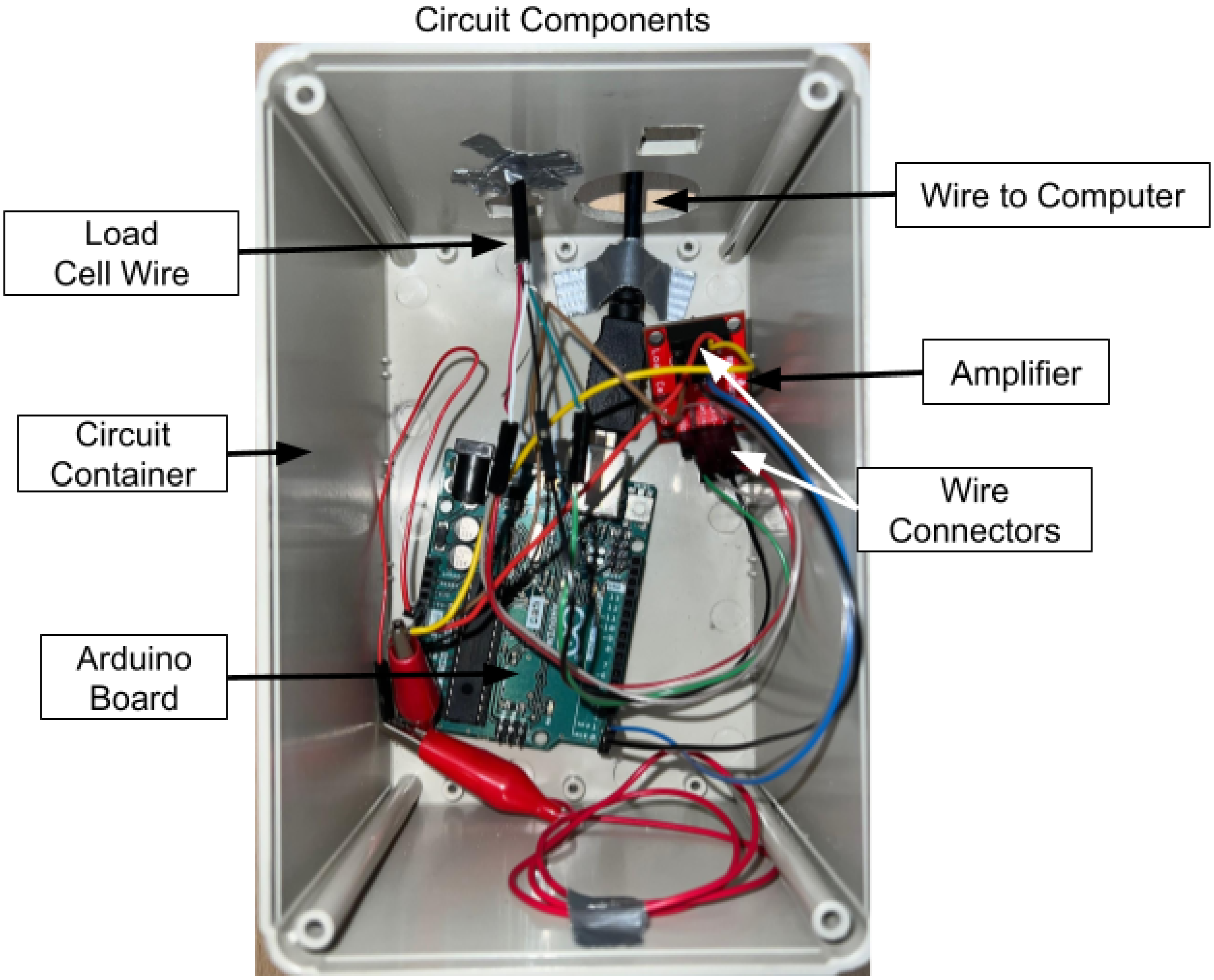


Figure 15: Final Circuit Prototype

The circuit wiring was placed in a container to hold components for simple transportation. An Arduino Uno board is connected to the load cell and its compatible amplifier. Two wire connectors were soldered to the amplifier for assembly. Wires and alligator clips connect the three components. The Arduino was connected to a computer with a USB cord for data interpretation.

Testing

The purpose of the testing procedure was to ensure that the load cell circuits accurately and reliably captured the forces exerted from the three phases of weight exertion. The three phases included calibration using smaller known weights, measuring team members' weights, and measuring a former UW rowing athlete's force exertion on the ergometer. The first phase of calibration involved measuring and recording the load cell output of a known 500 g and 1 kg weight for five trials to ensure repeatability. Calibration procedure followed the documentation of the purchased load cell [26], and a full calibration protocol can be found in Appendix D. The process of load cell calibration involved commencing with a 500g weight that was strategically positioned on the load cell within its housing to ensure the point load area fully captured the weight. A full calibration protocol can be found in Appendix D.The calibration factor in the Arduino code in Appendix F was systematically adjusted until the recorded readings were in precise alignment with the actual weight. This calibration procedure was subsequently replicated for a 1kg weight. Once a consistent calibration factor was achieved, it served as a baseline for measuring the weights of team members in the second iteration of testing.

For the second phase of testing, all six team members balanced on the load cell prototype and the most consistent force reading was recorded. The most consistent reading was the value that displayed most often on the serial monitor of the Arduino while the subject balanced on the load cell within its housing. Two trials of measuring weight for each subject were conducted to measure reliability. The actual and expected value for each team member's weight was recorded. This second phase of testing was to ensure the calibration factor from phase one was reliable. Since the load cell measured approximately to the team members' body weight, the calibration factor was not adjusted further.

The third phase of testing involved executing in-person testing with a former UW rower in order to evaluate the load cell's performance with rowing movements. The load cell prototype was placed on one of the ergometer's foot plates near the center of pressure of the foot while rowing. The load cell housing was affixed securely using duct tape with additional HDPE blocks fastened with tape on the heel of the foot plate. The subject then engaged in multiple 40-60 second intervals of rowing at a steady state, with a real-time force output display and simultaneous data storage on the Arduino. Throughout the testing phase, modifications were made to enhance the device's positioning and attachment. The load cell housing was moved downwards on the footplate to achieve better alignment with the subject's metatarsophalangeal joint. Additionally, Velcro was introduced as an alternative method of attachment, showing promising results in terms of stability. This iterative testing and refinement process aimed to optimize the load cell's functionality and reliability during ergometer use. With the final changes, two trials of steady state rowing were conducted on the left leg and one trial on the right leg.

Throughout all the testing, the team ensured that the baseline and full-force calibration values remain consistent over time. After data collection, the team analyzed the load cell data from Arduino's EEPROM to evaluate the athlete's force distribution during the steady-state training session and when they shift weight onto one leg. A successful load cell design would result in distinct force magnitude readings between each leg when the team members and athletes exert force through rowing or balancing. During steady state rowing, the load cells should detect around 900 newtons (within 5% margin) for the peak force of rowing which is the catch to drive position [27].

VI. Results

After the load cell was calibrated as described above, several team members and the rower test subject stood on the load cell and maximum readings were recorded in Table 3 after the subject was balanced with as much of their weight over the load cell as possible. Percent error of the load cell reading was calculated to be an average of 1.43% across five test subjects, which is below the PDS criteria of 5% error.

Table 3. Load cell readings as compared to actual weight of test subjects.

Subject	Actual Weight (N)	Load Cell Reading (N)	Percent Error
1	889.64	889.64	0%
2	524.89	520.44	0.85%
3	511.55	498.20	2.61%
4	600.51	578.27	3.70%
5 (Rower)	778.44	778.44	0%
		Average Percent Error	1.43%

To visualize testing data from the rower, the force readings that were stored in the Arduino EEPROM were read and imported into MATLAB. The force readings were plotted against time to produce Figure 16(A) through 15(E). Time values were assumed based on the delay of the Arduino loop, which was set to record data every 50 ms.

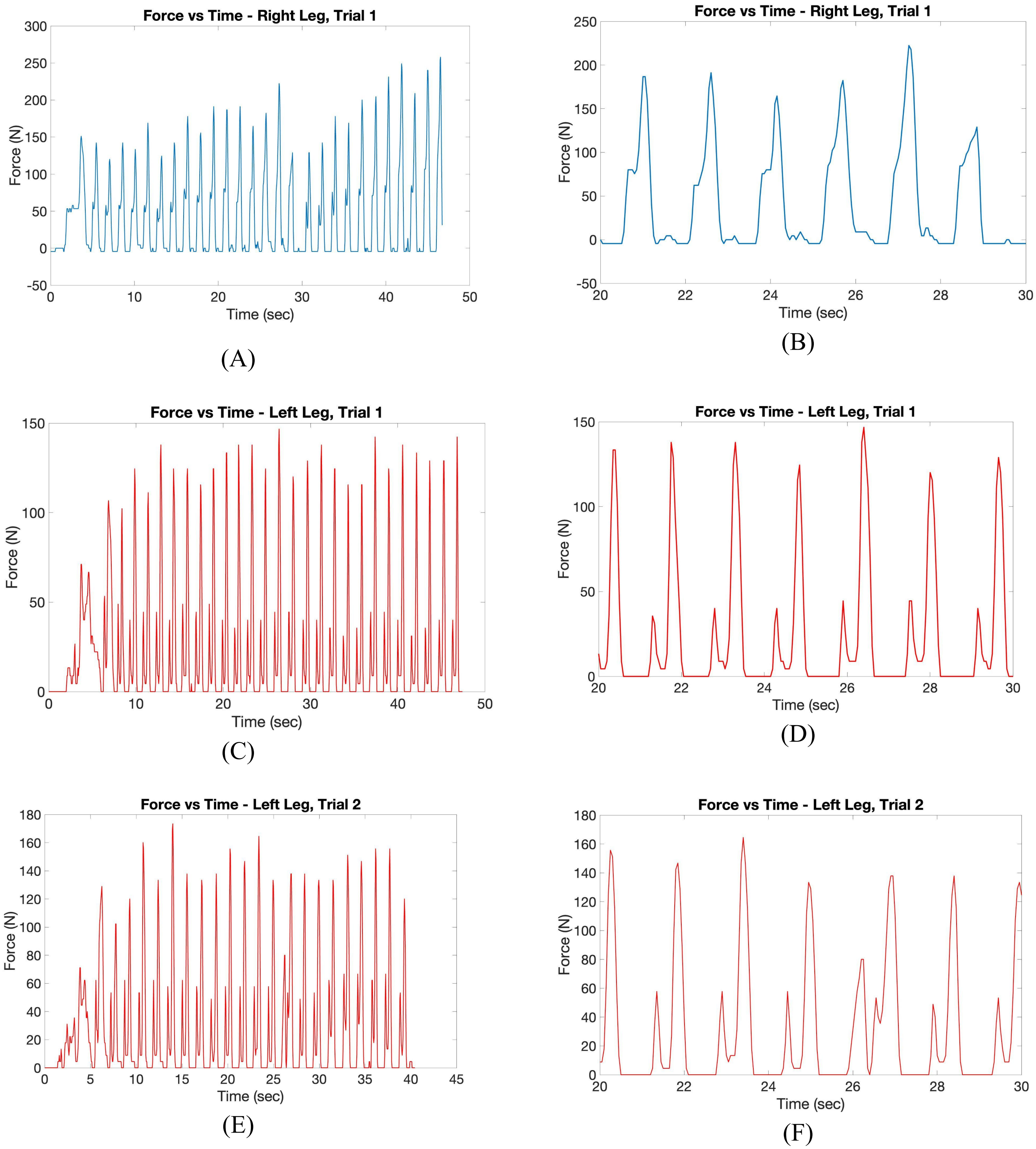


Figure 16. Force vs time graphs for each trial conducted. (A), (C), and (E) show the full testing time and (B), (D), and (F) isolate a ten-second interval.

For each stroke, two peaks can be observed: a tall primary peak and a smaller secondary peak. Table 4 shows the average primary peak force values for each trial. Between the two trials on the left leg, there was a 7.29% difference in average peak force value. Between the trials on the right and left legs, there was a 29.5% difference.

Table 4. Average peak force value for each trial.

Trial	**Average Primary Peak Force (N)**
Right leg, Trial 1	176.3402
Left leg, Trial 1	131.0203
Left leg, Trial 2	140.9277

To analyze the above rowing data for asymmetry, Trial 1 of steady-state rowing on the right and left were further divided into three ten-second intervals to increase the number of trials in our dataset. For each 10-second bin on the right and left side, peak force values were found and a two-tailed, paired t-test was performed to assess the significance in asymmetry. The interval from zero to ten seconds was omitted to allow the rower time to reach steady state. Since a family-wise comparison of t-tests was being performed, a Bonferroni correction was used to adjust the p-value for each interval, as calculated in Equation 1. Table 5 shows the p-values for each of these trials, and Figure 17 shows the distribution of peak force values on the right and left sides.

$$\alpha^* = \frac{\alpha}{\binom{k}{2}} = \frac{0.05}{3} = 0.0166667 \quad (1)$$

Table 5. P-value by time interval for a Trial 1 of steady-state rowing on the right and left side. The significant p-value is colored in red.

Time Interval (sec)	**P-value (α = 0.016667)**
10-20	0.02225
20-30	0.00536
30-40	0.02243

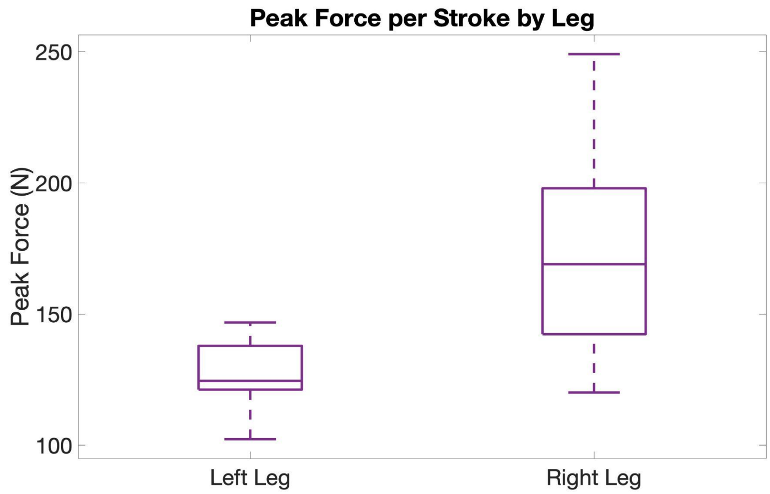


Figure 17. Boxplot of peak forces per stroke on left and right leg from Trial 1.

VII. **Discussion**

Implications of Results

After calibrating and testing the device, the team was able to make several conclusions about the device's efficacy and the results it revealed. Firstly, the team could verify that a load cell is a reliable force sensing method through its calibration method. The Arduino code in Appendix F was used to calibrate the load cell to an average percent error of 1.43% over five trials, which meets the PDS criteria of sensing force to an accuracy within 5% (Appendix A). However, more trials are necessary to determine the reproducibility and repeatability of the device. There was a 7.29% difference between the two trials on the right and left leg, which is over the 5% threshold set by the PDS; it is unclear whether this was due to the test subject's variability or the device itself. In order to make this determination, more trials would need to be conducted on this test subject, as well as on other subjects.

Regarding asymmetry of the rower, there was one significant p-value between the three t-tests that were conducted on data from the right and left legs. Despite the percent difference in average peak force magnitude being almost 30%, there was not significant asymmetry across multiple time intervals so we cannot conclude the rower consistently exhibits asymmetry. The high percent difference could be attributed to the fact that the rower's steady state may have been reached at a different time on the right leg than on the left. In addition, this difference in magnitude could have been due to human error as the data from the right and left legs were not collected simultaneously. Again, more trials are necessary to fully understand the extent to which this discrepancy was due to device error or true rower asymmetry.

The team also conducted a biomechanical analysis of the force profile of a stroke. On our test subject, a two-peak force profile can be seen. There is an initial, smaller peak, a slight taper (as seen in the right leg) or steep dropoff (as seen in the left leg), and a final large peak. After visually correlating the force profile with the phases of rowing as seen on the test subject, the team concluded that the initial smaller peak corresponds to the drive phase, where the rower initiates leg extension, and the larger peak that occurs immediately after that corresponds to the finish phase, where the rower pushes to complete extension. These discrete peaks can be seen more in the left leg than in the right as in Figures 16(B) and 16(D), revealing that our test subject most likely favors their right leg during extension and is more fluid in their motion on that side. Consultation with the University of Wisconsin Rowing Team coaches revealed that an ideal rowing force profile does not have the double-peaked structure observed on our subject, but rather is a smooth, single-peaked curve.

Sources of Error

Since this device is an initial prototype, it presented several potential sources of error. Using an Arduino for the necessary circuitry, firstly, allowed for technical issues to arise. The Arduino loop, for example, was set to a constant 50ms delay to prevent overwriting to the EEPROM. This meant that the Serial Plotter display was 50 ms behind real-time rowing. Additionally, the Arduino's EEPROM can only store integer values; as a result, readings were rounded for storage, reducing the prototype's accuracy [5]. When calibrating the load cell within its housing, the lowest weight placed upon the device was 500g. Due to this decision, any output that resulted in an exerted force less than 500g would not be represented correctly on the device's display.

The shape of the load cell, despite providing the necessary measurement capacity of 200kg, was not the ideal choice for the prototype [28]. Due to the cell's disc shape, it aptly recorded the heavy compression loads exerted by users, but likely only quantified a one-directional force component, meaning that possible relevant torques were not depicted [29]. In addition, the plate on top of the load cell could not accurately transmit all the force from the foot to the pin on the center of the load cell; therefore, due to other parts of the device absorbing force, our force values may have been lower than the actual values.

Finally, the different placements of the load cell device upon the footplate affected the accuracy of the reading. Aligning the housing with the metatarsophalangeal (MTP) joint, which is key to regulating force generation in muscles of the foot such as the toe flexors, more fully represented the heavy compressive force applied by rowers [30]. However, given the method of attachment of the prototype to the ergometer's footplates utilizing supplies such as velcro and duct tape, the device's shifting positioning could result in imprecise data collection. In addition, the alignment of the subject's MTP joint with the prototype was done qualitatively and may not have been exactly the same between feet.

Ethical Considerations

The design does not infringe on Bylaw 10 in NCAA Division 1 Legislation [31] as it cannot be used to give improper financial aid or banned substances to athletes, and cannot be used in sports wagering. In addition, the device fits well within NCAA regulation on practices or athletically-related activities [32]. The design will also take into account confidentiality of rowers' data in accordance with HIPAA, as rowers can be considered patients of the athletic trainers they work with. HIPAA guarantees that patient data will remain confidential between a patient and their provider [33]. Therefore, rowers' data will be stored on the Arduino only until it can be loaded onto a secure computer. After secure storage, it will be cleared from the EEPROM using the EEPROM Clear function of the Arduino [5].

Future Work

Though the device is accurate as specified by the Product Design Specifications, alterations and additional testing are necessary to ensure that it meets the full requirements as specified. Most importantly, a second load cell should be added and integrated into the display such that data can be collected from both legs at the same time. This would allow a more accurate assessment of the degree to determine whether the asymmetry observed between legs was as a result of two separate trials or purely due to the subject's form. In addition, a second integrated load cell and display would allow the rower to respond to the biofeedback on the display and adapt in real-time.

Changing the type of load cell shape would increase the precision of force measurements. Switching from a point force load to a straight bar load cell allows for greater surface area contact between the cell and the user, instead of having to concentrate the force to a single point [34]. The metal plate on top of the point load cell in our current design would not be needed anymore with a bar load cell, eliminating a potential source of error for data collection and fabrication.

An additional round of testing in the tank at the UW Porter Boathouse is also necessary to fully gauge asymmetry during sweep rowing, since sweep rowing is believed to be the primary cause of back pain due to asymmetry. The device should be tested on multiple rowers to gain an understanding of subject-to-subject variability in rowing form and force profiles. This testing could also be coupled with a motion-capture analysis and inverse kinematics to get a complete picture of how a rower's motion affects the force profile observed.

Further projections of device implementations involve use on the water. Once tested and observed in the tank, the design could be relocated to an 18.9m long shell, or an eight-seater rowing boat used for races shown in Figure 1. Gathering data from outdoor racing conditions would require waterproofing of the device and circuitry. The user interface would also need to be suitable for outdoor conditions. Usage of the device on the water would result in the most accurate data available for the UW Rowers to utilize.

VIII. Conclusions

The development of a real-time biomechanical measurement device for assessing lower extremity force in rowers is crucial towards addressing lumbar spine and enhancing overall performance within the UW-Madison women's rowing team. The adaptable design, incorporating a point load cell, HDPE plates, and Arduino-coded circuitry, is a practical and transferable solution that aligns with customer specifications. In-person testing with subjects with rowing experience highlighted areas for improvement, including integrating multiple load cells for simultaneous data collection, a unified display for efficient comparison, and altering the load cell's shape for enhanced accuracy. Future work emphasizes ongoing refinement, encompassing waterproofing circuit components, application in longer rowing shells, and continuous optimization for broader usage in competitive rowing. The collaborative effort signifies a promising step toward innovative solutions in injury prevention and biomechanics within the realm of elite rowing.

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X. Appendix

Appendix A: Product Design Specifications

PRODUCT DESIGN SPECIFICATIONS: FORCE PLATES FOR ROWING BIOMECHANICS

BME 300/200, Section 303

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Advisor: Dr. Joshua Brockman

Team Members:

Team Leader: Neha Kulkarni

Communicator: Simerjot Kaur

BSAC: Emily Wadzinski

BWIG: Bryan Topercer and Orla Ryan

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Function:

Force sensors have been widely used in sports biomechanics to measure load distribution and center of pressure for the purpose of correcting form and mitigating injuries. However, getting real time data during the sport is often difficult to obtain in non clinical settings and may be very expensive to implement. Rowing is a rigorous sport that can lead to numerous lower extremity injuries due to asymmetries in load distribution when not following proper technique. Additionally, this asymmetry is impossible to quantify visually and current methods include using stationary rowing simulation machines that disparately underestimate the mechanical power required against water currents [1]. Specifically, these current methods of evaluating rowing form focus mainly on upper body extremities such as stroke power and involve studies outside of the rowing environment. Our design aims to provide accurate real time data of lower extremities by integrating a force sensor system in the rowboat to transduce force loading measurements that rowers can view while on the water. The application of our design will allow athletes and coaches to limit injury through avoiding asymmetric force transmission.

Client Requirements:

- The design must be compatible and inclusive with all weight classifications of rowboats (50kg to 90kg +) and foot sizes [2].
- The device must be strong enough to withstand the force exerted by rowers during the drive phase of the stroke [3].
- The device must accurately measure the load in each leg and translate the data to an interface that provides real-time data viewing while rowing.
- The device must be able to operate in wet conditions and humid environments.
- The client desires an easily integrated force measuring system that should operate without requiring change in rowing technique.
- The device should be fairly lightweight so as to not affect the weight of the rowboat.

Design Requirements:

1. **Physical and Operational Characteristics:**

a. Performance Requirements:

- The product must track the degree to which rowers are exerting symmetric force through their entire lower extremity, to track any asymmetry present.
- The product should provide real time data during a rower's row time so they can monitor any fluctuations as they occur.
- The product should be able to store data and display it through a visual interface so coaches and rowers can see the data in real time and analyze it later.
- The product should be able to display a force vs time graph at the end of a row as well as show the force during the catch to drive phase.
- The product should be waterproof.

b. Safety:

- This product should not disrupt the motion of the rower or the ergometer as a stroke is completed.
- This product should not cause any electrical shocks to the rower's and have minimal large cords in close proximity to the rower. The device needs to be plugged into an outlet with standard voltage of 120 V [4].
- This product should be able to be cleaned between uses with alcohol-based solution or soap and water. Bleach and/or hydrogen peroxide should be avoided [5].
- This product should not have any sharp edges.

c. Accuracy and Reliability:

- The device should be easy to replace if any of the components fail.
- The product should give data with high accuracy with a margin of error at 5% [6].

d. Life in Service:

- A typical rowing career for an Olympic rower tends to end near a rower's late 20s or early 30s. From college to this time, the device would have to be in service for about 10-12 years [7].

e. Shelf Life:

- The product will have a shelf life of around 50,000 hours to be able to be used for multiple college careers. This will allow for an array of results and different data to see its full effectiveness.
- The design should not necessarily have any features that wear away with time.

f. Operating Environment:

- The client would like to have the device at least inside on an ergometer. This would consist of room temperature conditions. These conditions are around 20-22° C and low humidity
- The client would like the force plates to be inside of their boats, which travel through the water. This would be a wet environment, could be cold or hot in temperature, and can withstand natural conditions such as rain. The plates would have to be waterproof and functional in fluctuating temperatures. The outdoor rowing season takes place from April to around October, where it becomes too cold to row outside. The average conditions in Madison during this time are the following [8]:
    - Temperature Range: 8.3° C to 22.2° C
    - Humidity: 62% - 73%
    - Rain Levels: 2.9 cm - 5.44 cm

g. Ergonomics:

- The design will easily allow users to view real time data and get feedback while they are rowing.
- The plates will not add any unnatural feeling for the rowers, and therefore they will not have to change their technique in order to use them.

h. Size:

- The client has expressed a main interest in placing such a device in practice ergometers as well as practice rowing tanks.

- After determining the brand of ergs used by the client both for conditioning and in tanks to be Concept2, it is noted that the width of the machine is 60.96 cm [9] so the device should fit within those constraints.

i. Weight:

- On their own, the Concept2 RowErg® weighs between 25.9 and 30.8 kg [8]. The device should be able to withstand this weight.
- The device will need to be lightweight enough so that users have no trouble rowing with the same technique and efficiency.

k. Materials:

- Current force sensors are typically constructed of silicone rubber elastomer with magnetic powders or particles used in calculations [10].
- Additionally, they are often cased in pure silicone or a similar material to maintain their shape, then adhered to thin aluminum plates as is "standard in force plate fabrication" [10].
    - The team will try to hold to these industry standards, using these materials as guidelines.
- Finally, the client has mentioned that some level of waterproofing will be a necessity for the product, given the likelihood of water exposure or possible immersion. Past experiments with sensors indicate that a possible method is laser direct writing, in which a barrier is created using a 405 nm laser [11].

l. Aesthetics, Appearance, and Finish:

- At this moment, without an idea of specific materials that will be purchased, measurements for target placement of the device, and other necessary parameters, it is difficult to say exactly what the desired finish will be. Given that current practice ergometers used by the client are finished using a powder coat, and the devices' legs are made of both aluminum and steel, these materials can be kept in mind when considering aesthetics [9].

- Overall, the team aims to produce a product that seamlessly fits into a rowing boat or ergometer, prioritizes comfortable foot placement for rowers, and does not interrupt users' technique with any added bulkiness.

2. Product Characteristics:

a. Quantity:

- The client would like there to be at least 8 force sensor systems, in order to have one per person in a shell for 8 sweep rowers [12]. The sensors should be easily transferable between the shells and the rowing tanks, which hold a capacity of 24 rowers (12 per tank) [13]. With increased supplies and funding, the quantity of sensors may be considerably increased to eventually have one sensor for every rower, in which the University of Wisconsin's crew team currently has around 205 athletes.

b. Target Product Cost:

- The budget for this design project is between $100-$500 . The budget may be increased with approval from the UW Athletic Department.
- The competing designs listed in part 3d of the PDS have costs significantly greater than our budget. BioRow's 2D Flat stretcher force plate costs over $2000. Small-sized multi axis load cells can range from $300-$500 [14]. In order to make a product within our target, load cells are more cost efficient.

3. Miscellaneous:

a. Standards and Specifications :

- The device must not interfere with the construction of the Concept2 RowErg® such that it fails to comply with the ASTM Standard Specifications for Fitness Equipment (ASTM F2276 − 23) [15].

  - Specifies that edges should be free of burrs and sharp edges, and corners should be chamfered
  - Specifies that the ergometer should withstand 1560 on/off cycles
  - Specifies that the footplate should be slippage-resistant
  - Specifies that the ergometer should be able to withstand 136 kg or the maximum user weight, whichever is greater
- The device must also comply with the ASTM Standard Specification for Universal Design of Fitness Equipment for Inclusive Use by Persons with Functional Limitations and Impairments (ASTM 3021-17), such that rowers with functional limitations and impairments can use the device [16].
  - Specifies that color contrast on any visual display must be greater than or equal to 70%
  - Specifies that font size should be at least 10 mm
  - Specifies that the display should continue to display visual feedback at least 5 seconds after exercise has stopped.

b. Customer:

- The target customer for our product is the Physical Therapist and Athletic Training Staff for the University of Wisconsin Rowing Team.
- Because the product will be used by physical therapists and athletic trainers as they work with athletes, visualizing the magnitude of force asymmetry is extremely important for athlete understanding and adaptation; hence, the device should have an easily interpretable interface that is updated with real-time data from the athlete as they perform rowing strokes.
- The device should also be compatible with the Concept2 RowErg®, which is the ergometer used by the University of Wisconsin Rowing Team.
  - The footrests should remain adjustable, and the wheels and upright storage capabilities should be unimpeded [8].

c. Patient-Related Concerns:.

- The device should not interfere with proper rowing technique or injure the athlete in any way.
- The device should not interfere with the ergometer or boat such that they begin to degrade or malfunction.
- The device should be accompanied by a data storage drive or other technology that allows for patient performance data to be stored confidentially, in compliance with HIPAA [17].

d. Competition:

- Bertec® produces portable force plates for gait, balance, and performance analysis [18].
    - The load cells contained inside utilize strain gauges and transducers to measure forces and moments in the x, y, and z directions
    - The portable force plates have a sampling frequency of 1000 Hz.
    - The portable force plates have loading capacities of 4440, 8880, or 17760 N.
- Biorow produces a 2D force sensor that uses four load cells fixed to a plate, and the plate is screwed between the foot straps of the ergometer and the foot stretchers [19].
    - The load cells can measure from -800 to +3200 N.

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Appendix B: Materials and Expenses

Item	Description	Manufacturer	Mft Pt#	Vendor	Vendor Cat#	Date	QTY	Cost Each	Total	Link
Wire terminal	Connector for all 120V 16 AWG and 20 AWG wires	Multicomp pro	MC29391	Newark	34P2159	10/11/2023	$5.00	$0.08	$0.40	https://www.newark.com/multicomp/mc29391/terminal-female-disconnect-0-25in/dp/34P2159?ost=mc29391
Fuse	1 A, 125 V, 5mm x 20 mm	Littlefuse	26K7739	Newark	26K7739	10/11/2023	1	$0.89	$0.89	https://www.newark.com/littelfuse/0233001-mxp/fuse-cartridge-1a-5x20mm-med-acting/dp/26K7739
Wire - Black	16 AWG hook-up wire - hot wire (15 cm)	Multicomp pro	24-15050	Newark	44AC9035	10/11/2023	0.005	$17.09	$0.09	https://www.newark.com/multicomp-pro/24-15050/jacket-material-pvc/dp/44AC9035?ost=24-15050
Wire - White	16 AWG hook-up wire - neutral wire (15 cm)	Alphawire	461626 WH005	Newark	98B9507	10/11/2023	0.005	$38.32	$0.19	https://www.newark.com/alpha-wire/461626-wh005/hook-up-wire-100ft-16awg-copper/dp/98B9507
Wire - Green	20 AWG solid wire - ground wire (15 cm)	Alphawire	422001 GR005	Newark	28Y5639	10/11/2023	0.005	$24.48	$0.12	https://www.newark.com/alpha-wire/422001-gr005/hook-up-wire-0-52mm2-30m-green/dp/28Y5639
Wire - Blue	22 AWG solid hook-up wire - DC to thermistor connector (15 cm x 2)	Multicomp pro	24-15416	Newark	68X4805	10/11/2023	0.04	$2.49	$0.10	https://www.newark.com/multicomp-pro/24-15416/jacket-material-pvc/dp/68X4805
Wire terminal	Connector for 22 AWG wires to female DC connector	AMP-TE Connectivity	61048-1	Newark	07AH7925	10/11/2023	2	$0.36	$0.72	https://www.newark.com/amp-te-connectivity/61048-1/terminal/dp/07AH7925
Arduino Uno Rev	Microcontroller/signal processor	ARDUINO	A000066	Arduino	76300492	10/11/2023	1	$24.00	$24	https://store.arduino.cc/products/arduino-uno-rev3
Force Sensitive Resistor	Sensing area that detects pressure	Sparkfun	no part number	Sparkfun	no part number	10/11/2023	4	$7.50	$30	https://www.digikey.com/en/products/detail/ohmite/FSR07DE/14552734
Amplifier	External Input Sensor Amplifier	Sparkfun	SEN-13879	Digikey	1568-1436-ND	10/19/2023	2	$10.95	$21.90	https://www.digikey.com/en/products/detail/sparkfun-electronics/SEN-13879/6202732
10kg Load Cell	LOAD CELL - 10KG STRAIGHT BAR TA	Sparkfun	SEN-13329	Digikey	1568-1852-ND	10/19/2023	2	$9.69	$19.38	https://www.digikey.com/en/products/detail/sparkfun-electronics/SEN-13329/7393715
200kg Load Cell	LOAD CELL- 200kg cylindrical load cell	Sparkfun	SEN-13332	Digikey	474-SEN-13332	11/09/2023		$67.01	$268.04	https://www.mouser.com/ProductDetail/474-SEN-13332
Force Sensitive Resistor	Force Sensing Resistor Force Sensor 5.00kgf (11lbs)	Ohmite	FSR07DE	Digikey	273-FSR07DE-ND	11/15/2023	1	$7.78	$7.78	https://www.digikey.com/en/products/detail/ohmite/FSR07DE/14552734
Footstretcher Left	Base for foot on erg		1055	Concept 2 Inc.		11/15/2023	1	$2.75	$2.75	https://shop.concept2.com/parts/96-footstretcher-cover-right.html
Flexfoot	flexible foot adjustment for erg	Concept 2 Inc.	1063	Concept 2 Inc.		11/15/2023	2	$4.75	$9.50	https://shop.concept2.com/parts/87-flexfoot-gray.html
Footstretcher Right	Base for foot on erg		1054	Concept 2 Inc.		11/15/2023	1	$2.75	$2.75	https://shop.concept2.com/parts/95-footstretcher-cover-right.html
3D Printing	3D printing heel and toe					12/2/2023	1	$34.64	$34.64	
HDPE Scrap	2in x 4in					12/2/2023	5	Free	Free	
Steel scrap	2in x 4in					12/2/2023	4	Free	Free	
Velcro adhesive	Velcro with adhesive on one side					12/2/2023	1 roll	Free	Free	
Duct tape						12/2/2023	1 roll	Free	Free	
Double sided tape						12/2/2023	1 roll	Free	Free	

Appendix C: Fabrication Protocol

Drill Press

1. Obtain one block of HDPE and three plates of steel from the UW Madison's TEAM Lab.
2. Locate the center of the HDPE block and mark it.
3. Move the drill press table to the desired height.
4. Lock the block in a vice, and center the block to the drill.
5. Secure the vise to the table with clamps.
6. Secure the drill chuck and install a center drill into it.
7. Turn on the drill press, and adjust the speed to 1000 RPM.
8. Using the quill handle, lower the center drill into the HDPE at the marked spot and peck drill into the block, not all the way through.
9. Turn off the press and raise the handle. Switch the center drill to a 51/64" drill bit.
10. Turn on the press and lower the handle, peck drilling all the way through the block.
11. Turn off the drill press, remove the block from the vise.
12. Clean away excess drill fragments.

Band Saw

1. Take the drilled HDPE block and make two marks along the width, each one inch from both ends of the length.
2. Grab a push stick and place the block on the table.
3. Align the saw to one of the marks.
4. Press the on button, and slowly push the block along the mark with one hand and the push stick.
5. Once the block completely passes through the saw, repeat steps for the other end of the block.
6. Turn off the machine.
7. Wipe away dust with a brush once the saw is fully off.

Appendix D: Load Cell Calibration Protocol

1. Obtain a set of known weights, called calibration weights.
2. With the prototype assembled and the circuit powered on, use a permanent marker to mark on the top plate of the prototype the exact location of the pin of the load cell.
3. Upload the Calibration code in Appendix F to the Arduino. If a positive reading is desired for compressive values, ensure that the uploaded code has initiated a positive calibration factor. If a negative value is desired, ensure that the uploaded code has initiated a negative calibration factor.
4. Press Tools → Serial Monitor to view live readings from the load cell; ensure the prototype is reading 0.0 or -0.0 lbs with nothing placed on top.
5. Place a 1 kg calibration weight on the prototype, centered on the mark made in Step 2.
6. View the live reading and ensure that a value is being read almost instantaneously. Adjust the value of the calibration factor by typing “a” → enter or “z” → enter into the Serial Monitor. This will adjust the reading on the serial monitor. Continue adjusting the calibration factor incrementally until it reads (positive or negative) 2.2 lbs.
7. Remove the 1kg weight from the prototype. Ensure the readings go back to zero.
8. Repeat Steps 5 and 6, this time with a 500 g weight and adjust the calibration factor until the prototype reads a value of (positive or negative) 1.1 lbs.
9. To complete further validation, balance on the prototype with as much weight as possible on the mark indicating the location of the load cell and verify the prototype reads a value within 5% of your weight.

Appendix E: Testing Protocol

1. Once the prototype is assembled as in Figure 10, have the test subject place their foot on the footplate with their foot strapped in as they normally would. If needed, shift the box further down the footplate to better align with the metatarsophalangeal joint and have the subject re-align their foot.
2. Upload the Testing Code in Appendix F to the Arduino and press Tools → Serial Plotter to pull up the live display.
3. Have the subject complete a 30-40 second intervals of rowing at steady state, while monitoring the real-time force output display.
4. Once the interval is complete, unplug the Arduino from the laptop to stop data collection. Quickly plug the cable back into the laptop and upload the EEPROM Read code to the Arduino in Appendix F. Press Tools → Serial Monitor to display the stored values. Copy and paste these values into a .csv file for analysis.
5. Repeat Steps 1-4 for more intervals on the current leg.
6. Move the prototype to the other footplate and repeat Steps 1-5.
7. To analyze data, plot force readings over time, obtain peak force per stroke on each leg, and perform a t-test to assess significance in asymmetry.

Appendix F: Arduino Code

Calibration:

```
#include "HX711.h" //This library can be obtained here http://librarymanager/All#Avia_HX711

#define LOADCELL_DOUT_PIN  3
#define LOADCELL_SCK_PIN  2

HX711 scale;

float calibration_factor = 4555;

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.begin(LOADCELL_DOUT_PIN, LOADCELL_SCK_PIN);
  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 += 5;
    else if(temp == '-' || temp == 'z')
      calibration_factor -= 5;
  }
}
```

Testing Code:

```
#include "HX711.h" //This library can be obtained here http://librarymanager/All#Avia_HX711
#include "EEPROM.h"

#define calibration_factor 4555 //This value is obtained using the SparkFun_HX711_Calibration
sketch

#define LOADCELL_DOUT_PIN  3
#define LOADCELL_SCK_PIN  2

HX711 scale;
int addr = 0;

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

```
  scale.begin(LOADCELL_DOUT_PIN, LOADCELL_SCK_PIN);
  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:");
  for (int i = 0 ; i < EEPROM.length() ; i++) {
    EEPROM.write(i, 0);
}}

void loop() {
  delay(50);
  float val = scale.get_units();
  int val_int = int(round(val));
  Serial.print("Reading: ");
  Serial.print(val); //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.print(addr);
  Serial.println();

  EEPROM.write(val_int, addr);
  addr = addr + 1;

}
```

EEPROM Read:

```
#include <EEPROM.h>

int a = 0;
int value;

void setup()
{
  Serial.begin(9600);
}
```

```
void loop()
{
  value = EEPROM.read(a);

  Serial.print(a);
  Serial.print("\t");
  Serial.print(value);
  Serial.println();

  a = a + 1;

  if (a == 1024)
    a = 0;

  delay(500);
}
```