Final Report: Force Sensor for Rowing Biomechanics

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BME 301

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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 open weight women's rowing team is seeking a way to measure real-time biokinetic data in the form of approximate right and left foot force in order to determine the presence of any bodily asymmetries and correct athletes' form. Existing products such as the BioRow Force Plates, often involve expensive and highly advanced equipment such as small, accurate load cell sensors [3]. In an effort to reach a more affordable solution, a working prototype was developed using a rotating foot plate secured to a Concept2 RowErg. When an athlete rows asymmetrically, the footplate rotates a shaft. An angular encoder senses this rotation and sends a signal to a Raspberry Pi. The Raspberry Pi converts the angle to force difference using a predetermined calibration curve and displays it using a graphical user interface. Testing of the device revealed that subjects place more force on their oarside foot, though more trials are necessary to determine the root cause of this asymmetry. Future work will involve testing more rowers to correlate asymmetry with anthropometric data.

Table of Contents

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 [4]. 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 [5]. 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 much 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 [6]. 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.

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 1000 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 [7]. 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 push the 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 [8]. As a result, the most commonly cited injuries in rowers are those of the lumbar spine [9].

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

Relevant Design Information

The two main forms of rowing are sculling and sweeping. Sculling is symmetric as rowers hold onto one handle of an 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.

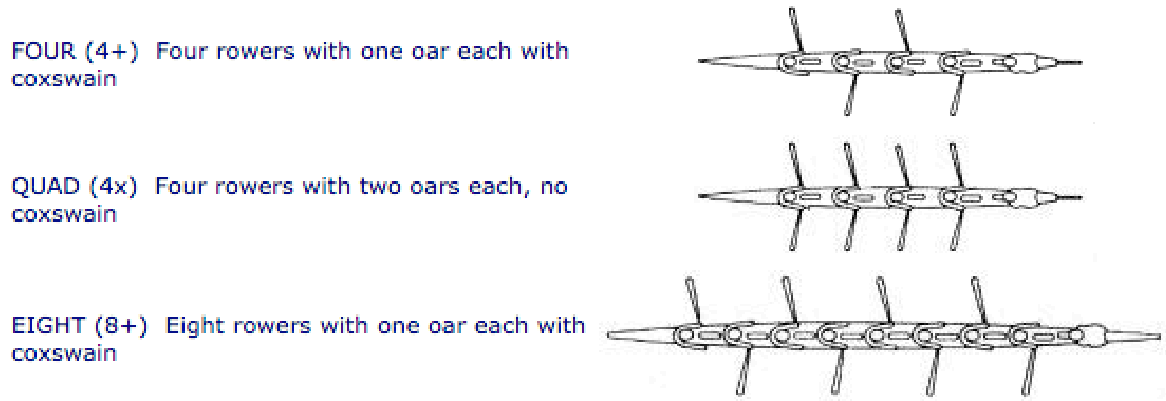


Figure 2. Configurations of boats for competition rowing [10].

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. 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 2. Figure 3 shows the footplate on the ergometer, which features a detachable heel portion that allows for rowers 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. Concept2 RowErgs configured in the tank at the UW Boathouse.

Figure 4. Footplate of a Concept2 RowErg.

Client Information

The clients for the project 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 [11]. 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 [12]. 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 UW boathouse rowing tanks, as this is the rowing tank used by the rowing team during indoor practices to practice sweep style rowing. This will entail taking certain dimensions into consideration, such as the tank's footplate height and width of 30.7 cm by 13.3 cm. The device must not impede normal rowing motions, so it should not noticeably affect the shape of the rowing tank footplates. 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% [13]. The product should be engineered to last a service life of around 10-12 years, approximately the length of an average rower's career [14]. 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 [15]. 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**

Footplate: Stationary Uniplate

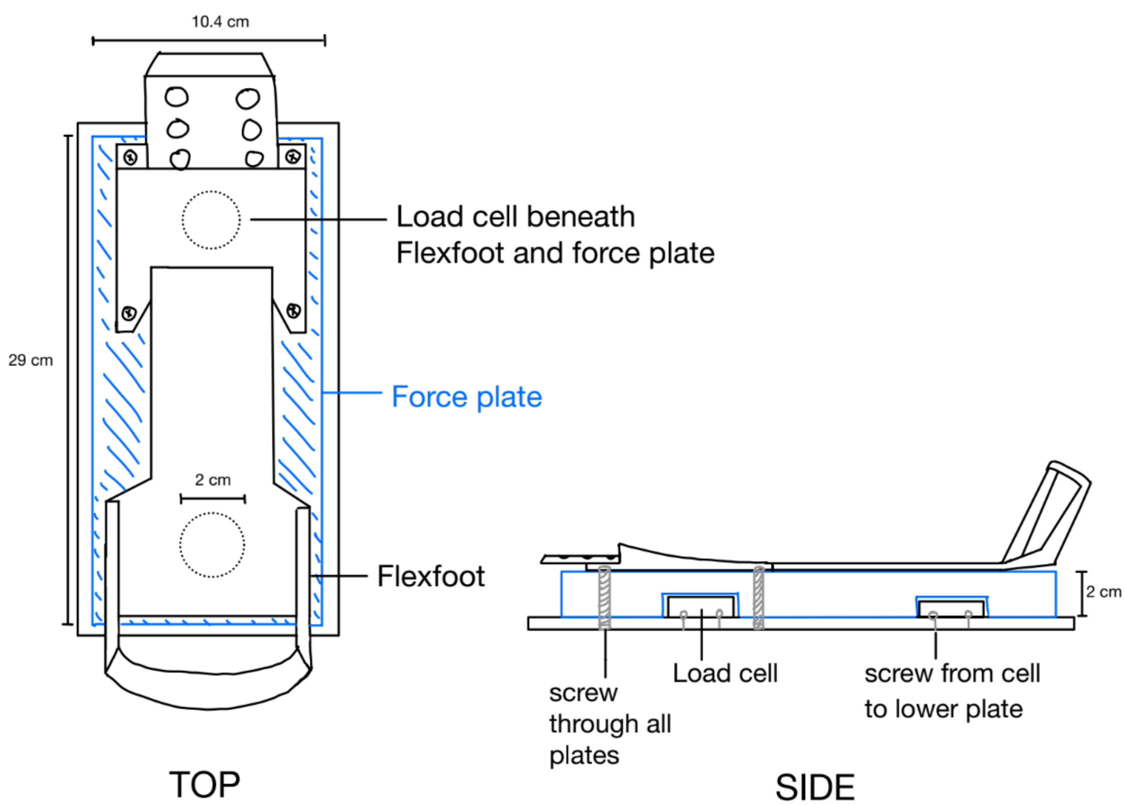


Figure 5: Drawing for Stationary Uniplate Design

The Stationary Uniplate design illustrated in Figure 5 is the simplest of the three footplate designs. This design includes a singular, 2 cm tall plate to screw in between the Flexfoot and lower metallic plate. The load cells are embedded underneath the force plate and on top of the lower base plate. A long metallic screw secures all three components together linearly. Some advantages of this design are the simplicity providing easy fabrication and the load cells will be the most secure in the housing force plate. A key disadvantage of this design is that the load cell positioning cannot be adjusted based on the rower's foot size. Additionally, there is a possibility of signal interference between the toe and heel load cell force readings as they are in a single force plate. Overall, the Stationary Uniplate design provides optimal load cell housing but lacks adjustability for the athletes.

Footplate: Multiplate Slider

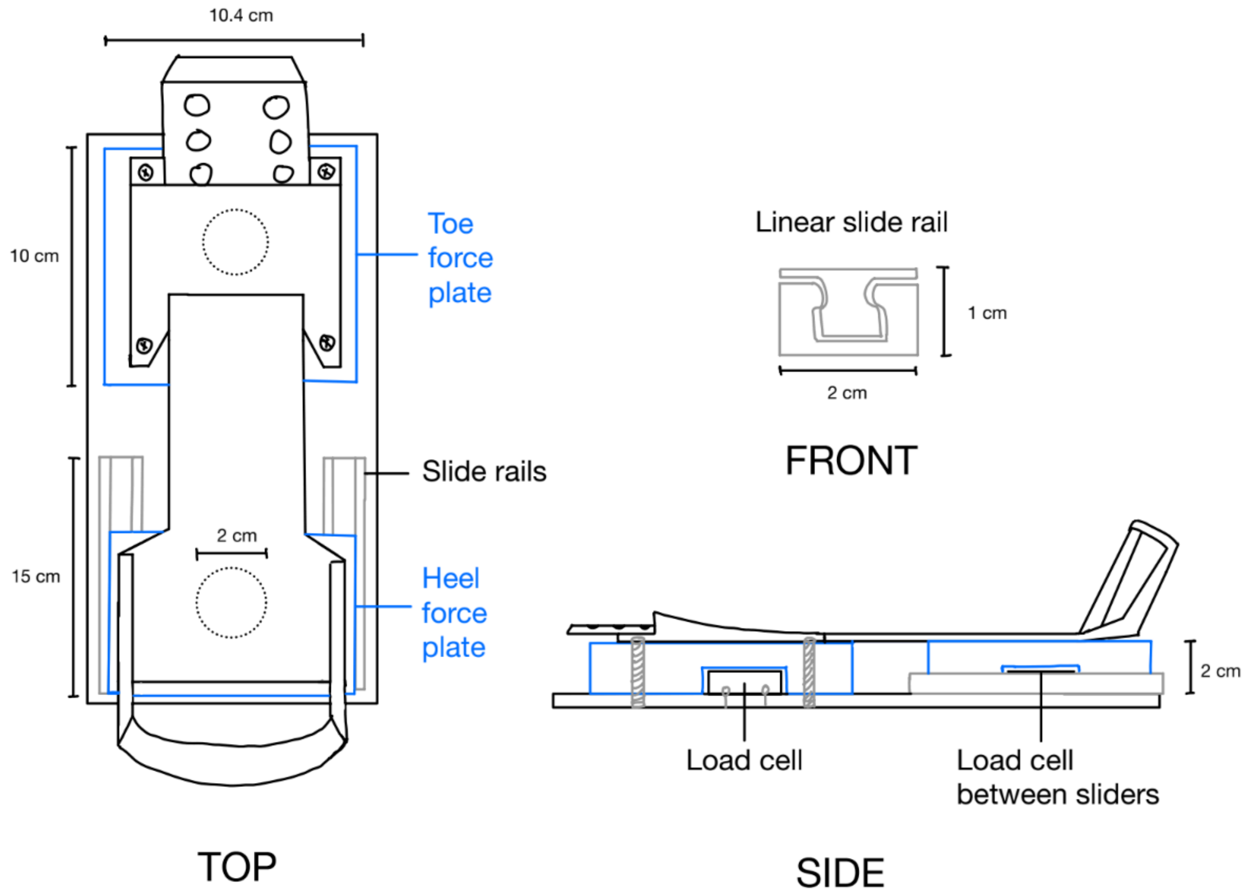


Figure 6: Drawing for Multiplate Slider Design

The Multiplate Slider design shown in Figure 6 is highly adjustable due to its sliding component. Instead of one plate that spans the whole foot, the plate is broken into two, one for the toe and one for the heel. Both plates sit between Flexfoot and lower base plate. The toe plate is screwed directly to the base and Flexfoot with one load cell embedded in it. Two linear, 1 cm by 2 cm slide rails are screwed into the back of the foot plate, with the heel plate fixed between. A load cell is housed in the plate, able to slide along the rails based on foot size. The Flexfoot is placed above and retains its mobility to change lengths. With the heel's load cell able to adjust per athlete, more accurate load cell readings can be recorded, and signal interference between toe and heel load cell readings will be limited due to the separation of plates. However, since the heel force plate and its load cell are not securely fixed to the base, there is a possibility of unwanted movement of the load cell causing inaccurate readings.

Footplate: Multiplate Placer

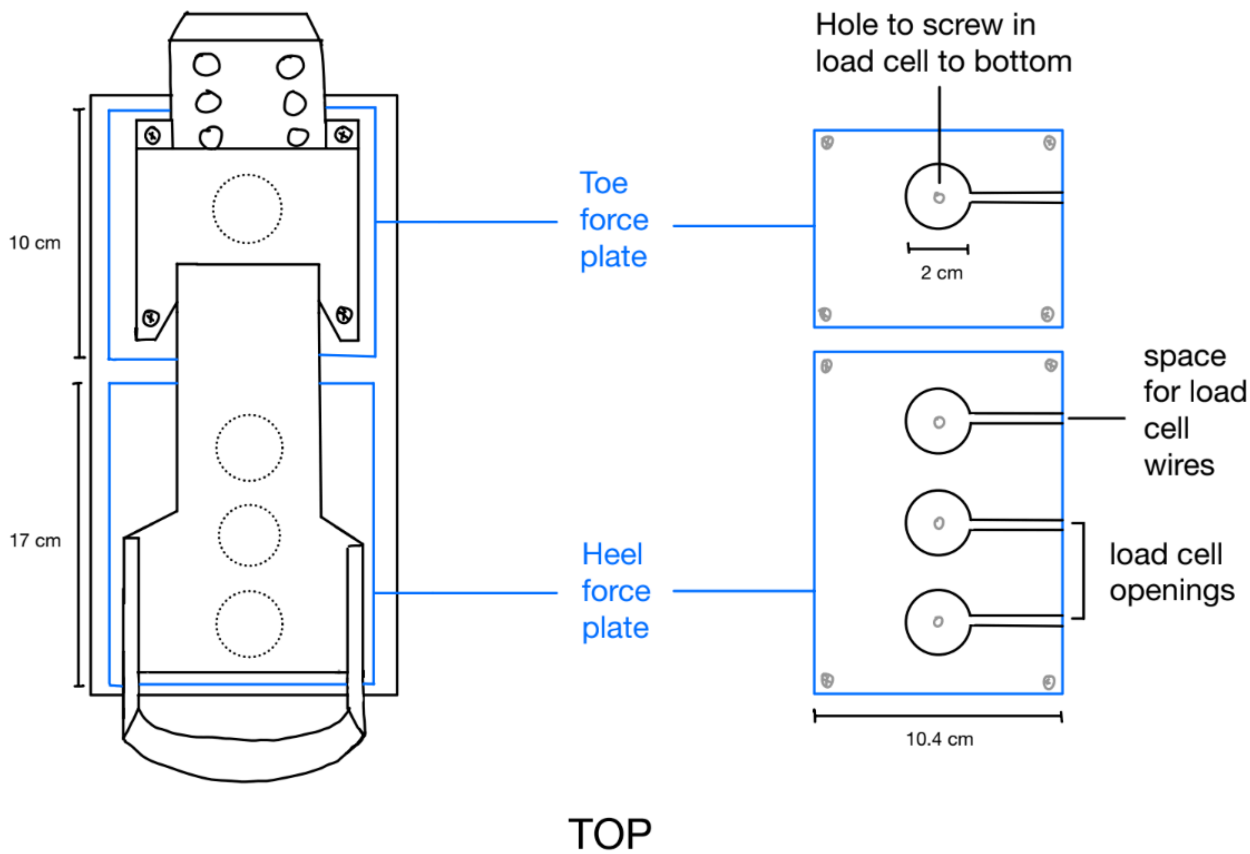


Figure 7: Drawing for Multiplate Placer Design

The Multiplate Placer design illustrated in Figure 7 is more secure than the slide rails and still adjustable. This design is separated into two force plates, located between the lower metallic plate and Flexfoot, fastened with long metallic screws in each corner. The heel plate has three openings to place the heel's load cell in multiple positions, based on foot size. Each space allows for the cell to screw to the base, affirming its stability. Even though this design is more adjustable than the first design, a disadvantage of the Multiplate Placer is the time the user must take to screw and unscrew the load cell for adjustments. In addition, the athlete's foot size may be in between placement options, making the design not completely inclusive.

Display: LED Array

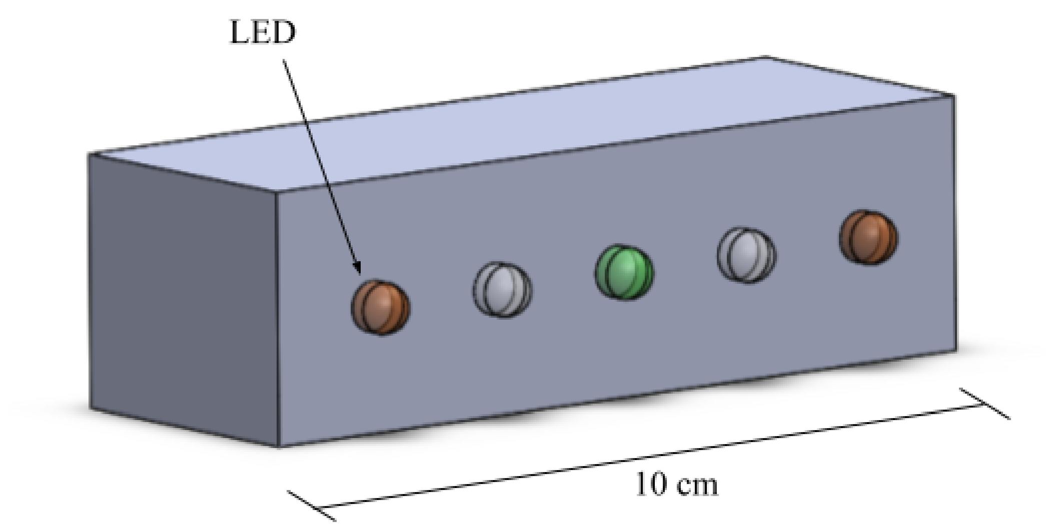


Figure 8. SolidWorks representation of the LED Array design.

The LED Array design is a series of 5 LEDs housed in a plastic box connected to an Arduino Uno microcontroller which compares the relative force magnitudes from the right and left foot plates and lights up LEDs when specific asymmetry thresholds are crossed. For example, if the rower pushes on the left footplate over 10% more than the right footplate, the left red LED would light up to indicate this asymmetry in real time. Because the Arduino Uno only has 512 bytes available for data storage and a finite number of write cycles, incorporating data storage into this design would require an SD card and an SD card module [16].

Display: Arduino 5” Display

Figure 9. 5 inch LCD TFT display [17].

This design utilizes a 5 inch LCD display connected to an Arduino Uno to present real-time information to the rower through a graphical user interface (GUI) [17]. The GUI would be made with the TkInter python library, which is compatible with Arduino. Like the LED array design, this design lacks storage space for raw data, and may require an SD card and SD card module.

Display: Raspberry Pi + 7” Display Monitor

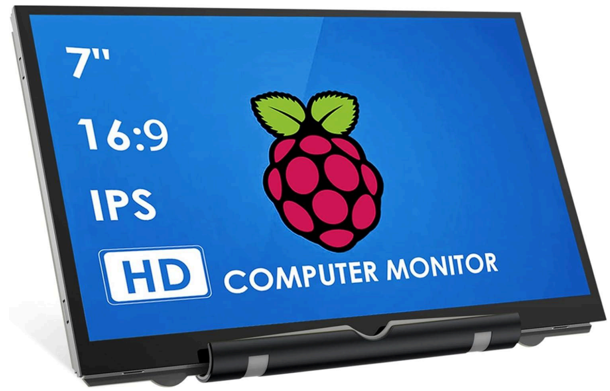


Figure 10. 7” Raspberry Pi HDMI display. [18]

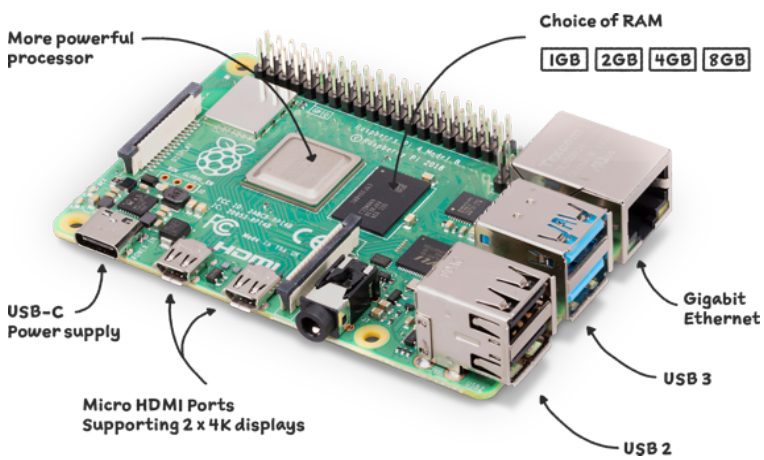


Figure 11. Raspberry Pi 4 Model B [19].

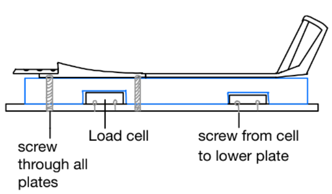
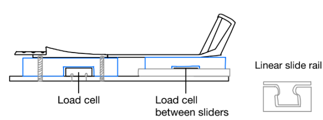
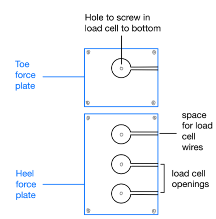
This design utilizes the Raspberry Pi 4 as a microcontroller which will interface with the load cell amplifier and a 7” LCD display which will show a GUI comparing real-time force asymmetry [18][19]. This design involves reconfiguring the load cell amplifier with Raspberry

Pi instead of the Arduino Uno, which was used last semester. Because the Raspberry Pi has a microHDMI port and an SD card slot, it is much better equipped to output graphics to larger displays and save large amounts of data. The Raspberry Pi can be programmed in python, unlike Arduino which is programmed in C++, which makes Raspberry Pi compatible with any python GUI library, not just TkInter.

IV. Preliminary Design Evaluations

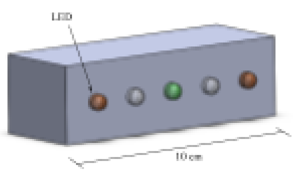
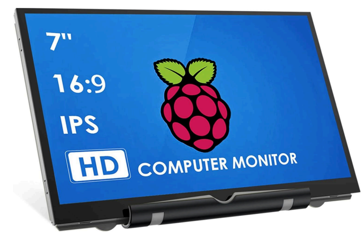
Design Matrices

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

		 Stationary Uniplate		 Multi-Plate Slider		 Multi-Plate Placer	
Criteria	**Weight**	Score (5 max)	Weighted Score	Score (5 max)	Weighted Score	Score (5 max)	Weighted Score
Reliability	25	5	25	4	20	2	10
Adjustability	25	2	10	5	25	3	15
Cost	20	4	16	3	12	4	16
Ease of Fabrication	20	5	20	3	12	4	16
Technique Interference	10	4	8	2	4	3	6
Sum	**100**	**Sum**	79	**Sum**	73	**Sum**	63

Display Design Matrix:

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

		LED Array		**Arduino + 5" LCD**		**Raspberry Pi + 7" HDMI**	
							
Criteria	**Weight**	Score (5 max)	Weighted Score	Score (5 max)	Weighted Score	Score (5 max)	Weighted Score
User experience	35	3/5	21	4/5	28	5/5	35
Frame rate	25	5/5	25	3/5	15	5/5	25
Value of data	20	2/5	8	4/5	16	5/5	20
Ease of Fabrication	10	4/5	8	3/5	6	5/5	10
Cost	10	5/5	10	4/5	8	2/5	4
Sum	**100**	**Sum**	72	**Sum**	73	**Sum**	94

Design Evaluations

Footplate Matrix Category Descriptions and Evaluations:

The design matrix to determine the best location to install our device includes the following criteria: Reliability, Adjustability, cost, Ease of Fabrication, and Technique

Interference. Reliability refers to how secure the load cell is mounted and the repeatability of the configuration after adjustment. The Adjustability aspect of the matrix measures the degree to which the design can be adjusted to rowers' varying foot sizes. For rowers with larger feet, the load cells will have to be repositioned to meet the anatomical landmarks of their feet. Cost is a criterion to ensure that we are taking into account the budget constraints before moving forward with a design. The Ease of fabrication category refers to how easily the design can be fabricated and fitted to the current RowErg setup. Lastly, the Technique Impedance criterion refers to how the design may possibly hinder or alter the rowing motion of the athlete.

Footplate Score Distributions:

The Stationary Uniplate design received a 5/5 in the Reliability category because its load cells are permanently mounted; this ensures that they can be perfectly calibrated and secured to the setup and the tests conducted in the setup will be repeatable. A 2/5 was awarded in the Adjustability category, however, because the design is not adjustable; though the Flexfoot will change the athlete's heel position, the load cell may not perfectly align with their calcaneus for every test, which creates error in force measurement and repeatability issues. Regarding Cost, this design received a 4/5 since the design only requires the purchase of two metal or 3D-printed plates on top of the two load cells, which are common to each design. In Ease of Fabrication, a 5/5 was awarded because all machining could be done on a mill and/or lathe, which the team is trained to do and would require no extra cost. Finally, in Technique Interference, the design received a score of 4/5 because the only difference the rower might feel is the thickness of the plates; this shouldn't greatly alter their technique.

The Multiplate Slider design received a 4/5 in the Reliability category because the load cells are mounted securely on a plate so they can be flush with a flat surface; however, the plates can move which compromises the reliability of the wiring and presents the possibility of the plates moving during a test. This design is the most adjustable with 5/5 in the Adjustability category due to the rails. Both the Flexfoot and load cell can move so that the load cell is perfectly aligned with the center of the athlete's calcaneus. This design received a 3/5 in the Cost category due to the added cost of the rails. The rails also make fabrication slightly more difficult so this design received a 3/5 in the Ease of Fabrication category. The design also received a 2/5 in the Technique Interference category because the rails and plates add a lot of extra thickness, which might make the toe strap tighter on the athlete. In addition, the gap between the heel and toe plates makes it so that the entire rower's foot will not make contact with a flat surface; this will impede a rower's ability to row as normal.

The Multiplate Placer received a 2/5 in Reliability category because the heel load cell is mounted temporarily and moved for each athlete, making their stability variable between tests and subject to error. A 3/5 was awarded in Adjustability because there are three different heel load cell placements but the Flexfoot has 6 levels of adjustment, so some rowers' foot size may fall between load cell slots. The design received a 4/5 in the Cost category because the design requires the purchase of two metal or 3D-printed plates. For Ease of Fabrication, the design received a 4/5 because the machining or 3D printing is slightly more complicated due to the tolerances required to ensure the load cell fits perfectly. Finally, a 3/5 was awarded in Technique Interference because of the aforementioned gap between the toe and heel plates.

Display Design Matrix Category Descriptions and Evaluations:

The design matrix for the display includes the following categories: User Experience, Value of Data, Frame Rate, Ease of Fabrication and Cost. The User Experience refers to the ease of usability for the rowers and the viewability while they receive the real time data through the display. The User Experience also takes into account the inclusivity of viewing the display as the team will ensure that display will be interpretable for everyone, as well as the aesthetic appeal of the GUI. The Value of Data refers to the relevancy of the data on the display as well as ability to save and communicate the raw force vs time data after a rowing session. The Frame Rate refers to the frequency that data will be displayed and the length of iterations before a signal is relayed. For Ease of Fabrication, the team has to take into consideration the compatibility of the display with the microcontroller and load cell circuit as well as availability of GUI libraries. The display connections must not intersect with the connections for the load cell and Raspberry Pi. Lastly, the cost must be taken into account for the client's budget as mentioned earlier.

Display Design Explanations and Score Distributions:

The LED array got an overall score of 72/100. For User Experience the LED array got a 3/5 as it provides a simple light up color configuration where athletes will get signals through different colored lighting. However, detailed feedback is not possible as athletes would not get numeric force measurements which is why the LED array ranked the lowest in this category. The display also does not take into account color blindness which might make it difficult for athletes to interpret the feedback they receive from the display. In the Value of Data criteria, the display got a 2/5 score as the data is only given through lights which isn't fully indicative of the performance of the athlete. For the Ease of Fabrication category, the LED array would not require complex configurations. Additionally, the code for this design can be written easily.

The Arduino Uno with a 5" LCD Display scored 73/100 in the design matrix, with notable strengths and weaknesses. The User Experience (4/5) benefits from easy integration into the existing design and the potential for a richer data display through GUI. However, uncertainties exist about the ease of creating a GUI using TkInter. TkInter is a very basic GUI library and likely would not create a very aesthetically-appealing interface. The Value of Data (4/5) is strong, offering a more comprehensive presentation of data techniques, but it did not score perfectly due to lack of raw data storage space. The Frame Rate (3/5) and Ease of Fabrication (3/5) pose challenges, with potential issues related to the GUI's ease and a lower refresh rate compared to Raspberry Pi. Cost (4/5) considerations include a $35 display cost, an $8 wall adapter, and potential challenges with Arduino GPIO pin usage, smaller display size limitations, and onboard storage issues. Additional costs may arise if integrating a microSD card module.

The Raspberry Pi with a 7" HDMI display got an overall score of 94/100. It scored 4/5 for User Experience, 5/5 for Value of Data, Frame Rate, and Ease of Fabrication, but 2/5 for Cost. The strength lies in the fast 60 Hz refresh rate, enabling real-time display of rich data, including heel/toe force differentials with graphics, and the SD card slot allowing for up to 64 GB of storage space for raw data. The GUI built with TkInter or other Python-based libraries offers symmetry assessment through color-coded flashes. The large display, leaving 40 GPIO pins open, facilitates force plate integration, and potential exploration of WiFi capabilities. However, the $35 Raspberry Pi 4, $34 7" non-touch display, and additional costs for a wall adapter raise cost concerns. Integration challenges may arise, requiring a stand/base, and compatibility with load cells needs verification. Despite cost considerations, the Raspberry Pi setup excels in user experience, data value, frame rate, and ease of fabrication.

Proposed Final Design

Despite the preliminary design evaluations, the proposed final design was revised to no longer include load cells. Although load cells were primarily considered in each design of the design matrix, after consultation with design engineers from load cell manufacturers and BME faculty, they were advised against. With outside input, the team decided it was not feasible to move forward with load cells for a multitude of reasons. One constraint was the budget; load cells are highly expensive to purchase and implement as they require expensive signal processing equipment. Another constraint was that single-axis load cells cannot pick up off axis and dynamic loading. Load cells typically need to be secured to a flat, level surface and subjected to direct, normal loads. Due to the nature of rowing, the feet may make contact with the cells at varying angles. The ergometer's footplate is also at an incline. Therefore, while load cells may pick up some loading in this situation, the data would not be accurate enough for clinical implementation.

Instead, the team proposed a rotatory footplate design with a digital angular encoder. Angular encoders measure the angle of rotation of a shaft or point and convert it into analog or digital output signals [20]. Angular encoders have very high sensitivity and accuracy, outputting the smallest of changes into applicable signals. The proposed final design consists of a lower and upper footplate with a shaft attached to an encoder in between, that rotates side to side along the shaft based on which foot is applying more pressure. Springs between footplates add resistance to the rotation to warrant minimal movement, in order to more closely mimic the fixed plate rowers are used to pushing on. Due to the angular encoder's high sensitivity, it can still pick up these minute changes and relay information to the Raspberry Pi with a 7" HDMI display, which is the display that scored highest on the design matrix. Unlike the load cell designs, the rotational footplate design does not directly display absolute force from each foot. Instead, the force difference between feet is measured, which can further be analyzed with anthropometric and clinical data.

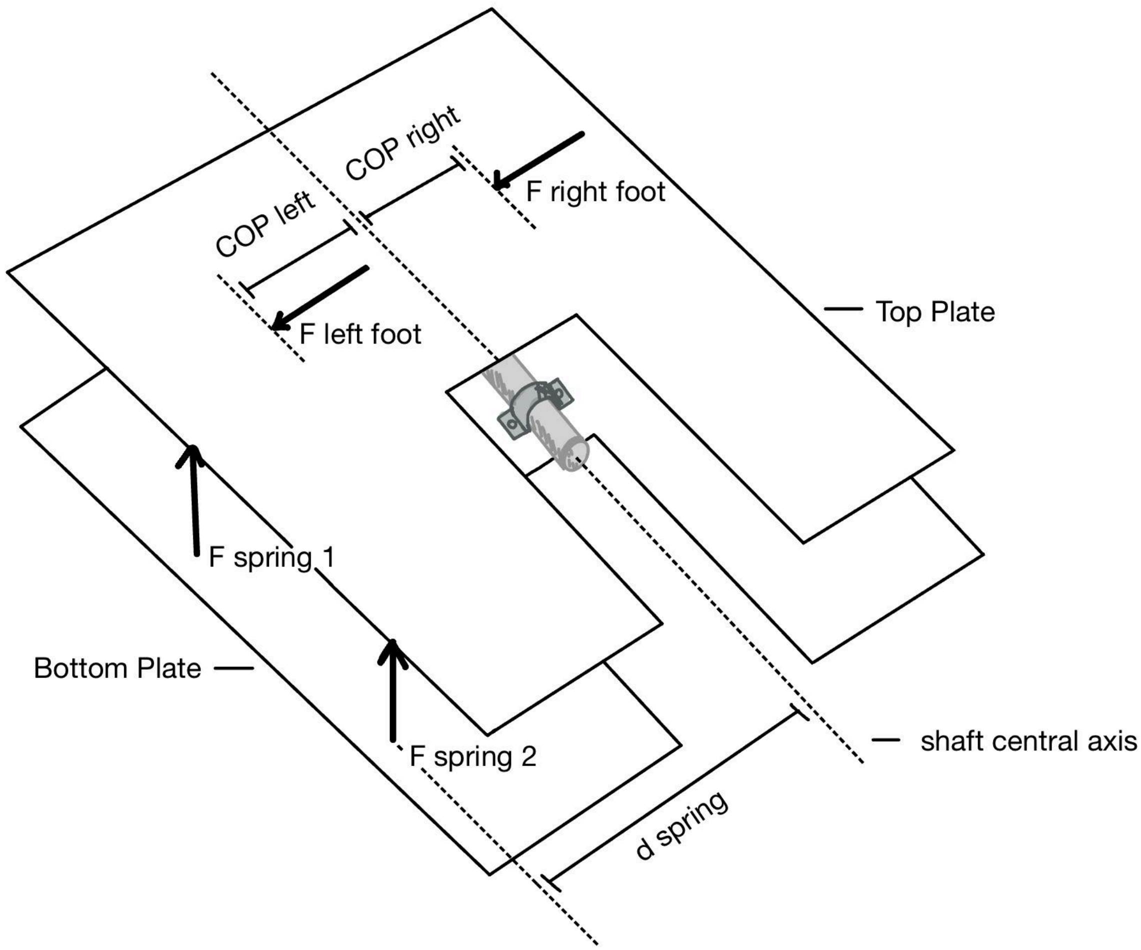


Figure 12. Free body diagram of footplates.

$$\sum M_{shaft\ axis} = F_{left\ foot}COP_{left} - F_{right\ foot}COP_{right} - F_{spring\ left}d_{spring\ left} + M_{friction} = 0$$

Assumptions:

- $COP_{left} = COP_{right} = COP$
- $M_{friction} = 0$

$$\sum M_{shaft\ axis} = F_{left\ foot}COP - F_{right\ foot}COP - F_{spring\ left}d_{spring\ left} = 0$$

$$F_{spring\ left} = k\Delta L$$

$$\Delta L = d_{spring\ left} * \tan(\theta) \approx d_{spring\ left} * \theta$$

(Small angle approximation)

$$F_{spring\ left} = \left(\frac{COP}{d_{spring\ left}}\right) * \left(F_{left\ foot} - F_{right\ foot}\right) \approx k * d_{spring\ left} * \theta$$

$$F_{left\ foot} - F_{right\ foot} = \left(\frac{{d_{spring\ left}}^2 * k}{COP}\right) * \theta$$

$$F_{left\ foot} - F_{right\ foot} \propto \theta$$

Figure 13. Equations associated with the footplate's free body diagram.

This free body diagram (Figure 12) and associated equations (Figure 13) show how the angle of the top footplate is proportional to the difference in normal force applied to the top footplate by the left and right feet. It should be noted that this free body diagram assumes the force on the left is greater than the right, which is why the force from the right side springs is 0 (plate is not in contact with springs on the right). The assumptions made in these equations are that the reaction moment from the friction of the bearings is negligible, that the center of pressures of the left and right feet are mediolaterally equidistant from the shaft, and that the top plate is in static equilibrium (not accelerating). By computing the sum of the moments about the shaft's central axis, it is evident that the force of the spring is proportional to the difference in force between the left and right feet, therefore the compression of the spring is proportional to this force difference. Due to the small angle approximation, the force difference of the feet is proportional to the angle of the top plate. This proportionality allows for the calculation of left and right force difference using only the angle of the top plate and a calibration curve (see Testing: Force-Angle Calibration).

V. **Fabrication**

Materials

Footplates:

To fabricate the base and top plates, the team opted to use 0.5 inch thick plywood plates. The plywood provides an excellent compressive strength of 27.3 - 43.5 MPa [21]. This will ensure that the plates do not yield under high compressive strength from the rowers' lower limbs. Additionally, the plywood provides easy integration with the plastic Flexfoot, aluminum shaft collars, and metal RowErg base with wood-screw or bolt connections.

Rotary Mechanism:

The mechanism allowing the footplate to rotate consists of a 0.5"-diameter aluminum rod with collars attaching to it that will connect to the top plate. The shaft with attached collars is threaded through bearings that will rotate with the shaft and are secured with set screws.

Bearings are mounted to the bottom plate via compatible bearing mounts. Between the top plate and the baseplate, springs are utilized to keep the plate from excess rotation. The springs are mounted onto an aluminum base that keeps it upright. The spring mounts attach to the bottom plate with velcro. This mechanism gives the rower an adequate amount of balance and does not impede the rowers form, while still maintaining some degree of rotation for the angular encoder to read.

Electronics/Display:

The angular encoder used to measure the angle of the top footplate was the ERCF 1 05SPI 360 Z Absolute Rotary Encoder from P3 America (Figure 14). The P3 encoder interfaces with an Arduino Uno R3, which then sends the angle data to a Raspberry Pi 4 Model B (2GB RAM) to power and control a display screen. For the display component, the team initially planned to use a 7" HDMI screen, but ended up using a computer monitor with an HDMI port. Additional materials used for the electronics of this prototype include a 32 GB SD card to upload the Raspberry Pi operating system, a Raspberry Pi wall adapter to provide power, a USB cord to power the Arduino, a HDMI - Micro HDMI cable to connect the Raspberry Pi to the monitor, and a variety of resistors. A full materials and expenses table can be found in Appendix B.

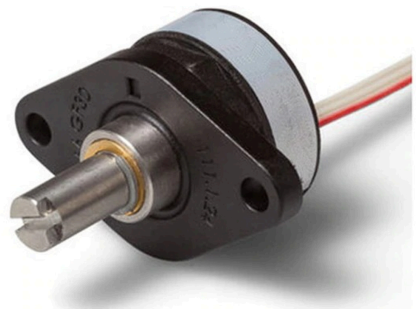


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Figure 14. P3 America ECFR 1 05SPI 360 Z Angular Encoder. [22]

Methods

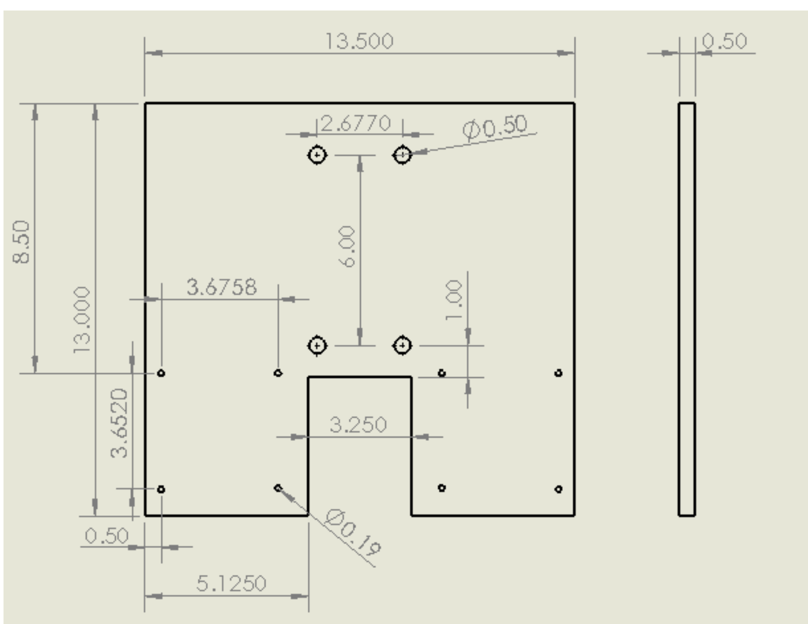


Figure 15. Dimensions of base plate in inches.

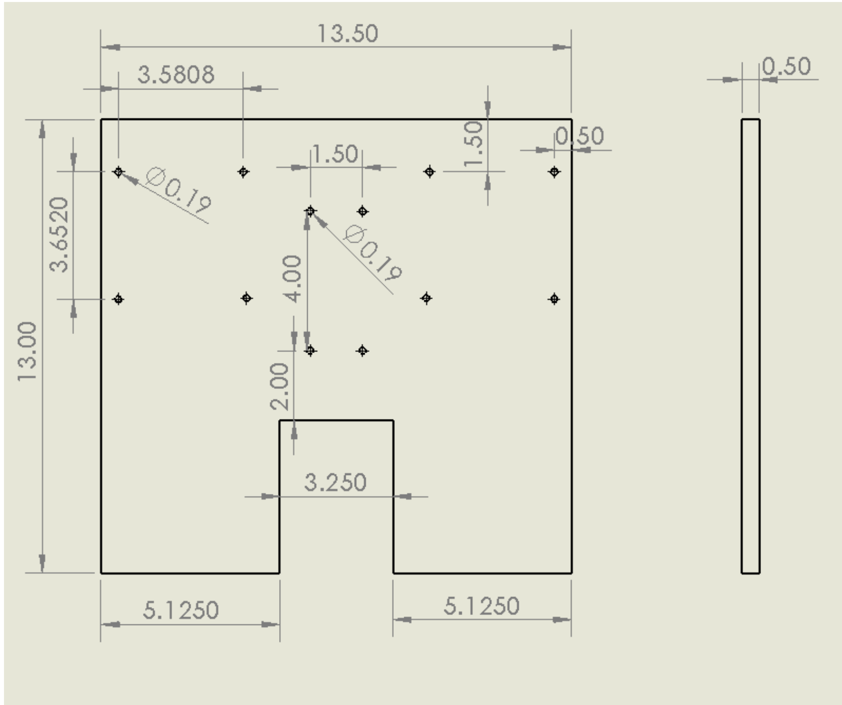


Figure 16. Dimensions of top plate in inches.

Footplate:

The footplates were fabricated by creating a SolidWorks drawing seen in Figures 15 and 16, then using the water jet cutter provided by the TeamLab. The holes were also made using the waterjet cutter. The use of this machinery ensured that the hole sizes and locations were precise when mounting to the shaft collars. A full fabrication protocol can be found in Appendix C.

Electronics/Display:

The P3 angular encoder measures the angle of its shaft and converts it into a 16-bit digital number between 0 and 360 degrees. The Arduino UNO reads the digital signal from the P3 encoder via Serial Peripheral Interface (SPI) communication (see Appendix D: Code / Arduino

Angular Encoder SPI C++ Code). This code follows the timing diagram provided in the datasheet for the MLX90316 Rotary Position Sensor, which is the chip on the p3 angular encoder [23]. The Arduino sends out 2 starting bytes (1 low, then 1 high), then receives 4 bytes containing the 16-bit digital signal, then it sends out 4 more high bytes, as seen in Figure 17, The code then extracts the data from the received signal and converts it from binary into a decimal value.

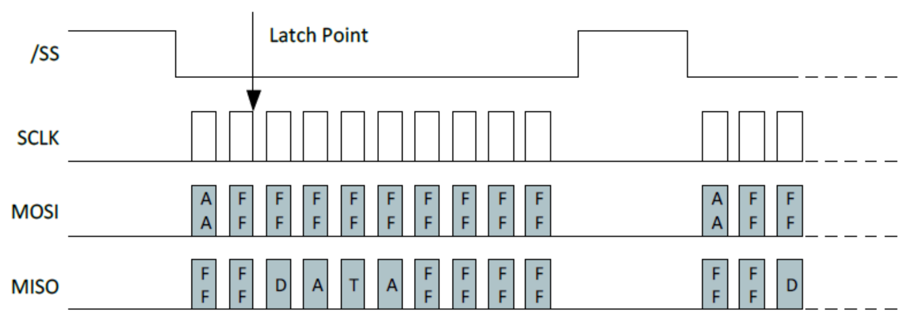


Figure 17. Timing diagram of the SPI communication to and from the p3 angular encoder. [23]

The P3 encoder only has 5 wires (Supply, Ground, Clock, Chip Select, and Data), while SPI products tend to have 6 wires (MOSI and MISO rather than one data line) to allow for bi-directional communication. To integrate this with the Arduino, the data wire was connected to the MOSI pin and also to the MISO pin in series with a 10 kOhm resistor (Figure 18).

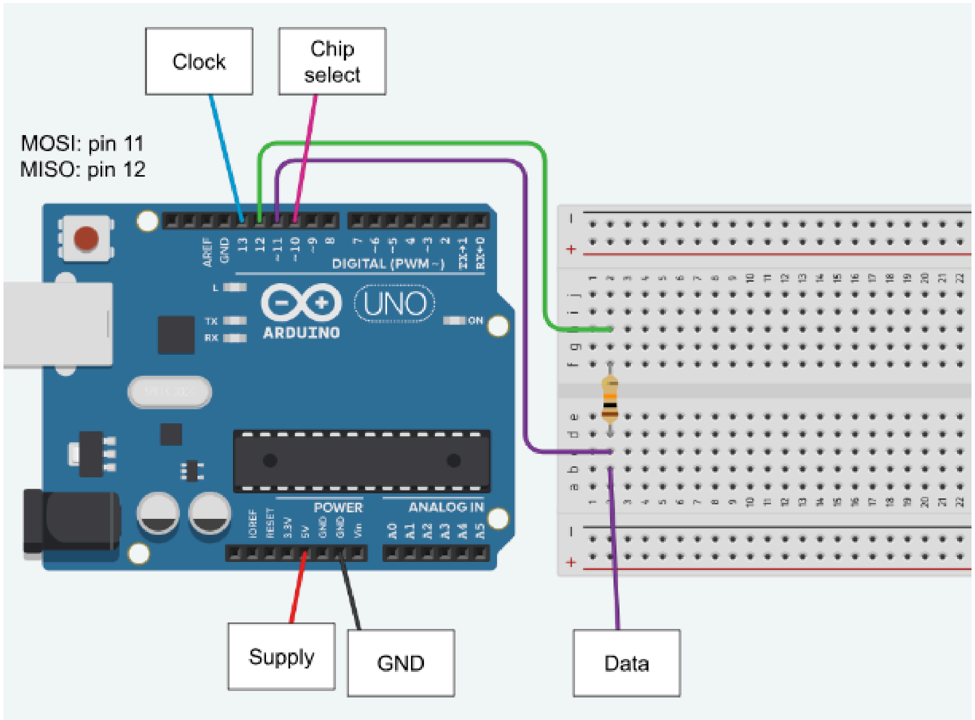


Figure 18. Fritzing diagram showing the connection of the P3 encoder wires to the Arduino Uno SPI pins with a 10 kOhm resistor.

Then, the Arduino prints the raw angle data to its serial monitor, and this data is sent to the Raspberry Pi via Universal Asynchronous Receiver/Transmitter (UART) communication (Figure 19). Finally, the python program on the Raspberry Pi integrates this angle data into a live GUI which shows the rower the real-time angle of the top foot plate (see Appendix D: Code / Raspberry Pi GUI Python Code and Figure 20). Figure 21 shows the entire logic flow of the circuit.

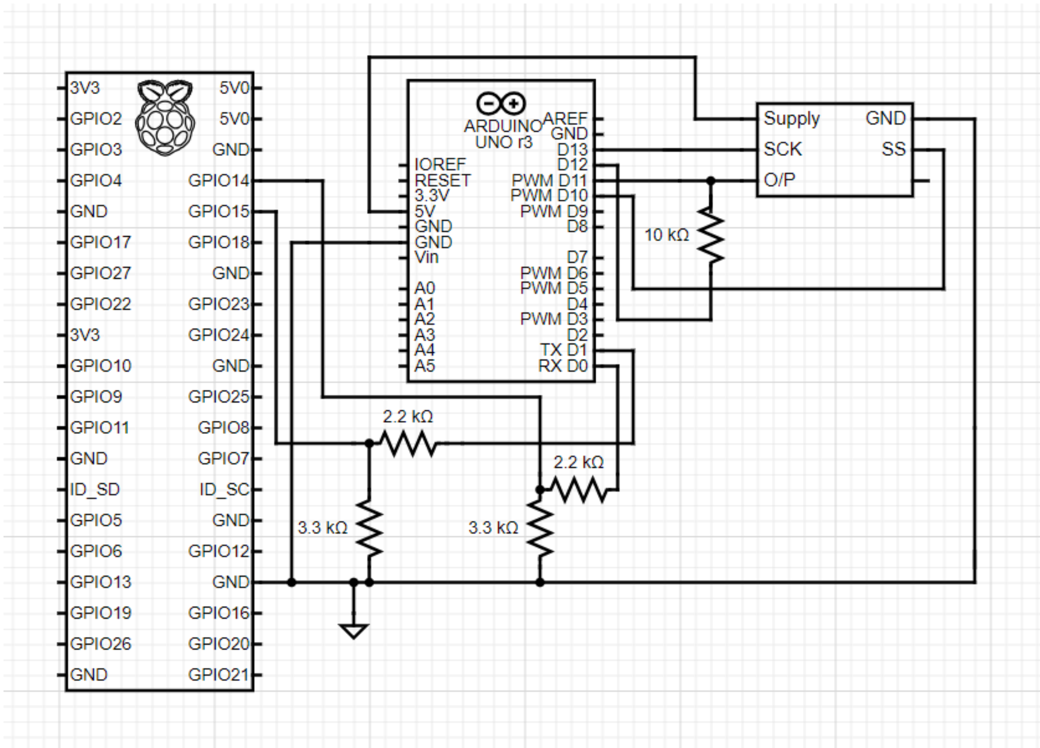


Figure 19. Circuit diagram of the final design with the Raspberry Pi (left), Arduino UNO (middle), and p3 angular encoder (right).

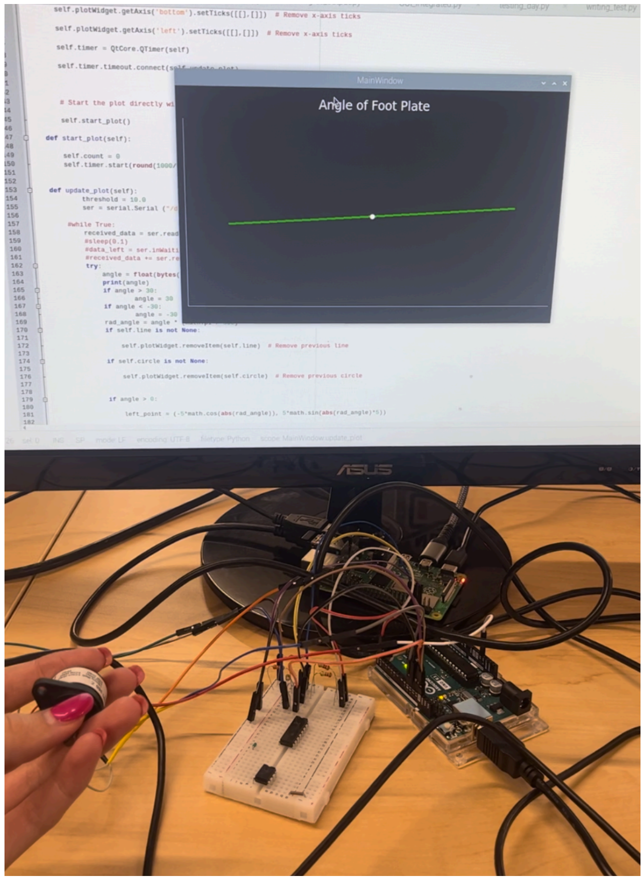


Figure 20. GUI showing the real-time angle of the p3 angular encoder shaft.

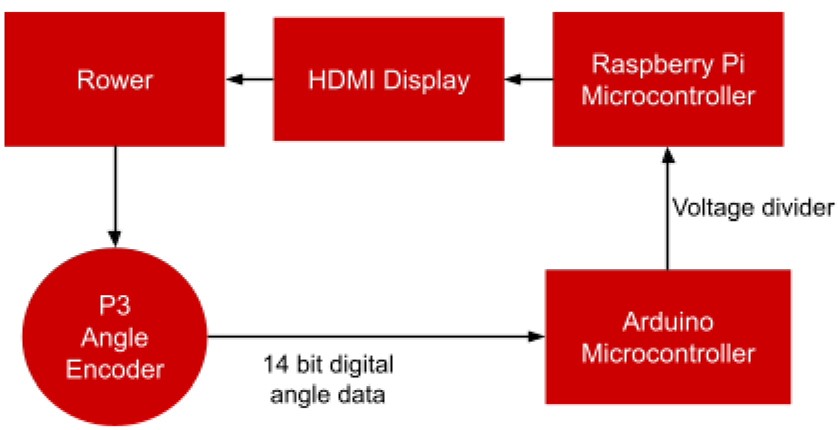


Figure 21. Logic diagram of the circuit providing real-time feedback to the rower.

Final Prototype

Figure 22. Footplate mounted on ergometer with accompanying circuitry.

Figure 23. Rower’s feet strapped into footplate with GUI on monitor.

The complete prototype shown in Figures 22 and 23 is a compilation of all its different components. The overall design consists of a rotational footplate that turns from one side to the other based on which side is receiving more force in the normal direction from the foot. The bottom footplate is made up of thick plywood and contains most of the mechanical components of the design, which is broken down in Figures 24 and 25. A 0.5” shift sits in the middle of the footplate, held by two rotational shaft bearings on either end. The bearings are secured with screws and nuts and bolts. There are four springs placed near each corner supported by aluminum mounts. The springs placement line up with the rower’s heel and metatarsophalangeal joints. The springs are adhered to the plate by velcro and the springs closest to the toe have adjustability based on foot size.

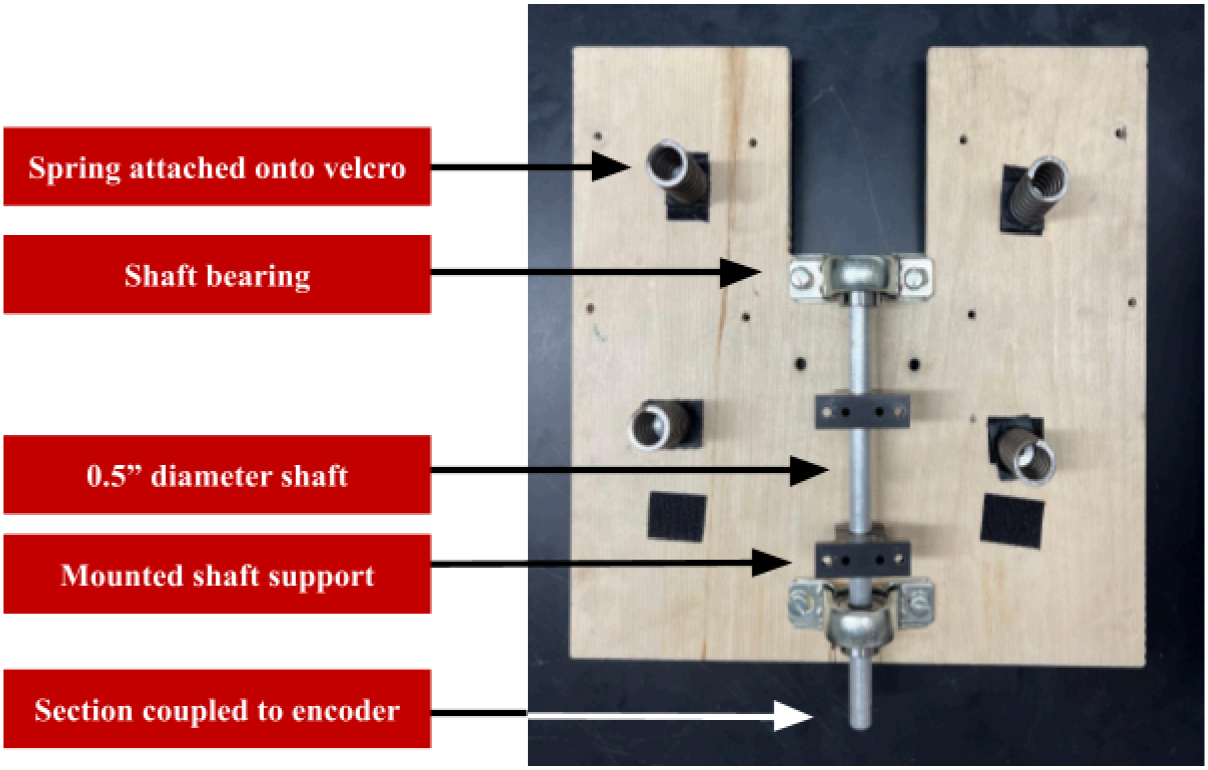


Figure 24. Bottom footplate with components.

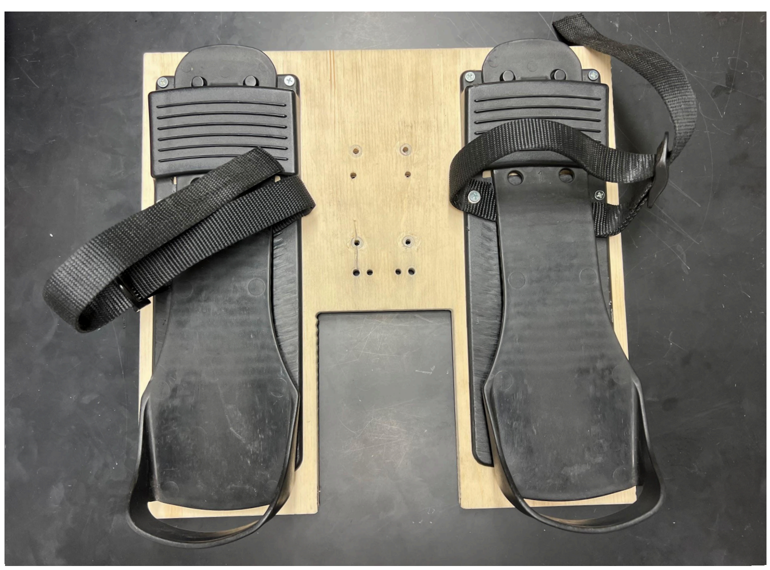


Figure 25. Top plate with Flexfeet attached.

The top footplate is screwed into the bottom plate through the two T-shaped, mounted shaft supports that lie between the bearings. Flexfeet were attached on top of the footplate with bolts in order to best mimic the surface that rowers are used to practicing on, including footstraps. Due to the added height of the foot plates, the seat height also needed to be adjusted accordingly to maintain correct knee flexion angles and form. Two wooden blocks were drilled and placed between the seat and its mount, held by four bolts, as seen in Figure 26. Additional seat pads can be added or removed on top based on the rower's individual preference.

Figure 26. Adjusted seat height with wooden block and additional seat pads.

The circuitry sits on a table next to the rower, as in Figure 27. The angular encoder is mounted to the end of the footplate's shaft with an aluminum coupler which sits near the top of the plate. Two set screws hold the coupler onto both the encoder and footplate shafts. A circle was cut out of a small wooden block and the other end of the encoder was press fit inside in order to securely fix its base so there’s only movement on one end. The wooden block was secured to the bottom footplate with an aluminum bracket, as in Figure 28.

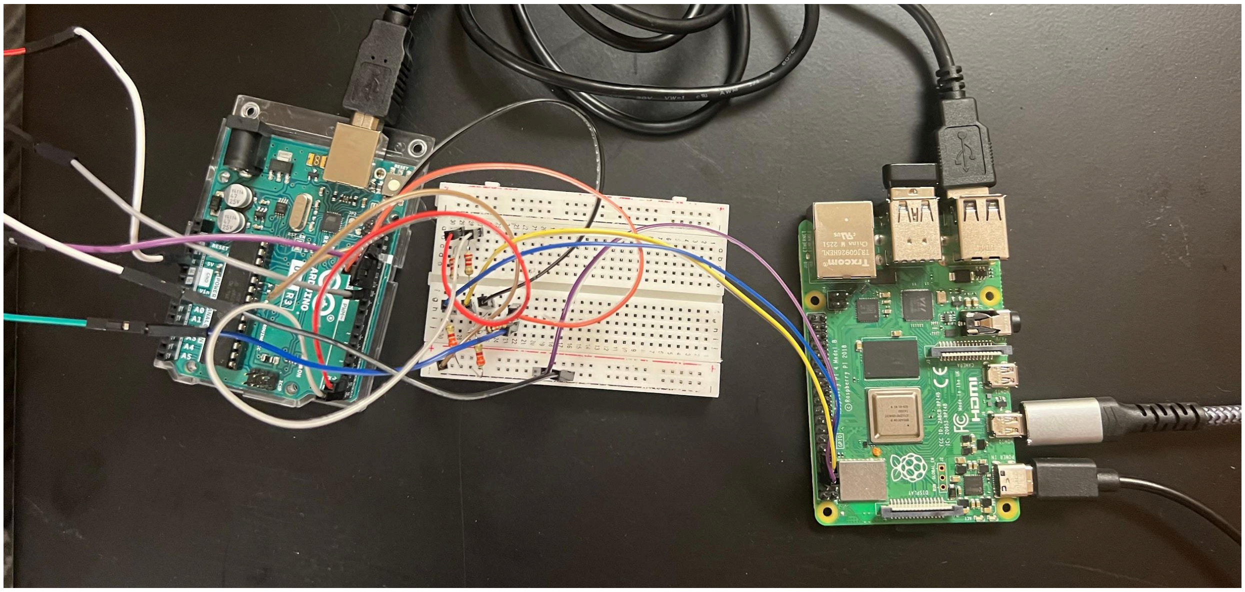


Figure 27. Arduino (left), breadboard with voltage dividers (center) and Raspberry Pi (right).

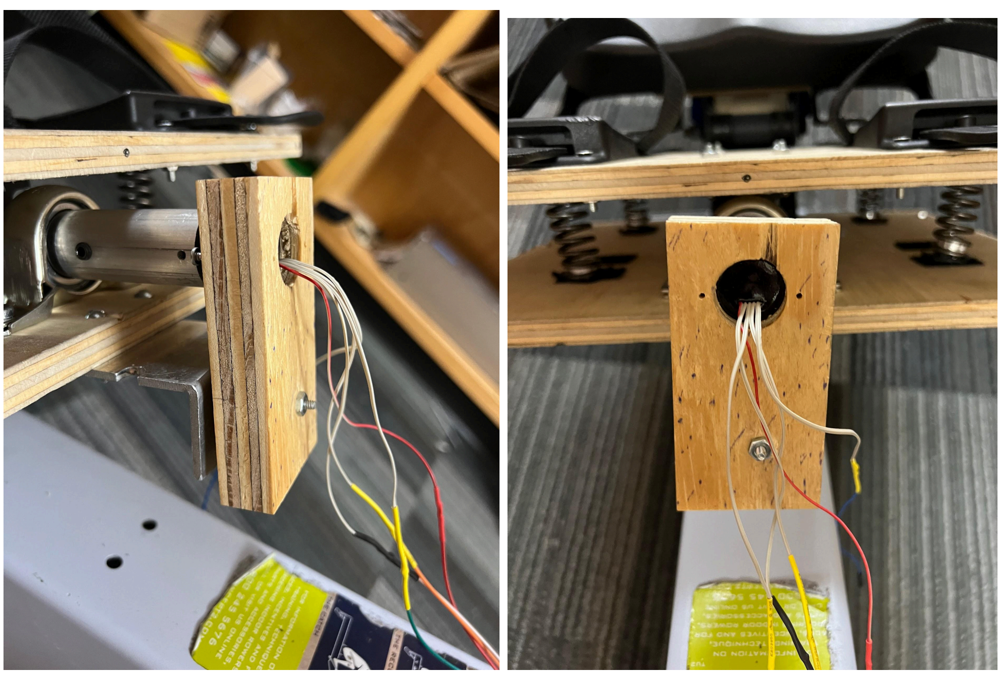


Figure 28. Side view (left) and front view (right) of angular encoder and mount.

As the upper footplate rotates along the shaft's axis when the left and right foot forces are unequal and the encoder's shaft rotates with it, outputting a digital signal corresponding to its angle. The signal is sent from the Arduino to the Raspberry Pi where it is processed, and the angle then displayed onto a monitor in real-time using the graphical user interface in Figure 29.

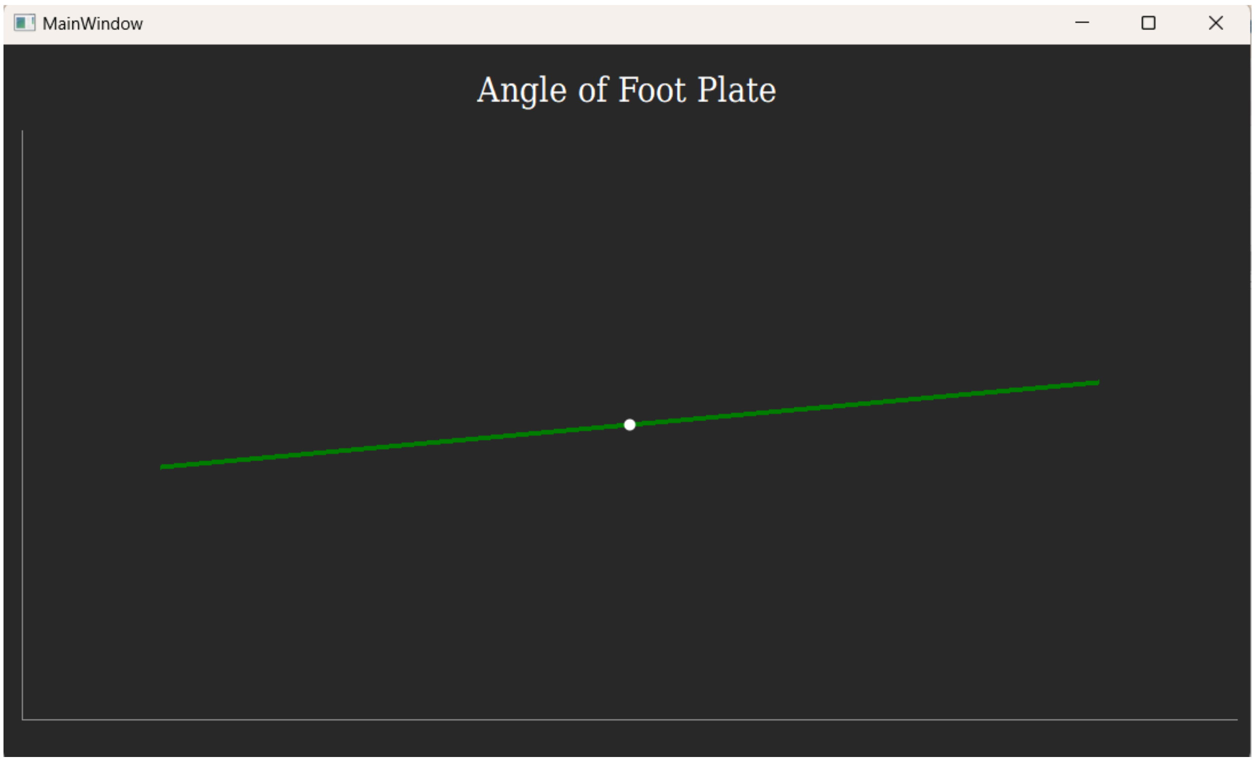


Figure 29. GUI showing the real-time angle of the top footplate using angle data from the P3 encoder.

Testing

Live Testing with Rowers:

The purpose of the live testing procedure was to ensure that the final design accurately and reliably captured the angle difference without impeding on rower form. Live testing took place at the UW boathouse on the rowing tanks in the sweep style configuration. A full testing protocol can be found in Appendix C. Four rowers were tested; one men's rower, two women's openweight and one women's lightweight. Patient metrics like weight and height were recorded for each participant. A handheld iphone was used to record while the athletes rowed on the prototype and was held at a steady position to capture a complete trial as seen in Figure 30. Due to malfunction in the angular encoder, videos were captured of a side view of the front edge of the footplate. These videos would later be imported into Kinovea for angle measurement. Testing consisted of athletes rowing at steady state for 1 minute, then rowing with emphasis on the left leg for 1 minute and lastly rowing with emphasis on the right leg for 1 minute as can be seen in Figures 31 and 32. Each athlete did two sets of testing; one with the stiffer spring and one with the more compliant spring. Athletes also qualitatively assessed their ergonomic comfort with both spring stiffnesses. Throughout all the testing, the athletes ensured that their rowing form was not drastically impeded by raising their seat with seat cushions or changing the position of the springs although they noted some slight discomfort due to the footplate height. After data collection, the testing videos were then analyzed with Kinovea to get angle data.

Figure 30. Team member recording side view of footplate during testing.

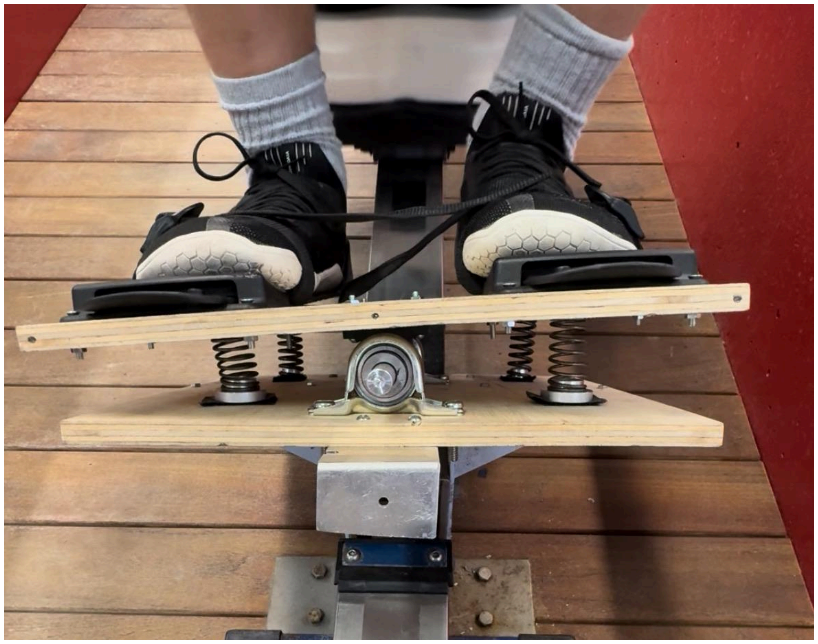


Figure 31. Video of footplate during testing captured for angle analysis.

Figure 32. Front view of rower during testing.

Angle-Force Calibration:

The prototype was calibrated by placing an object of known weight directly on top of the top plate, taking a side view image of the resulting rotation of the footplate, and measuring the angle through Kinovea. This was repeated with multiple weights from 15 to 40 pounds in five-pound increments. This process was repeated for both the stiffer and more compliant spring as the buffer material between the top and bottom plate. A line of best fit was plotted for both springs with angle difference as the x-axis and applied weight as the y-axis. The line of best fit for each spring type was used as the conversion factor from angle in degrees to force in pounds. The conversion factor was verified by testing 5 different objects of known weight and comparing those values to the output weights from the angular encoder to ensure the output is consistently within a margin of error of 5%. A full calibration protocol can be found in Appendix C.

VI. Results

After completion of the Angle-Force Calibration protocol described above, images of the footplate with the different weights applied on it for both spring configurations were imported into Kinovea. Angle with respect to the horizontal was measured by placing a coordinate system at the center of the footplate and using the angle feature, as in Figure 33 and Table 3. The measured angle was plotted against applied force to produce the correlation curve in Figure 34.

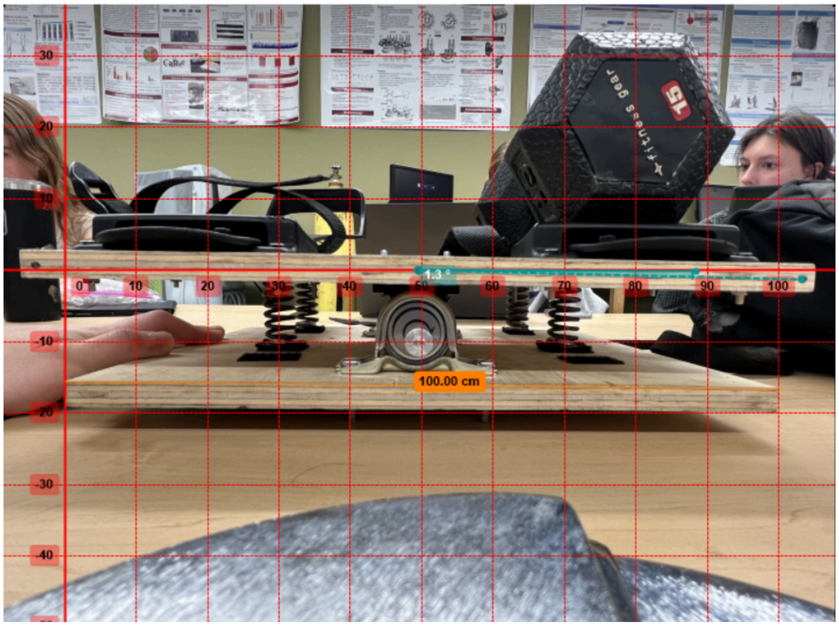


Figure 33: Calibration curve table and device set up for testing

Table 3. Applied Weight and Measured Angle for Force-Angle Calibration.

Weight (lbs)	**Stiff Spring Angle (deg)**	**Compliant Spring Angle (deg)**
15	0.5	0.9
20	0.7	1.7
25	1.1	3.3
30	1.4	3.5
35	1.8	4.4
40	2.0	5.3

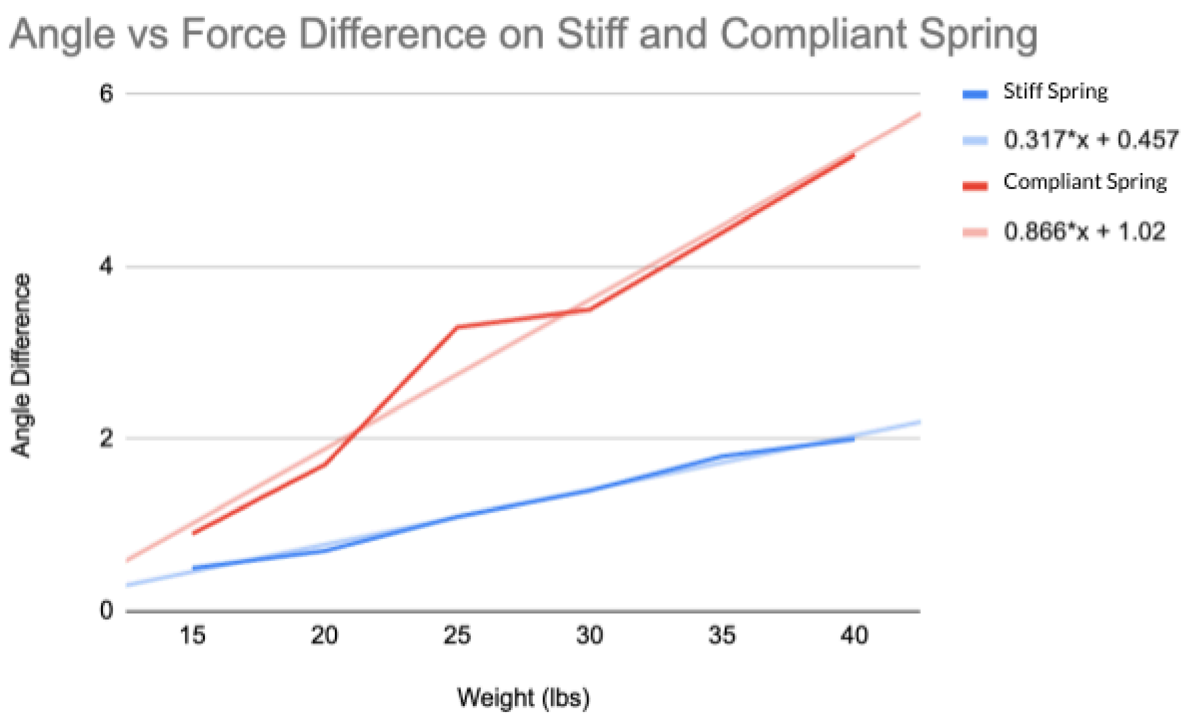


Figure 34. Angle vs force difference on stiff and compliant springs with the line of best equations.

The videos recorded during in-person testing with rowers were imported into Kinovea for analysis of the angle of the footplate. As shown in Figure 35, a side view of the footplate was recorded and a coordinate system was placed at the center of the footplate. Then, using the motion path tracking feature, the coordinates of a dot marked on the right end of the footplate were recorded. The angle of the footplate with respect to the horizontal was then calculated in MATLAB using the code in Appendix D. The calculated angle was then converted to force difference using the calibration curve above to create the plots in Figure 36.

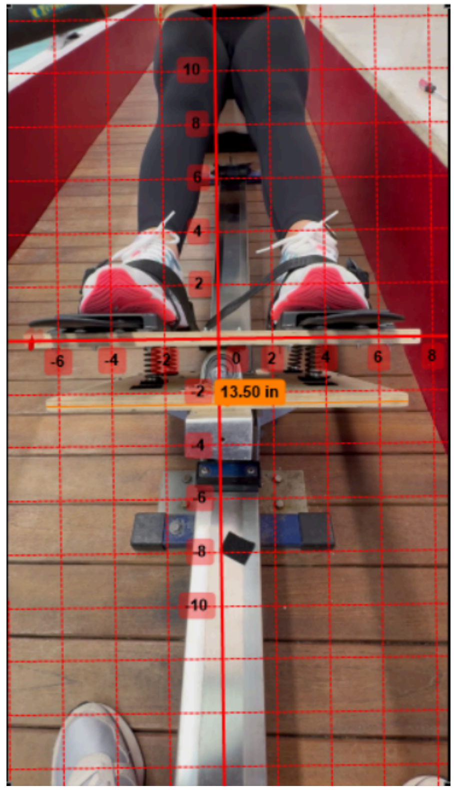
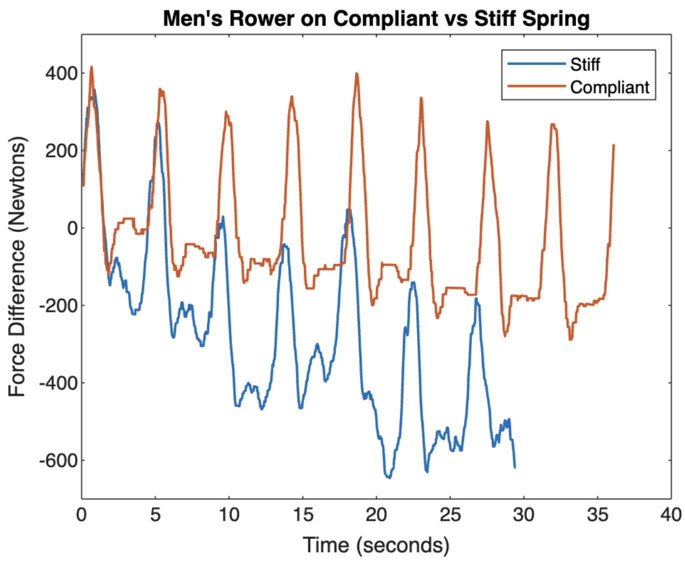
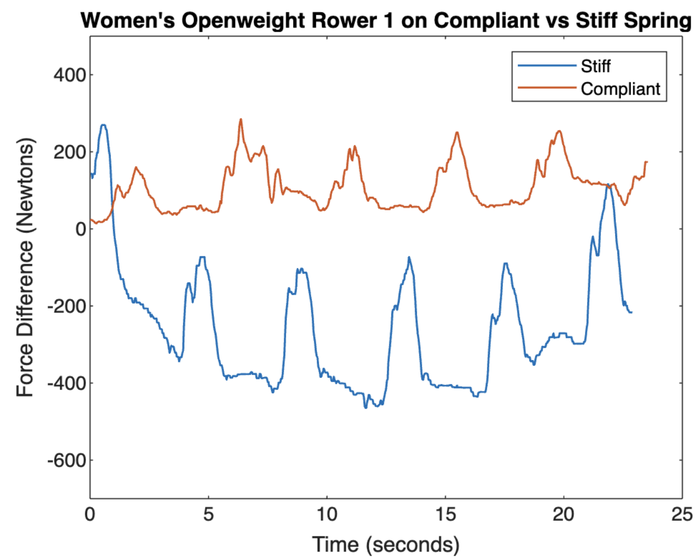


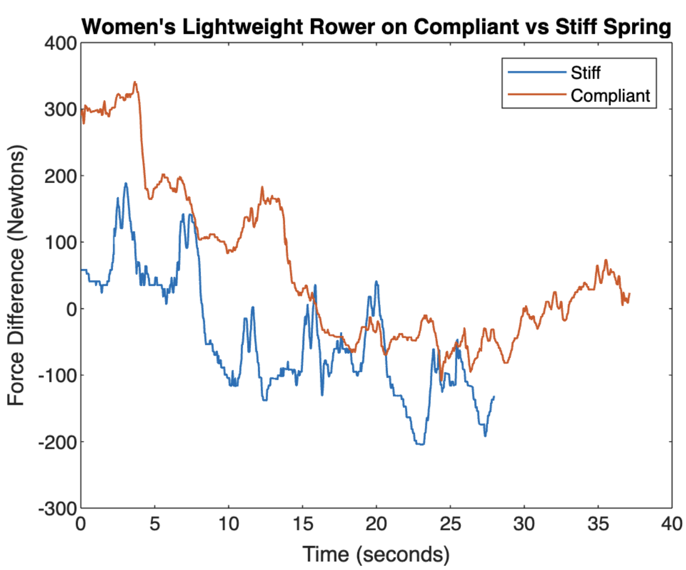
Figure 35. Side view of the footplate during testing imported in Kinovea with coordinate system.



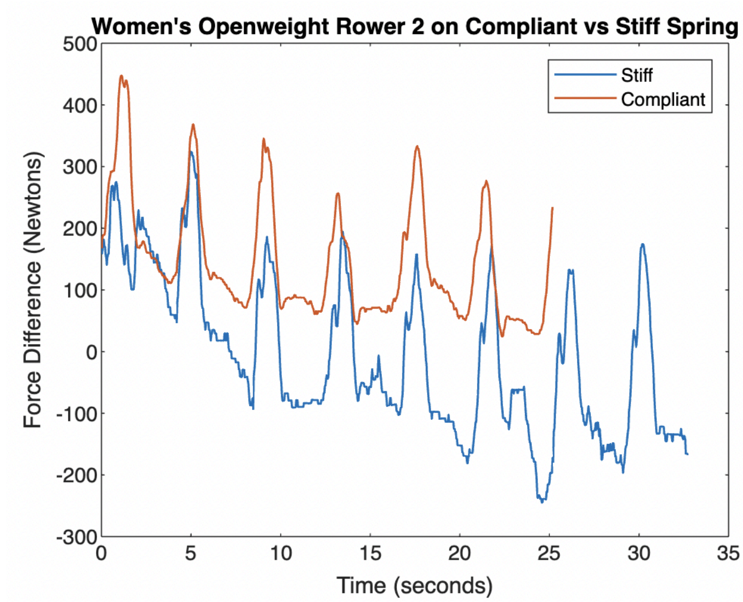
(A)



(B)



(C)



(D)

Figure 36. Force Difference vs Time for a Men's rower (A), Women's Openweight rower 1 (B), Women's Lightweight rower (C), Women's Openweight rower 2 (D). Positive force difference denotes emphasis on right leg while negative force indicates emphasis on left leg.

Peak force difference per stroke was recorded for each rower's testing period on the stiff and compliant spring configurations. A paired, two-tailed t-test was performed to compare measured peak force difference on the stiff and compliant springs. Table 4 shows the obtained p-values for the four rowers tested.

Table 4. P-values for comparing stiff and compliant footplate configurations for four rower test subjects. Significant p-values are highlighted in red.

Athlete	**P-Value (α = 0.05)**
Men's Rower	0.1879
Openweight 1	0.0052
Openweight 2	0.0045
Lightweight	0.6006

To analyze potential anthropometric risk factors for asymmetry, average measured peak force difference was plotted against rower weight (Figure 37) and rower height (Figure 38).

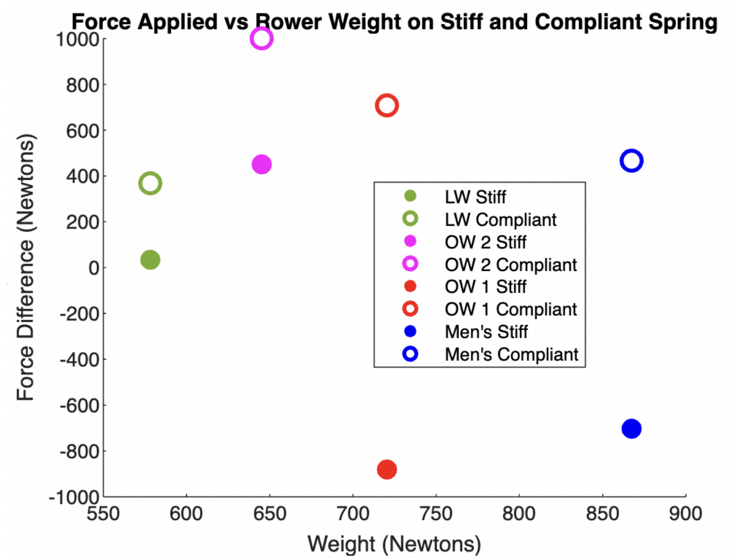


Figure 37. Force Difference vs Athlete Weight on Stiff and Compliant springs.

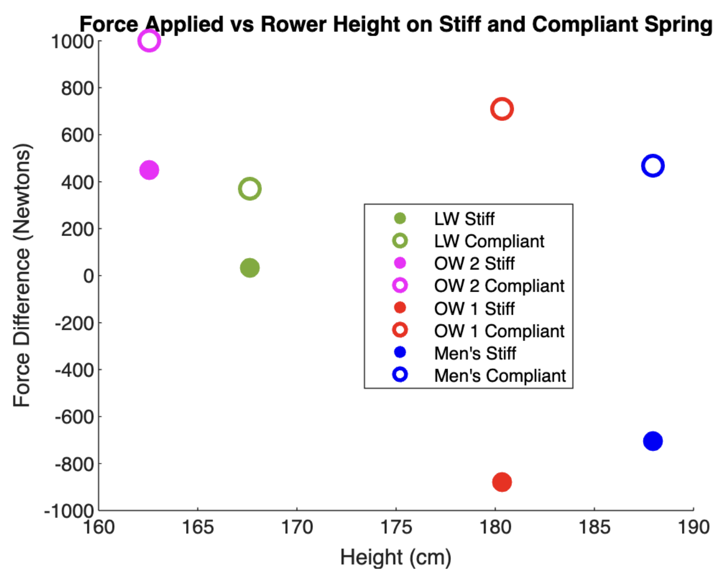


Figure 38. Force Difference vs Athlete Height on Stiff and Compliant springs.

VII. Discussion

Implications of Results

Qualitative feedback from rowers during testing was generally positive with regards to ease of use and value of data. Rowers noted that while using the device, they could feel the plate rotating underneath their feet slightly, but the springs still had enough stiffness to push off to complete the drive. Most rowers preferred the stiff springs to the compliant springs, since they are more accustomed to pushing off a rigid surface. The main issue with the design that rowers pointed out was the height difference; with the footplate moved higher up, they noted that they could not reach full flexion for the catch due to their seat being too low. Even with an added seat height extender that was part of the design, many requested three additional stacked seat pads to return to their normal form. In this way, the design does somewhat impede rowers' natural motion. With regards to the GUI, rowers found the graphic of the tilting line to be easily interpretable and did not notice a delay.

The data acquired with subsequent analysis reveals that rowers put more force on their oarside foot. During testing, all subjects rowed port, holding the oar across the right side of their body. The force peaks in Figure 36 are towards the positive direction, confirming that more rowers favored their right foot over their left. Additionally, the data reveal that compliant springs measure a higher degree of asymmetry than the stiff springs. For openweight rowers, the difference between the stiff and compliant springs was statistically significant. These findings suggest that in a clinical setting, a physician conducting a test with the device would have to tailor the spring stiffness used for a given patient, and would likely have to use different springs for different patients. The springs chosen for a particular rower would have to be compliant enough for asymmetry to be measured via the encoder or Kinovea, but would also have to be stiff enough for the rower to drive with their typical form. In practice, this would look like a physician having a set of different springs with varying spring constants, and conducting an initial calibration by testing different configurations to find the optimal setup. Then, the physician must use this same set of springs throughout the athlete's diagnosis and recovery process to effectively compare tests and track their progress.

Investigation into whether a patient's height or weight made them more likely to be asymmetric revealed no clear linear correlation; however, additional tests with at least 30 more rowers are necessary to compute a Pearson's correlation coefficient to make a final determination of whether height or weight is a risk factor for asymmetrical force output. Additionally, further research into other patient metrics such as torso length and leg mass to whole body ratio must be considered.

Sources of Error

Angular Encoder Circuit

Over time, the mechanical components of the encoder and its mounting can wear down, especially since the encoder operates in a high load bearing condition. This can lead to increased mechanical play and degradation of signal quality. Additionally, fluctuations in the power supply can affect the encoder's performance. The encoder may react differently when plugged into different supplies like outlets compared to a computer. These variations in voltage can lead to incorrect readings of angle measurements.

Reaction Moment Due to Bearing Stiffness

The mathematical derivation of force difference from angle of the top plate relies on the assumption that the top plate can rotate freely about the central shaft. One potential source of error is that the bearings used to attach the rotating shaft to the base plate are not perfectly frictionless, and seem to have a starting torque that has to be overcome before rotation occurs. This rotational friction could result in a reaction moment about the shaft that interferes with the free rotation of the top plate and the mathematical equation relating angle to force difference, resulting in errors in the force difference data.

Center of Pressure Assumptions

The design assumes that the center of pressure of each foot during rowing is at its mediolateral center. This assumption allows for the rotation of the shaft to be purely a result of force difference, and not a difference in moment arm, as can be seen in Figure 12. In addition, the springs were placed in line with the mediolateral center of the Flexfoot such that they would be aligned with the assumed center of pressure. However, the center of pressure changes dynamically while rowing due to body posture and fatigue and the center of pressure isn't always symmetrical between the feet as athletes may have more dominant sides. This makes it so that rotation of the shaft is not purely proportional to force difference and other moments could have arisen as a result of the spring placement as well.

Data Analysis Methods

Due to a malfunction in the angular encoder, angle data from a recorded video was analyzed in Kinovea. Videos were recorded on a handheld iPhone camera, and were sometimes inconsistent with viewing angle and orientation. This detrimentally affected the accuracy of motion path tracking since the software was sometimes tracking motion of the camera rather than motion of the device. In addition, the coordinate system and motion tracking markers were manually placed in the software based on visual analysis of team members. Then, motion tracking was confirmed to be accurate by looking at each frame of the video and adjusting the path of the object as necessary. This process was subject to human visual assessment error and inconsistency. These sources of error would be mitigated by use of the angular encoder circuit.

Ethical Considerations

The team has also considered ethical considerations in its design. The design does not infringe on Bylaw 10 in NCAA Division 1 Legislation 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 [24]. The design also takes 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 [25]. Therefore, rowers' data is written onto a file on the Raspberry Pi, transferred to a USB drive for secure storage, then deleted from the Raspberry Pi.

Future Work

There are several design changes that should be made to improve the accuracy and efficacy of the device. Firstly, additional springs need to be purchased with known spring constants such that rowers can have the optimal spring stiffness that is individually aligned. In addition, frictionless bearings should replace the bearings used in the current design to more accurately measure direct rotation as a result of force difference. In the case that frictionless bearings cannot be purchased, the team must recalibrate the device to account for the starting torque necessary to initiate rotation. Finally, the team must develop a proper height compensation method to raise the seat and oar placement in accordance with the height that the footplate was raised. This method should be adjustable, so that each rower can find their optimal position.

Beyond these changes to the existing rotary footplate design, any future work should involve changes such that direct force output, rather than force difference, can be measured. As of now, the device can only measure force difference between legs, but absolute force output is more clinically relevant data that is useful to track athletes' return from injury. In order to modify this design to measure absolute force output, load cells must be incorporated. A potential idea to protect load cells from the off-axis and dynamic loading that were previously discussed is building a mechanical shielding device that converts any off-axis loading into a normal load. Another potential method is the use of clamps to secure the footplate in the x and y axis, ensuring that the load is applied directly downwards, aligning with the primary sensing axis of the load cell. This would help in isolating the load cell from any lateral or torsional forces that might occur.

Additional testing of the device is also required to gather clinically relevant data. More rowers should be tested to validate the device's accuracy. These rowers should vary demographically, ranging from injured to healthy and women's lightweight to men's. Following validation data collection, patient anthropometric data should be correlated to assess risk factors for asymmetry. Potential anthropometric data that could be assessed in relation to force asymmetry are leg length, torso to leg length ratio, or range of motion of the hip, knee, or ankle. Asymmetry could also be a result of performance metrics like stroke rate or power output, which should be investigated in the future.

VIII. Conclusions

The development of a biomechanical measurement device for assessing lower extremity force in rowers is pivotal for improving lower back injuries and overall performance in the UW-Madison women's rowing team. The final design features an angular encoder mounted on a shaft with a top plate that pivots in response to the force exerted by the rower's legs. The springs that are the buffer materials between the top and bottom provide a rigid surface that rowers are used to while also maintaining some fluidity to allow for pivot measurements. This setup captures precise angular displacement and allows for easy force measurement conversion. The system utilizes a Raspberry Pi to process the data, which is then displayed through a graphical user interface (GUI) on a display that provides real-time feedback. This design not only aligns with client specifications on real-time feedback but also enhances transferability through its ease of portability and practicality as it doesn't impede on rower technique or significantly modify existing equipment. Live testing with experienced rowers has identified potential enhancements, such as the integration of load cells to provide specific force readings for each leg and integration of data analysis with other patient metrics to consider more factors in asymmetry. This collaborative project marks a significant advancement in the integration of innovative biomechanical solutions for injury prevention and performance enhancement in elite rowing.

IX. References

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X. Appendix

Appendix A: Product Design Specifications

THE UNIVERSITY of WISCONSIN MADISON

PRODUCT DESIGN SPECIFICATIONS: FORCE PLATES FOR ROWING BIOMECHANICS

BME 301, Section 302

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Advisor: Dr. John Puccinelli

Team Members:

Team Leader: Neha Kulkarni

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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 injuries in the lumbar spine, the shoulders, the knees, and the hips when the right and left lower extremities generate asymmetrical forces [1]. 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 [2]. 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 on the ergometer base in the tank 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 device must be strong enough to withstand the force exerted by rowers during the drive phase of the stroke, which peaks at 900 N [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 provide real-time data on the amount of force transmitted by the toe and heel (separately) of each foot onto the tank footplate.
- The client desires an easily integrated force measuring system that should operate without requiring change in rowing technique.
- The device must alert the rower when force exerted by the right and left foot are asymmetrical.
- The frequency and duration of force data storage during rowing sessions must be adjustable.

<u>Design Requirements:</u>

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 device should quantify the degree of asymmetry using the magnitude of relative force between limbs.
    - The device must provide data on the amount of force transmitted by the toe and heel (separately) of each foot onto the tank footplate.
- 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 so coaches and rowers can see the data in real time and analyze it later.
- The real-time display must be easily interpretable by the user(s) using simple visual cues like colors, lights, figures, and text.

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 made with easily available parts such that they are replaceable in the event of malfunction or failure.

- The product should display and store data with high accuracy with a margin of error at 5% [6].
- The product must have no more than a 0.5 second delay between a rower's stroke and the real-time display so as to provide feedback at least once per stroke [7].

d. Life in Service:

- The NCAA in-season hourly practice limitation is no more than 20 hours per week and roughly 8 months out of the year or about 34 weeks [8].
- The product should remain functionable for the duration of a full collegiate rowing career. The typical career of a collegiate rower is 4 years. This equates to roughly 6,800 - 8,160 hours.
- The Concept2 RowERG® requires all screws and connections to be thoroughly checked every 250 hours of use [7]. The product's connections and integrity should be checked concurrently.

e. Shelf Life:

- The average lifespan of a load cell is around 10 years with proper usage, maintenance, and protection [9].
- The appropriate range of ambient temperature for load cell storage is from -10°C - 40°C [10].

f. Operating Environment:

- The client would like this device to be compatible with the ergometer next to the tank. This would consist of room temperature conditions. These conditions are around 20-22° C and low humidity.
- An outlet or extension cord should be provided in the room to power the device.

g. Ergonomics:

- Display
  - The display will be at eye level from the rower as they are rowing, roughly 1.1 m from the ground [11].

  - The feedback will be easy to interpret quickly, so that the rower can quickly adjust their form.
- Force Plate
  - 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.
  - The force plate must be adjustable to different foot sizes.
  - The force plate must include passive mechano-transduction through a textured surface with a height of 3mm. This will ensure optimal force transmission and greater area contact between the footplate and foot. [12]

h. Size:

- Display
  - The visual display should be at least 12 cm wide and 6.75 cm tall so that the screen size allows alphanumeric text to be 10 mm tall (*see Standards and Specifications)*.
- Force Plate
  - The width of a singular footplate of the 2005 Concept2 ergometer model D in the rowing tank is 13.3 cm and the height is 30.7 cm. The force plate must be the same size or smaller than these dimensions to fit on top of the foot plate.
  - The average 200kg load cell thickness is between 10-35 mm [13][14]. Therefore the thickness of the product should not be thicker than 35mm in order to maintain a relatively level surface and not impede upon the toe or heel straps of the flexfoot.

i. Weight:

- Maximum user weight for the RowERG is 227 kg [1]. The weight range of a woman crew athlete is on average 50 - 84 kg [15]. To not exceed this scale, the product weight should not exceed 143 kg.

k. Materials:

- A strain gauge load cell will be used for measuring force in a force plate to provide a greater surface area for force distribution applied by the foot. The chosen strain gauge load cell will operate by measuring electrical resistance changes in response to applied strain or pressure on the load cell. This load cell should accurately assess and withstand weights of 200 kg applied while rowing based on surface strain. [16]
- Additionally, housing material for load cells should be safe to use in a sports testing environment and be in compliance with the Sports and Recreational Equipment General Safety Requirements (*see Standards and Specifications*)
- A load cell amplifier compatible with the chosen strain gauge load cells will be utilized and have an operation voltage of 5 Volts.
    - Will be used to amplify signals from the load cells for accurate weight measurements. It will also be compatible with microcontrollers for data acquisition. [17]

l. Aesthetics, Appearance, and Finish:

- Display
    - The visual display must have a frame rate of at least 24 Hz, which is the standard frame rate of motion pictures, so that changes on the display appear continuous to the human eye [18].
- Force Plate
    - The constructed force plate should have clean lines and match the neutral gray and black colors of the ergometer so that it blends in as an attachment.
- Any hardware or electronics used to connect the force plates to the display should be hidden in an electronics box, to maintain a neat appearance.

2. Product Characteristics:

a. Quantity:

- The team aims to fabricate one functioning prototype this semester, consisting of a right and left force plate connected to a display screen. In the future, the client would like a total of 8 prototypes for the 8 ergometers fit to the tank.

b. Target Product Cost:

- The budget for this design project is $1000 . The budget may be increased with approval from the UW Athletic Department.

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) [19].
  - 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 [20].
  - 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.

- The device must comply with the Sports and Recreational Equipment General Safety Requirements (ISO 20957) to enhance safety and reliability of athletic testing equipment [21].
    - It includes guidelines for mechanical strength and endurance testing to ensure material can withstand forces applied during athlete testing.

b. Customer:

- The primary target customer for the product is the Physical Therapist and Athletic Training Staff for the University of Wisconsin Rowing Team.
    - University of Wisconsin collegiate rowers will be the primary operators of the device during use.
    - The device will also be used by the coaching staff of the University of Wisconsin Rowing Team.
- The customer(s) will use the device for routine evaluation of rowers' form, diagnosis of injury, and assessing progress during rehabilitation and return from injury.
    - Quantitative markers of asymmetry are required for determining the degree of injury and stage of progress during rehabilitation.
    - Positional placement must be adjustable between the ergometer and port or starboard sides of the tank.

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 [20].
    - The storage drive must be able to store multiple runs of longer rowing sessions between 40-100 minutes.

d. Competition:

- Bertec® produces portable force plates for gait, balance, and performance analysis [22].
  - 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 [23].
  - 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	#	Cost Each	Total	Link
Electronics										
Raspberry Pi	Microcontroller	Raspberry Pi		Sparkfun	DEV-15446	2/15	1	$45	$60.43	Link
Raspberry Pi	7" Display Screen	Raspberry Pi		Amazon		2/23	1	$33.99	$33.99	
Raspberry Pi	20W 5V 4A Power Supply	Raspberry Pi		Amazon		2/23	1`	$11.99	$11.99	
MicroSD Card	32GB 3D NAND High Speed MicroSD Card with Adapter	Silicon Power USA		Amazon		2/23	1	$8.99	$8.99	
HDMI Cable	4K Micro HDMI to HDMI Cable 1 FT Adapter 2.0	Szsea US		Amazon		2/23	1	$8.99	$8.99	

Display Case	7" Raspberry Pi Case Holder	Longruner		Amazon		3/18	1	$13.99	$13.99	Link
Undersized Rotary Shaft	1/2" diameter, 12" length	McMaster Carr	4149N15	McMaster Carr		4/05	1	$22.18	$22.18	Link
Aluminum Easy-Access Base-Mounted Shaft Support	Low-Profile T-Shaped, for 1/2" shaft dia.	McMaster Carr	1865K3	McMaster Carr		4/05	1	$28.20	$28.20	Link
Low-Profile Mounted Sealed Steel Ball Bearing	with Set Screw, for 1/2" shaft dia.	McMaster Carr	5913K6	McMaster Carr		4/05	2	$10.95	$21.90	Link
Aluminum Shaft Support, Black Anodized, T-Shaped, for 1/2" Shaft Diameter	Taller, T-shaped for 1/2" dia. With set screw	McMaster Carr	1865K109	McMaster Carr	2	4/18	2	$31.43	$62.86	Link
Aluminum Bolt-Together Framing	1-1/2" Square Rail, 6 ft length	McMaster Carr	8809T7-8809T21	McMaster Carr		4/05	1	$47.20	$47.20	Link
Marine-Grade Plywood Sheet	24" x 24" x 3/8"	McMaster Carr	1125T23	McMaster		4/05	1	$33.71	$33.71	Link

				Carr						
Corner Surface Bracket		McMaster Carr	4931 T221	McMa ster Carr		4/05	8	$9.96	$79.68	Link
Load-Rated Threaded Bumpers	2" height	McMaster Carr	9377 K23	McMa ster Carr		4/05	2	$26.67	$53.34	Link
Compression Spring	352 max load	McMaster Carr	9657 K695	McMa ster Carr		4/05	8	$10.06	$80.48	Link
Compression Spring	124 max load	McMaster Carr	9657 K374	McMa ster Carr		4/05	2	$25.92	$25.92	Link
Raw Materials										
Wood Scrap	TEAM Lab					3/23		$0.00	$0.00	
Aluminum Scrap	TEAM Lab					4/3		$0.00	$0.00	
8” Aluminum Rod	TEAM Lab					4/18		$8.27	$8.27	
								TOTAL:		**$539.26**

Appendix C: Protocols

Footplate Fabrication Protocol

Materials

1. Footplate SolidWorks Drawing
2. Plywood
3. Cylindrical aluminum stock
4. Aluminum rod
5. Shaft bearings, collars, and support mounts
6. Wooden block
7. Aluminum bracket
8. Nuts and bolts
9. Velcro
10. Compression Springs

Methods

1. Upload SolidWorks file to the waterjet's control panel's programming.
2. Mount a 0.5" thick piece of plywood to tank with clamps and line up the jet to the starting point on the wood.
3. Zero the machine. Start the machine and cut the wood according to the SolidWorks' dimensions.
4. Repeat with the other footplate.
5. Allow both plywood pieces to dry for a day.
6. Cut 0.5" diameter aluminum rod using the drop saw to a length of 7.875".

7. Loosen set screws on shaft support mounts and slide them onto the rod at the desired position then tighten the provided set screws.
8. Attach shaft bearing and collars on the end of the rod at the desired position.
9. Secure the bearing collars to the bottom footplate with stainless steel #10-12 x 3/4" bolts and nuts.
10. Tighten shaft bearings to the rod with set screws.
11. Place the top footplate onto the shaft support mounts and align holes.
12. Screw #8-32 x 1" bolts from top footplate into the support mount and secure with nuts.
13. Create encoder-shaft couple from cylindrical aluminum stock:
    a. Drill 1" diameter hole 0.5" deep into one face.
    b. Drill a 6mm hole of encoder shaft diameter into the other face 12.7mm deep.
    c. Drill holes for set screws on both sides using the mill.
    d. Place endcoder's shaft into its corresponding hole and fix with set screw.
14. Attach couple to the top end of the aluminum rod on the footplate and secure with set screws.
15. Create support mount for encoder.
    a. Take a scrap piece of wood and drill a 22mm diameter hole.
    b. Press fit the encoder's housing into the drilled hole.
    c. Acquire a metal bracket and drill 3 holes with a #29 drill bit.
    d. Drill a hole into the wooden block with the same drill bit size and two holes into the bottom footplate near its top edge.
    e. Align bracket to the holes on the bottom footplate and the hole in the wooden block

f. Secure components with 8/32 x 3/4” bolt and according nuts.

16. Remove each Flexfoot on the ergometer with a wrench and transfer them to the top footplate.
17. Screw in the Flexfeet to the top footplate with the same bolts that were removed from the ergometer.
18. Attach the entire footplate design to the ergometer’s footplate.
19. Align the holes of the bottom footplate to the location of the Flexfeet’s original location and secure prototype with 5mm bolts and nuts.
20. Create spring support mounts.
    a. Cut a cylindrical aluminum stock into four 0.5” thick disks using the drop saw.
    b. Using the lathe, trim down the disk diameter to a size slightly larger than the inner diameter of the springs.
    c. Press fit the springs into the disk mounts using a mallet.
    d. Add velcro adhesive to each bottom of the mounts as well as in each corner of the bottom footplate near where the toe and heel joints would be.
    e. Squeeze in the springs between the footplates and stick the velcro pieces to each other.
21. Add seat mount.
    a. Unscrew seat from its mount.
    b. Aguire two wooden blocks and place one atop another onto the drill press.
    c. Clamp to secure and drill four holes into the wood
    d. With a #12 bit drill size

e. Align wood between the seat and mount and screw everything together with #8-32 x 2” bolts and nuts.

Angle-Force Difference Calibration

Materials

1. Footplate Design
2. 15-, 20-, 25-, 30-, 35-, and 40-lb weights

Methods

1. Place the footplate on a flat surface. Have someone hold the footplate flat to the surface if necessary.
2. Place the 15-lb weight on one side of the footplate.
3. Use a camera to take a picture of a side view of the top edge of the footplate.
4. Remove the weight then repeat steps 1-3 with the subsequent weights.
5. Import all photos into Kinovea and use the angle tool to measure angle as a result of applied weight.
6. Plot applied weight against measured angle and determine a linear trendline to generate a calibration curve.

Qualitative Rower Testing

Materials

1. Angular Encoder,
2. LCD Display or Monitor

3. Laptop
4. Footplate Design

Participants: Members from the rowing team in the Lightweight, Openweight, and Men's divisions of the UW Rowing Team.

Methods

1. Mount the pivot footplate design to the Concept2 RowErg in the rowing tank and configure the angular encoder to 0 degrees by rotating the shaft and zeroing the encoder in the code.
2. Unscrew the seat of the RowErg and screw in the wooden seat extender.
3. Allow rowers to sit on the seat, adjust the Flexfoot and strap their feet into the footplate. If rowers feel their feet are too high up, have them sit on additional seat pads as necessary.
4. Allow rowers 3 minutes to warm up at a comfortable pace on the rowing tank/ ergometer.
5. Qualitatively assess rowers' preference on material between the two plate: bumpers, high stiffness springs, medium stiffness springs and combinations
6. Conduct testing on angle difference during steady state, right leg emphasis and left leg emphasis.

In-Person Rower Testing and Data Collection

Materials

1. Angular Encoder
2. LCD Display or Monitor

3. Laptop
4. Footplate Design
5. Wooden Seat Extender
6. Additional Seat Pads
7. Rowing Tank at UW Porter Boathouse

Participants: Members from the rowing team in the Lightweight, Openweight, and Men's divisions of the UW Rowing Team.

Methods

1. Mount the pivot footplate design with stiff springs as the buffer material to the Concept2 RowErg in the rowing tank and configure the angular encoder to 0 degrees by rotating the shaft and zeroing the encoder in the code.
2. Unscrew the seat of the RowErg and screw in the wooden seat extender.
3. Allow rowers to sit on the seat, adjust the Flexfoot and strap their feet into the footplate. If rowers feel their feet are too high up, have them sit on additional seat pads as necessary.
    a. If using Kinovea to analyze angle data, set up a camera to record a side view of the top edge of the plate and mark three dots along the edge of the top plate to aid with motion tracking. Start the video recording.
4. Allow rowers to warm up for two minutes by rowing at steady state (consistent, moderate effort). This will allow baseline data for each rower to be collected.

1. Have rowers row with increased force applied through the right foot. This will capture data reflecting angle difference and allow rowers to see the dynamic GUI.
2. Repeat Step 7 but with left leg emphasis.

3. Switch the stiff springs out for more compliant springs and repeat steps 1-8, but keep the video running.
4. Once all testing is complete on both spring configurations, stop video recording and analyze data in Kinovea.

Appendix D: Code

Data Analysis MATLAB Code

```
%Hard Spring Angles
data = readtable('HansStiff.xlsx');
x = data.x;
y = data.y;
time = data.t;
rad = tan(y./x);
deg = rad .* (180/3.14);
force = ((15.6.*deg)+ 7.96) * 4.4482216153
[pksHans,locs] = findpeaks(force, MinPeakProminence=25);
plot(time,force,time(locs),pksHans,"o", LineWidth=1);
title("Men's Rower on Stiff Spring");
xlabel('Time (seconds)');
ylabel('Force Difference (lbs)');
%%
data1 = readtable('VickyStiff.xlsx');
x1 = data1.x;
y1 = data1.y;
time1 = data1.t;
rad1 = tan(y1./x1);
deg1 = rad1 .* (180/3.14);
force1 = ((15.6.*deg1)+ 7.96) * 4.4482216153
[pksV,locsV] = findpeaks(force1, MinPeakProminence=10);
plot(time1,force1,time1(locsV),pksV,"o", LineWidth=1);
```

```
title("Women's Openweight 1 on Stiff Spring");
xlabel('Time (seconds)');
ylabel('Force Difference (lbs)');
%%
data2 = readtable('ToriStiff.xlsx');
x2 = data2.x;
y2 = data2.y;
time2 = data2.t;
rad2 = tan(y2./x2);
deg2 = rad2 .* (180/3.14);
force2 = ((15.6.*deg2)+ 7.96) * 4.4482216153
[pksT,locsT] = findpeaks(force2, MinPeakProminence=10);
plot(time2,force2,time2(locsT),pksT,"o", LineWidth=1);
title("Women's Lightweight on Stiff Spring");
xlabel('Time (seconds)');
ylabel('Force Difference (lbs)');
%%
data3 = readtable('Maddy stiff.xlsx');
x3 = data3.x;
y3 = data3.y;
time3 = data3.t;
rad3 = tan(y3./x3);
deg3 = rad3 .* (180/3.14);
force3 = ((15.6.*deg3)+ 7.96) * 4.4482216153
[pksM,locsM] = findpeaks(force3, MinPeakProminence=20);
plot(time3,force3,time3(locsM),pksM,"o", LineWidth=1);
title("Women's Openweight 2 on Stiff Spring");
xlabel('Time (seconds)');
ylabel('Force Difference (lbs)');
%Soft Spring Angles
datas = readtable('HansSoftSpring.xlsx');
xs = datas.x;
ys = datas.y;
times = datas.t;
times = times - 23.88;
rads = tan(ys./xs);
degs = rads .* (180/3.14);
forces = ((15.6.*degs)+ 7.96) * 4.4482216153
```

```
[pksHanss,locss] = findpeaks(forces, MinPeakProminence=12);
plot(times,forces,times(locss),pksHanss,"o", LineWidth=1);
title("Men's Rower on Compliant Spring");
xlabel('Time (seconds)');
ylabel('Force (lbs)');
%%
data1s = readtable('VickySoftSpring-Edited.xlsx');
x1s = data1s.x;
y1s = data1s.y;
time1s = data1s.t;
time1s = time1s - 5
rad1s = tan(y1s./x1s);
deg1s = rad1s .* (180/3.14);
force1s = ((5.62.*deg1s)+ 9.62) * 4.4482216153
[pksVs,locsVs] = findpeaks(force1s, MinPeakProminence=8);
plot(time1s,force1s,time1s(locsVs),pksVs,"o", LineWidth=1);
title("Openweight Rower 1 Compliant Spring");
xlabel('Time (seconds)');
ylabel('Force (lbs)');
%%
data2s = readtable('ToriSoftSpringEdited.xlsx');
x2s = data2s.x;
y2s = data2s.y;
time2s = data2s.t;
rad2s = tan(y2s./x2s);
deg2s = rad2s .* (180/3.14);
force2s = ((5.62.*deg2s)+ 9.62) * 4.4482216153
[pksTs,locsTs] = findpeaks(force2s, MinPeakProminence=7);
plot(time2s,force2s,time2s(locsTs),pksTs,"o", LineWidth=1);
title("Women's Lightweight on Compliant Spring");
xlabel('Time (seconds)');
ylabel('Force (lbs)');
%%
data3s = readtable('Maddy soft.xlsx');
x3s = data3s.x;
y3s = data3s.y;
time3s = data3s.t;
rad3s = tan(y3s./x3s);
```

```
deg3s = rad3s .* (180/3.14);
force3s = ((5.62.*deg3s)+ 9.62) * 4.4482216153
[pksMs,locsMs] = findpeaks(force3s, MinPeakProminence=8);
plot(time3s,force3s,time3s(locsMs),pksMs,"o", LineWidth=1);
title("Women's Openweight 2 on Compliant Spring");
xlabel('Time (seconds)');
ylabel('Force (lbs)');
```

Arduino Angular Encoder SPI C++ Code

```
#include <SPI.h>
const uint8_t CS_PIN = 10;
void setup() {
  Serial.begin(9600);
  pinMode(CS_PIN, OUTPUT);
  digitalWrite(CS_PIN, HIGH);
   SPI.begin();  delay(20);
}
void loop() {
  /*A data frame consists of 10 bytes:
    • 2 start bytes (AAh followed by FFh)
    • 2 data bytes (DATA16 – most significant byte first)
    • 2 inverted data bytes (/DATA16 – most significant byte first)
    • 4 all-Hi bytes  */
  uint8_t data[10] = {0};
  int index = 0;
```

```
  //min time between each bit transfer is 7 microseconds so set to 125kHz
which is the lowest
  SPI.beginTransaction(SPISettings(125000, MSBFIRST, SPI_MODE1));

  //Start transaction
  digitalWrite(CS_PIN, LOW);
  delayMicroseconds(20);
  //Send start byte
  data[index++] = SPI.transfer(0xAA);
  delayMicroseconds(50);
  //Send and receive data bytes
  for(uint8_t i = 1; i < 10; i++){
    data[index++] = SPI.transfer(0xFF);
    delayMicroseconds(40);
  }

  //End transaction

  digitalWrite(CS_PIN, HIGH);
  SPI.endTransaction();

  //Extract and calculate angle
  uint16_t data_bytes = (data[2] << 8) | data[3];  // Combine two bytes
  uint16_t first14 = data_bytes >> 2;  // Extract first 14 bits
  float value = float(first14 / 16384.0000);  // Divide by 2^14 and
multiply by 360 to get degrees
  float angle = value * 360.0;  Serial.println(angle,6);
```

```
  delay(100);
}
```

Raspberry Pi GUI Python Code

```
import sys
import pyqtgraph as pg
from PyQt5 import QtCore, QtGui, QtWidgets
import pandas as pd
import math
import serial
from time import sleep
class Ui_MainWindow(object):
    def setupUi(self, MainWindow):
        MainWindow.setObjectName("MainWindow")
        MainWindow.setGeometry(0,0,800,480)
        MainWindow.setStyleSheet("background-color: #2A2A2A;")  #sets background to dark gray
        self.centralwidget = QtWidgets.QWidget(MainWindow)
        self.centralwidget.setObjectName("centralwidget")
        self.verticalLayout = QtWidgets.QVBoxLayout(self.centralwidget)
```

```
self.verticalLayout.setObjectName("verticalLayout")

self.frame_3 = QtWidgets.QFrame(self.centralwidget)

self.frame_3.setFrameShape(QtWidgets.QFrame.NoFrame)

self.frame_3.setFrameShadow(QtWidgets.QFrame.Raised)

self.frame_3.setObjectName("frame_3")

self.horizontalLayout_2 = QtWidgets.QHBoxLayout(self.frame_3)

self.horizontalLayout_2.setObjectName("horizontalLayout_2")

self.label = QtWidgets.QLabel(self.frame_3)

font = QtGui.QFont()

font.setFamily("DejaVu Serif Condensed")

font.setPointSize(18)

self.label.setFont(font)

self.label.setStyleSheet("color: rgb(255, 255, 255);")

self.label.setObjectName("label")

self.horizontalLayout_2.addWidget(self.label, 0, QtCore.Qt.AlignHCenter)

self.verticalLayout.addWidget(self.frame_3, 0, QtCore.Qt.AlignTop)

# Create PlotWidget

self.plotWidget = pg.PlotWidget()

self.verticalLayout.addWidget(self.plotWidget)

self.plotWidget.setBackground("#2A2A2A")
```

```
        MainWindow.setCentralWidget(self.centralwidget)
        self.menubar = QtWidgets.QMenuBar(MainWindow)
        self.menubar.setGeometry(QtCore.QRect(0, 0, 767, 26))
        self.menubar.setObjectName("menubar")
        MainWindow.setMenuBar(self.menubar)
        self.statusbar = QtWidgets.QStatusBar(MainWindow)
        self.statusbar.setObjectName("statusbar")
        MainWindow.setStatusBar(self.statusbar)
        self.retranslateUi(MainWindow)
        QtCore.QMetaObject.connectSlotsByName(MainWindow)
    def retranslateUi(self, MainWindow):
        _translate = QtCore.QCoreApplication.translate
        MainWindow.setWindowTitle(_translate("MainWindow", "MainWindow"))
        self.label.setText(_translate("MainWindow", "Angle of Foot Plate"))  #adds "Angle of Foot Plate" to
#top of the screen
class MainWindow(QtWidgets.QMainWindow, Ui_MainWindow):
    def __init__(self):
        super(MainWindow, self).__init__()
        self.setupUi(self)
        self.line = None  # Initialize line plot item
```

```
        self.circle = None  # Initialize circle plot item
        self.count = 0
        self.plotWidget.setRange(xRange=[-6, 6], yRange=[-6, 6])
        self.plotWidget.getAxis('bottom').setTicks([[],[]])  # Remove x-axis ticks
        self.plotWidget.getAxis('left').setTicks([[],[]])  # Remove x-axis ticks
        self.timer = QtCore.QTimer(self)
        self.timer.timeout.connect(self.update_plot)
        # Start the plot directly without the need for user interaction
        self.start_plot()
    def start_plot(self):
        self.count = 0
        self.timer.start(round(1000/24))  # Start timer with interval of 24 ms
    def update_plot(self):
            threshold = 10.0
            ser = serial.Serial ("/dev/ttyS0", 9600)    #Open serial port with baud rate
            received_data = ser.readline()              #read serial port from Arduino
            try:
                angle = float(bytes(received_data)) - 180  #subtract 180 from the angle to reset the angle range
#from 0-360 to -180-180
                print(angle)
```

```
if angle > 30:

    angle = 30  # sets angle values above 30 to 30 to set rotation limits on the GUI

if angle < -30:

    angle = -30   # sets angle values below -30 to -30 to set rotation limits on the GUI

rad_angle = angle * (math.pi / 360)  #converts degrees to radians

if self.line is not None:

  self.plotWidget.removeItem(self.line)  # Remove previous line

if self.circle is not None:

  self.plotWidget.removeItem(self.circle)  # Remove previous circle

if angle > 0:

  left_point = (-5*math.cos(abs(rad_angle)), 5*math.sin(abs(rad_angle)*5))   #uses sine and
#cosine to translate the angle into rectangular coordinates

  right_point = (5*math.cos(abs(rad_angle)), -5*math.sin(abs(rad_angle)*5))

elif angle < 0:

  left_point = (-5*math.cos(abs(rad_angle)), -5*math.sin(abs(rad_angle)*5))

  right_point = (5*math.cos(abs(rad_angle)), 5*math.sin(abs(rad_angle)*5))

else:

  left_point = (-5, 0)

  right_point = (5, 0)
```

```
            if abs(angle) > threshold:   #turns green line red if the angle crosses the threshold set in the
#code
                color = 'red'
            else:
                color = 'green'
            self.line = pg.PlotCurveItem(x=[left_point[0], right_point[0]], y=[left_point[1], right_point[1]],
pen={'color': color, 'width': 4})
            self.plotWidget.addItem(self.line)  # Add updated line plot item to plotWidget
            self.circle = pg.ScatterPlotItem(x=[0], y=[0], pen=None, brush=(255, 255, 255), size=10)  #
#White circle at (0, 0)
            self.plotWidget.addItem(self.circle)  # Add white circle plot item to plotWidget
            self.count += 1
        except:
            pass
if __name__ == "__main__":
    app = QtWidgets.QApplication(sys.argv)
    window = MainWindow()
    window.show()
    sys.exit(app.exec_())
```