Preliminary Report: Force Sensor for Rowing Biomechanics

March 8th, 2024

BME 301

Clients: Dr. Jill Thein-Nissenbaum, Ms. Tricia De Souza, Ms. Sarah Navin

Advisor: Dr. John Puccinelli

Team Members:

Team Leader: Neha Kulkarni

Communicator: Simerjot Kaur

BWIG: Emily Wadzinski

BPAG: Colin Fessenden

BSAC: Allicia Moeller

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 order to achieve a more affordable solution that still maintains an appropriate level of accuracy and does not disrupt users' rowing technique, several designs with cheaper alternatives to market-brand force cells were considered. The preliminary design that was deemed most suitable was a variation of the Stationary Uniplate design for the foot plate and the 7" HDMI screen for the display. A Raspberry Pi microprocessor will connect via HDMI cable to a 7" display to clearly illustrate a dynamic graphical user interface (GUI). The GUI will update automatically with real time data, easily showing trends for the team's physical therapists and coaches. The raw data will also be stored onto an SD card or a USB hard drive inserted into the Raspberry Pi circuit board. Upon completion of a working prototype and implementation into the tank RowErg, testing will be performed to evaluate the device's capabilities and performance, after which the design will either be revised and finalized.

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.

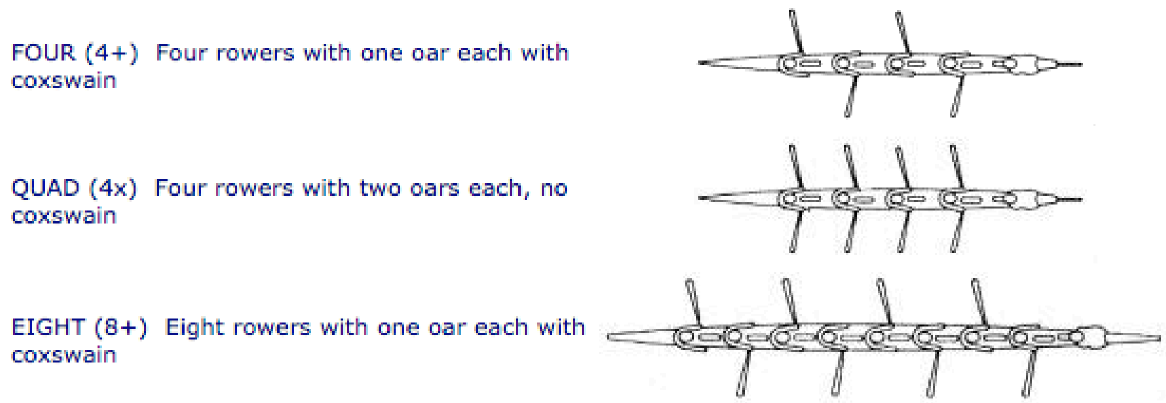


Figure 2. Configurations of boats for competition rowing [10].

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

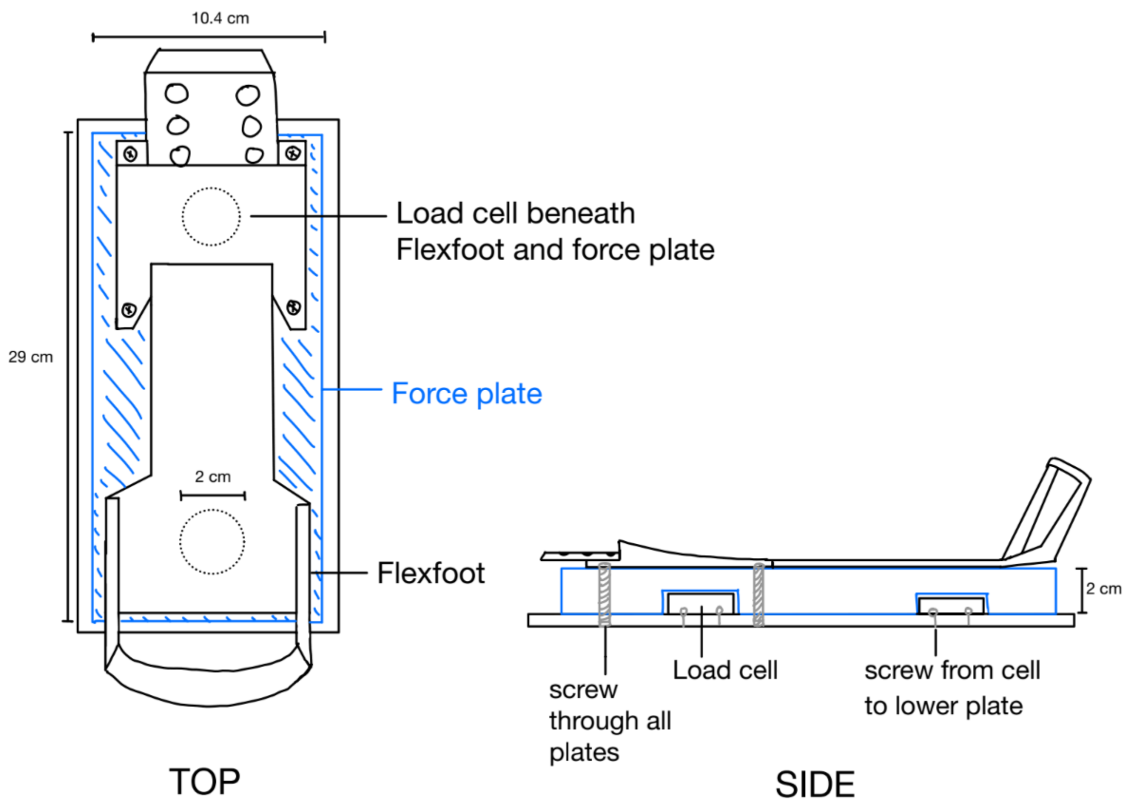


Figure 5: Drawing for Stationary Uniplate Design

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

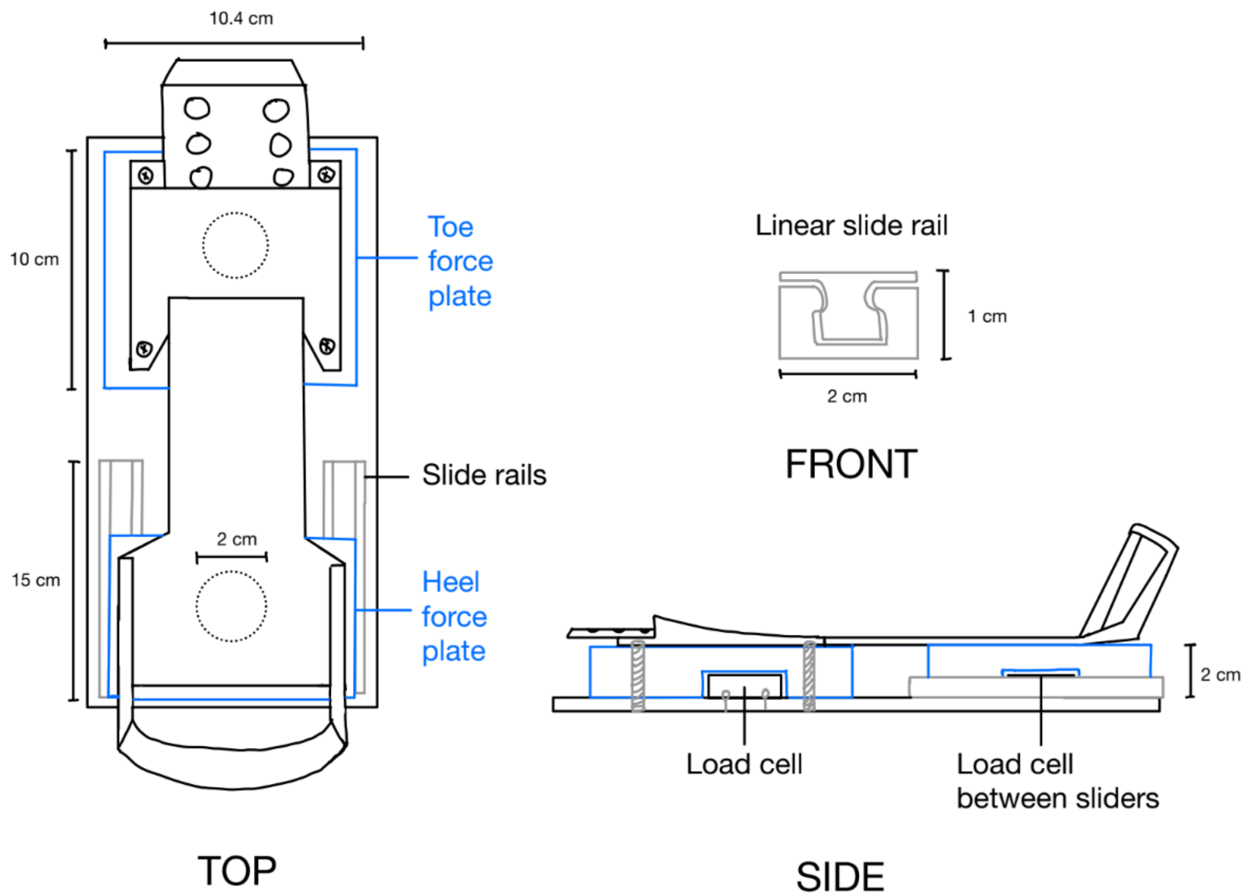


Figure 6: Drawing for Multiplate Slider Design

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

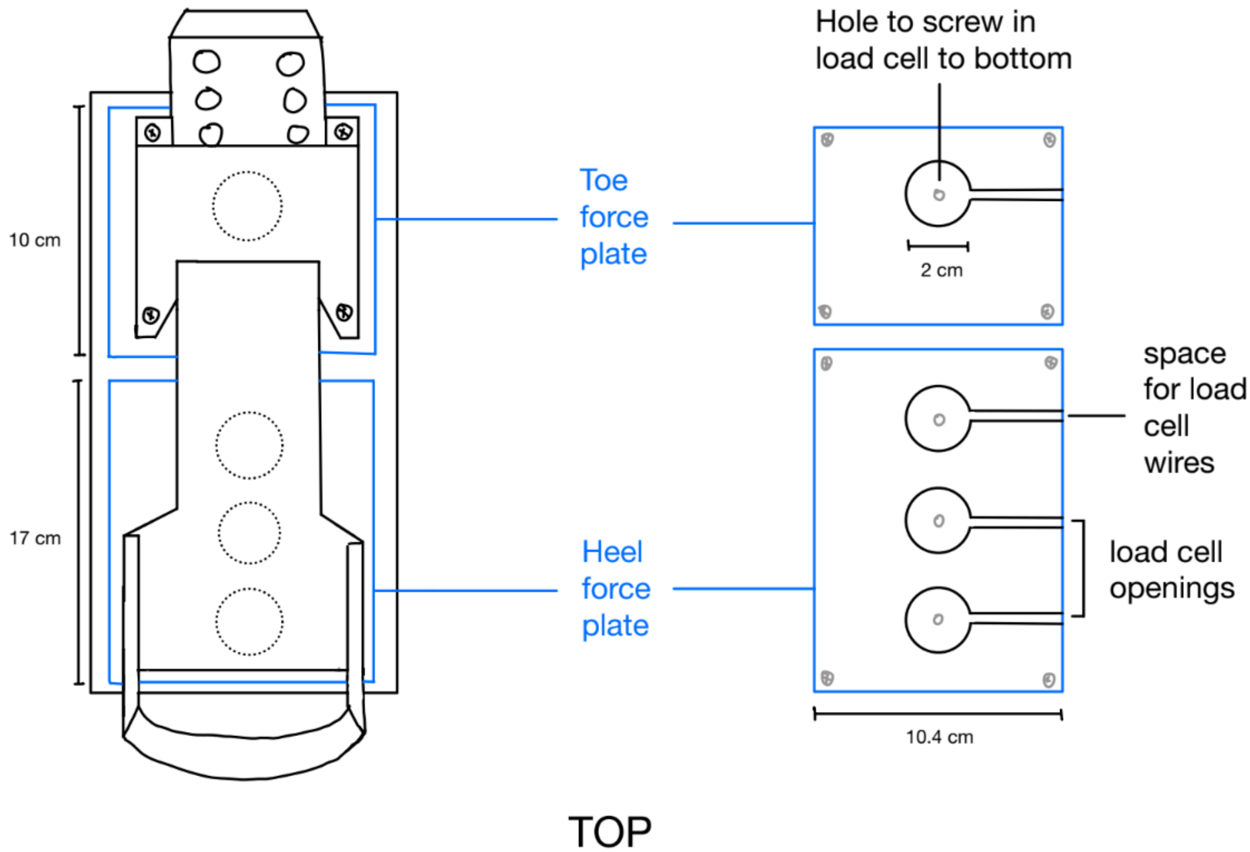


Figure 7: Drawing for Multiplate Placer Design

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

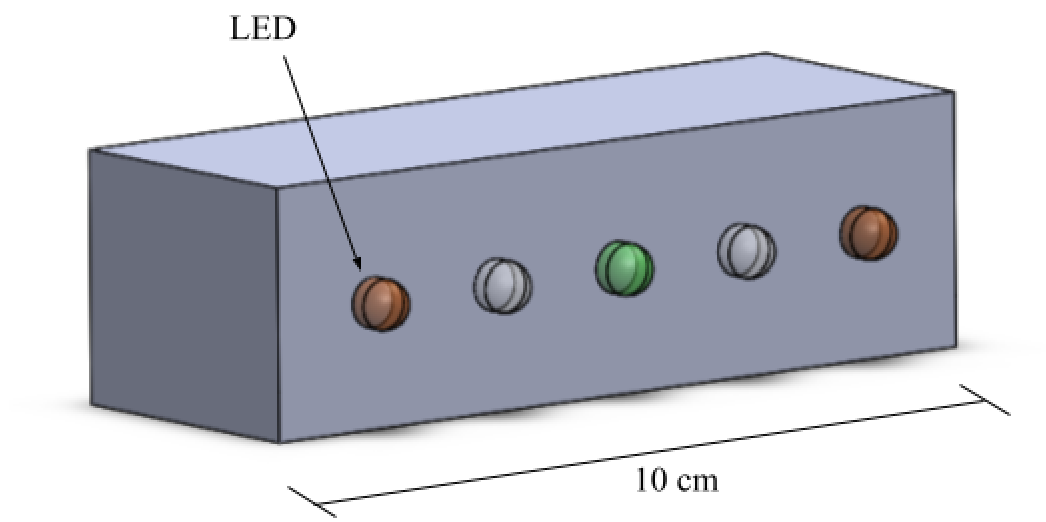


Figure 8. SolidWorks representation of the LED Array design.

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

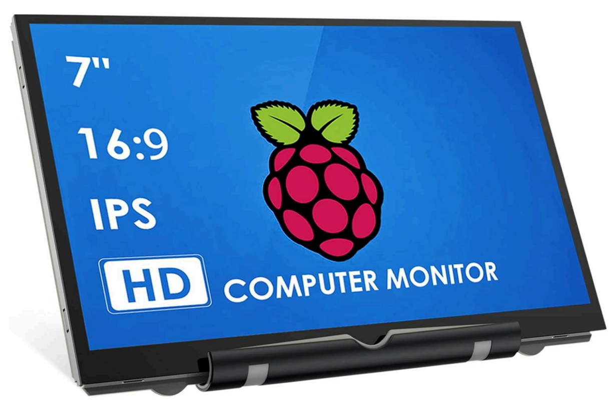


Figure 10. 7” Raspberry Pi HDMI display. [18]

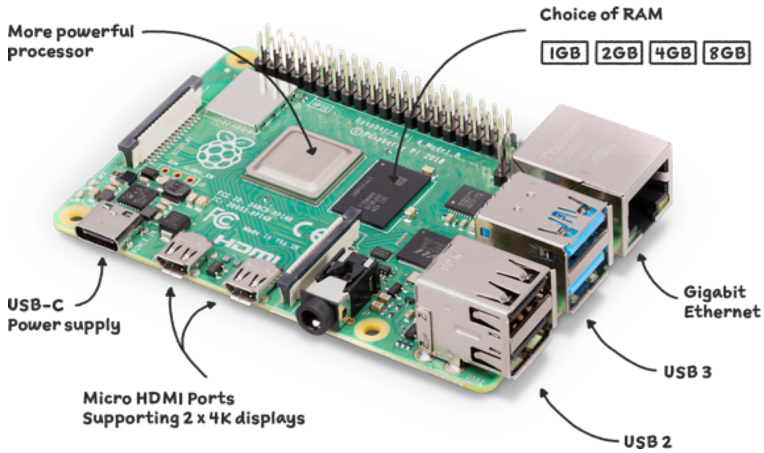


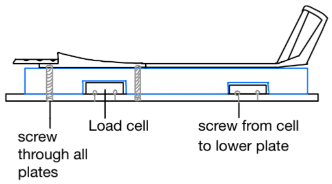
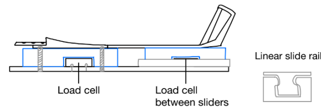
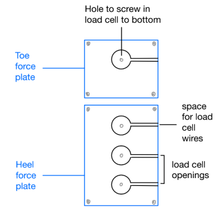
Figure 11. Raspberry Pi 4 Model B [19].

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

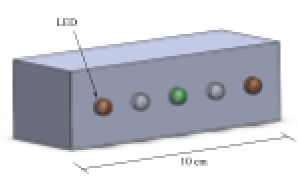
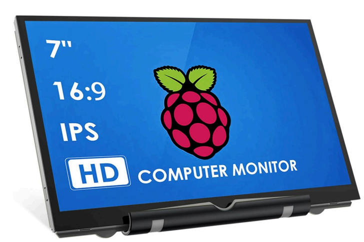
Design Matrices

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 74/100. 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

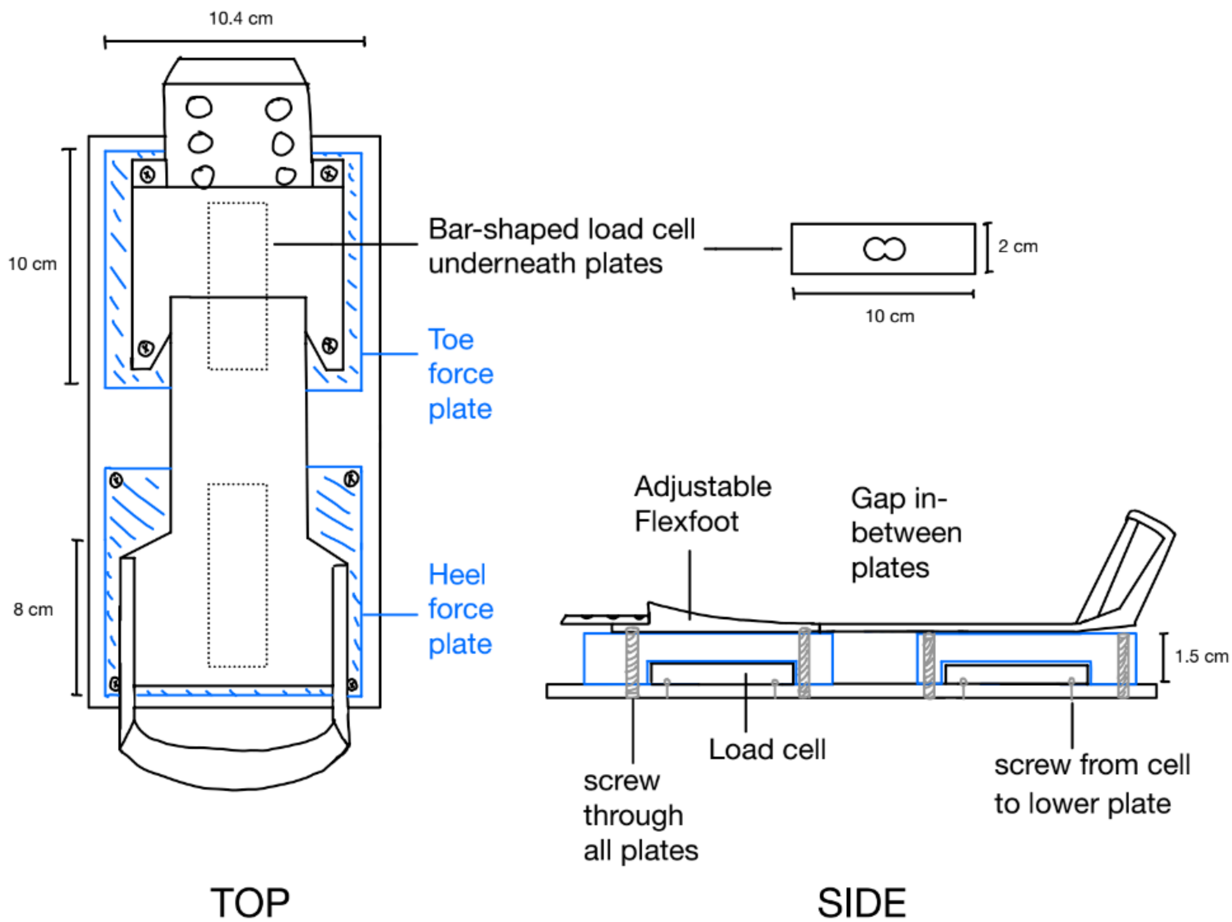


Figure 12. Drawing of Proposed Final Design.

The final design the team has proposed is a variation of the Stationary Uniplate design. The team decided to split the stationary uniplate in two separate heel and toe plates. This decision was made to retain the stellar reliability of the Stationary Uniplate design while reducing signal interference between the two load cells and properly isolating the heel and toe forces for accuracy. A model of the design is pictured in Figure X. This footplate design will be coupled with the Raspberry Pi and its compatible 7" display, which scored the highest on the Display Design Matrix due to its superiority in the User Experience and Value of Data categories. The team plans to move forward with fabrication of this Stationary Multiplate + Raspberry Pi Display design.

V. Fabrication/Development Process

Materials

Footplate:

To fabricate the heel and toe plates, the team has opted to use aluminum plates. Aluminum plates provide an excellent yield strength of 40 MPa [20], which will ensure the plates will not yield under the load from the rower. In addition, these plates also come in a textured variety, which could be beneficial to improve rower's grip on the footplate.

The team has not yet determined which load cell manufacturer to purchase load cells from; however, the load cells will have a capacity of at least 900 N and be at most 2.5 cm thick so they are thin enough to be housed within an aluminum plate.

Display:

For the display component, the team has chosen the Raspberry Pi paired with a 7" HDMI screen. This setup will have a high refresh rate of 60 Hz, which will ensure swift and accurate real-time data presentation to the rower. The choice of a Raspberry Pi 4 with 2GB RAM enhances processing capabilities, allowing for the development of a graphical user interface (GUI) using TkInter or other Python-based libraries. Overall, materials include a $35 Raspberry Pi 4, a $34 7" non-touch display, and an $8 wall adapter. Integration challenges with the tank may arise, which might require the fabrication of a stand or base. The system leaves 40 GPIO pins open on the Raspberry Pi for seamless integration with the strain gauge load cells. Raw data may either be saved to the SD card in the Raspberry Pi for later processing or written directly onto a USB hard drive, which seems to be the more user-friendly option.

Methods

Footplate:

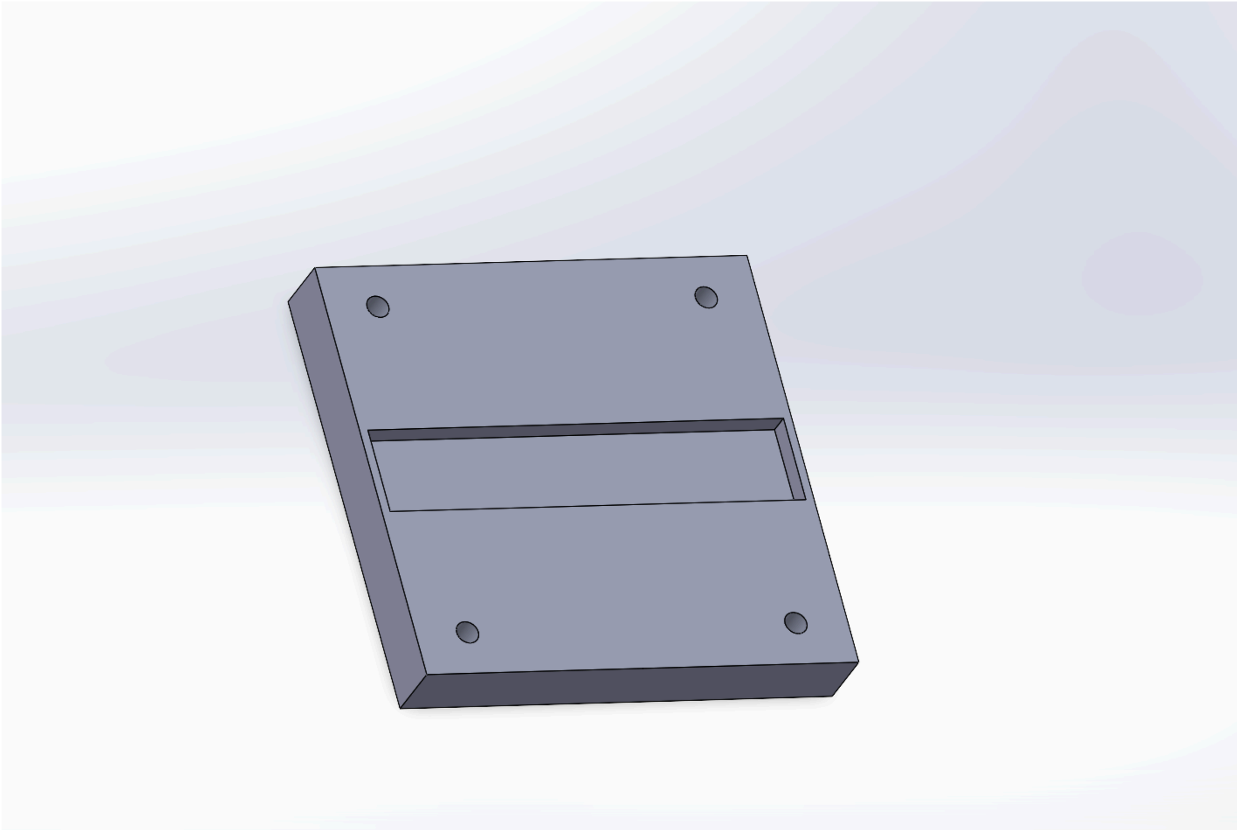


Figure 13: Visual Outline of Load Cell Housing

The method of fabrication for the footplate requires using the mill machine, thus requiring the TeamLab Green Permit. The team must start by obtaining a square piece of aluminum and cut it to size. The aluminum plate must then have a rectangular feature cut out from the plate 2 cm deep for fitting the load cell in. Lastly, the mill will be used to drill 4 circular holes on the corners of the plate. Figure 13 shows a SolidWorks model that outlines the general shape and features of the load cell housing footplate. The same process can be repeated for both the toe and heel footplate.

Display:

The fabrication of the display can be broken into 3 components: programming the GUI, integration of the physical display into the tank, and data storage and post-processing.

Programming the GUI will be done with the PyQt5 python library and an embedded matplotlib bar plot which updates 24 times per second. There will be two bars on the bar plot representing the left and right foot force, and when one bar is 10% greater than the other, it will turn red to indicate that the rower is pushing too hard with that leg (Figure 14). Additionally, there will be a 30 second calibration period before the graph is displayed to gather peak forces and set the axes for the bar graph. The python script that runs the GUI will read voltage values from the HX711 load cell amplifier and convert them into weight readings, then feed those values into the GUI program.

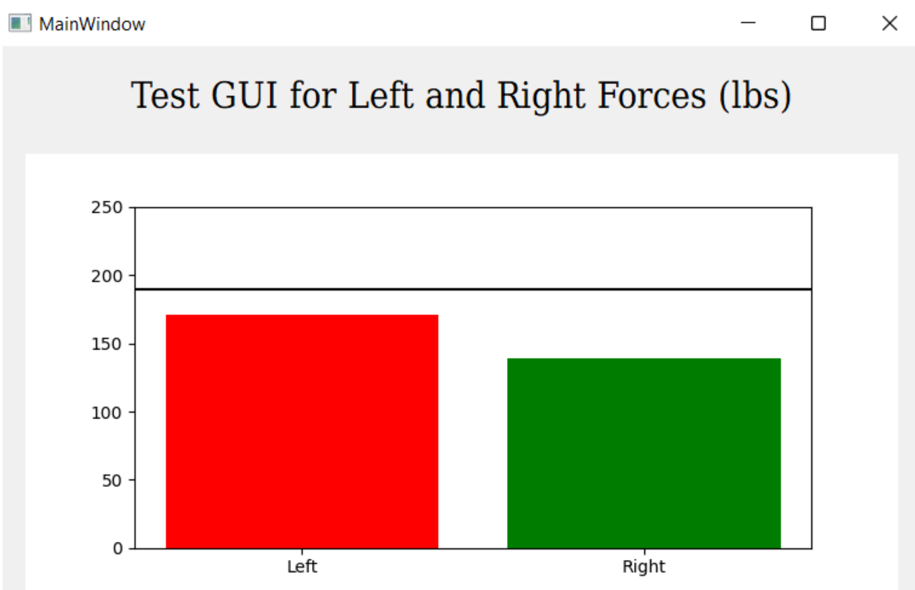


Figure 14. Demonstration of a potential GUI design.

Integration of the display into the tank will be done by making a monitor stand for the LCD display that stands 1m above ground, so that the rowers can read it at eye-level (Figure 14). We will 3D print a protective case for the LCD display with an attachment to connect it to the stand.

Figure 15. Location of the vertical stand for the display in front of the tank erg.

The raw force vs time data will either be stored directly to the Raspberry Pi SD card or directly to a USB hard drive plugged into the Raspberry Pi. Either the SD card or the hard drive will be removed after the rowing session of interest is complete and plugged into the physical therapists or trainers computer. We will make a python script to analyze the data and give a report with metrics such as peak force, time to peak force, and force asymmetry throughout the session. This python script will be converted into an executable file so that it is extremely user-friendly for physical therapists or trainers.

Final Prototype

The team does not yet have a final prototype.

Testing

Load Cell Calibration

Each load cell must be properly calibrated to output accurate force measurements. Each load cell will be calibrated by placing an object of known weight directly on top of the load cell, reading the output weight, then adjusting the scaling factor using the ratio of the known weight to the output weight. When the scaling factor is determined for each load cell, it will be verified by testing 5 different objects of known weight and comparing those values to the output weights to ensure the output is consistently within a margin of error of 5%. Once the load cells are individually calibrated, they will be arranged in the foot plate configuration laid out in *Proposed Final Design*. The load cells will be tared so that they do not output the weight of the plate on top of them. Then, we will place 5 different objects of known weight on top of each of the two foot plates and compare the output weight (the sum of the weight of the two load cells) with the known weight to verify a 5% margin of error. If the summated weight of the two load cells surpasses the known weight by more than 5%, we will redesign the force plate to minimize signal translation.

Sample Rate Testing

According to the Product Design Specifications (*see Appendix A: Product Design Specifications*), the display must update at a rate of 24 Hz. In order to test this, a counter and a timer will be implemented into the code to count the number of times the screen updates and measure the length of time the screen is on and functioning. The total number of updates will be divided by the total length of time in seconds to determine the refresh rate of the screen and verify that it is greater than 24 Hz.

Reliability and Validity Testing

To determine the test-retest reliability of the overall design, a multitude of data will be collected from numerous subjects. 10 women and 10 men between the ages of 18-40 with a minimum of 1 year of sweep rowing experience in the same class will participate in two collection periods. The first collection consists of a three minute warm up on the ergometer, followed by a three minute collection period. One to three days later the same collection process will be repeated for each subject. Shoes worn must be the same at each session. A second study will be focused on validity, comparing healthy rowers to injured ones. The 10 healthy women from the previous testing will be examined in addition to 10 women with the same requirements, however, are experiencing lower back pain while rowing. The collection follows the same procedure, a three minute warm up followed by a three minute collection period [21]. The SD card will be removed from the microprocessor and inserted into a computer, where linear regression tests will be performed using Python on both data collection types. Tests will be focused on the variability between the four load cells, toe and heel loading, average peak forces across collection periods, as well as effect sizes between groups. The side of the boat tested on, years of experience, sex, and class type will be grouped based on attributes before analysis [21].

VI. Results

There are no testing results available at this time, as the group is still in the process of creating a working prototype.

VII. Discussion

The team has identified several potential sources of error in the chosen preliminary design that it will work to address in testing and further iterations of the design. Firstly, the placement of the Flexfoot over both plates during testing presents the possibility of signal interference. Since the Flexfoot will contact both load cells, it may be difficult to isolate accurate forces coming strictly from the toe region and strictly from the heel region. The team plans to address this concern by conducting testing with and without the Flexfoot. If a significant difference in force values is revealed with and without the Flexfoot and the team determines that this difference impedes the measurement of asymmetry, the team will fabricate a separate moveable heel cup and toe rest that mimics the Flexfoot but separates the heel and toe parts such that interference does not occur.

In addition to the Flexfoot, the load cells used in the design are subject to error. Most load cells are optimally designed to measure forces that are normal to the direction they are mounted. However, due to the nature of the rowing motion, and the angle of the footplate of the RowErg, the orientation of the force vector on the toe and heel will change throughout a stroke.

Purchasing a load cell capable of handling off-axis loading without overloading will be key to minimizing error. The error produced should be less than the PDS criteria of 5%; however, this criteria could be adjusted because the typical asymmetry threshold the clients are looking for is around 10%.

The main sources of error relevant to the design of the display are insufficient sampling rates and inaccurate load cell readings by the HX711 amplifier. The HX711 amplifier acts as both a voltage amplifier and an analog-to-digital converter and will be used to interface the load cell with the Raspberry Pi. The HX711 has two sampling rates (how often it gathers data from the load cell), 10 Hz and 80 Hz. 10 Hz is insufficient according to our Product Design Specifications (*see Appendix A: Product Design Specifications*), which requires that the display updates at 24 Hz, so we will attempt to run the HX711 at 80 Hz. According to the HX711 datasheet, the input noise of the amplifier is 50 mV at 10 Hz and 90 mV at 8 Hz, which means that a higher sampling rate could cause inaccuracies in force readings due to noise [22]. If the HX711 proves to be insufficient in terms of sampling rate and/or accuracy, we will look into alternative load cell amplifiers.

The team has also considered ethical considerations in its design. The design does not infringe on Bylaw 10 in NCAA Division 1 Legislation [23] 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 will also take into account confidentiality of rowers' data in accordance with HIPAA, as rowers can be considered patients of the athletic trainers they work with. HIPAA guarantees that patient data will remain confidential between a patient and their provider [25]. Therefore, rowers' data will be stored onto a secure SD card or hard drive, available to only athletes and staff.

VIII. Conclusions

Asymmetrical load distributions contribute to lower extremity injuries for competitive, collegiate rowers. The goal is to design a low-cost force plate that can display real-time force data for the UW-Madison Rowing Team as the athletes actively sweep row. The chosen design consists of a force-sensitive load cell that will be housed in an aluminum plate in between the bottom most metallic plate of the Erg and the Flexfoot. As force is applied through the foot, the load cells will produce a signal to the Raspberry Pi Microprocessor, then to the 7" display screen via HDMI connection. The design will be placed in the indoor rowing tank located at the UW-Madison Porter Boathouse. The clients will be able to see and analyze the data from the graphical user interface and have access to the raw data off an SD card or USB hard drive inserted into the microprocessor. In the future, the design will be relocated to a racing boat on the water, in order to more accurately resemble outdoor racing conditions.

IX. References

[1] S, Arumugam, et al. “Rowing Injuries in Elite Athletes: A Review of Incidence with Risk Factors and the Role of Biomechanics in Its Management.” Indian Journal of Orthopaedics, vol. 54, no. 3, Jan. 2020. pubmed.ncbi.nlm.nih.gov, https://doi.org/10.1007/s43465-020-00044-3

[2] Buckeridge, E. M., et al. “Biomechanical Determinants of Elite Rowing Technique and Performance: Rowing Technique and Performance.” Scandinavian Journal of Medicine & Science in Sports, vol. 25, no. 2, Apr. 2015, pp. e176–83. DOI.org (Crossref), https://doi.org/10.1111/sms.12264.

[3] “2D_Stretcher,” Biorow. https://biorow.com/index.php?route=product/product&path=61_115&product_id=109 (accessed Sep. 21, 2023).

[4] A;, Buckeridge E;Hislop S;Bull A;McGregor. “Kinematic Asymmetries of the Lower Limbs during Ergometer Rowing.” Medicine and Science in Sports and Exercise, U.S. National Library of Medicine, pubmed.ncbi.nlm.nih.gov/22677926/. Accessed 10 Oct. 2023.

[5] “Lower Back Pain Relief for Rowers.” Performance Health, www.performancehealth.com/articles/lower-back-pain-relief-for-rowers. Accessed 11 Oct. 2023.

[6] Cheri, “Using the Force Curve,” Concept2, May 18, 2012. https://www.concept2.com/indoor-rowers/training/tips-and-general-info/using-the-force-curve (accessed Sep. 29, 2023).

[7] “Force Plates,” Bertec. https://www.bertec.com/products/force-plates (accessed Sep. 13, 2023).

[8] E. Wittich, “Symmetry - bat logic,” www.batlogic.net, https://batlogic.net/wp-content/uploads/2017/08/Row360-Issue-008-Symmetry-of-Sweep.pdf (accessed Oct. 12, 2023).

[9] R. E. Boykin et al., “Labral injuries of the hip in rowers,” Clinical Orthopaedics & Related Research, vol. 471, no. 8, pp. 2517–2522, 2013. doi:10.1007/s11999-013-3109-1

[10] “Rowing Terminology,” Titan Rowing. Accessed: Mar. 08, 2024. [Online]. Available: http://www.titanrowing.org/page/show/3145453-rowing-terminology

[11] “Jill Thein-Nissenbaum, Physical Therapy (PT) Program,” UW School of Medicine and

Public Health. Accessed: Oct. 06, 2023. [Online]. Available:
https://www.med.wisc.edu/education/physical-therapy-program/faculty-and-staff/jill-thein-nissenbaum/

[12] “Tricia De Souza | Women’s Rowing Coach,” Wisconsin Badgers. Accessed: Oct. 06, 2023. [Online]. Available:
https://uwbadgers.com/sports/womens-rowing/roster/coaches/tricia-de-souza/1617

[13] Q. Liu, Y. Dai, M. Li, B. Yao, Y. Xin and J. Zhang, "Real-time processing of force sensor signals based on LSTM-RNN," 2022 IEEE International Conference on Robotics and Biomimetics (ROBIO), Jinghong, China, 2022, pp. 167-171, doi: 10.1109/ROBIO55434.2022.10011703.

[14] R. Taylor, “How to Become an Olympic Rower: Our Ultimate Guide from an Olympian,” www.rowingcrazy.com, Apr. 27, 2023.
https://www.rowingcrazy.com/how-to-become-an-olympic-rower/ (accessed Sep. 22, 2023).

[15] “Climate & Weather Averages in Madison, Wisconsin, USA,” www.timeanddate.com.
https://www.timeanddate.com/weather/usa/madison/climate

[16] “A guide to EEPROM | Arduino Documentation.” Accessed: Mar. 05, 2024. [Online]. Available: https://docs.arduino.cc/learn/programming/eeprom-guide/

[17] “TFT 5 inch LCD Display Module w/Controller Board Serial I2C RA8875.” Accessed: Feb. 15, 2024. [Online]. Available:
https://www.buydisplay.com/tft-5-inch-lcd-display-module-controller-board-serial-i2c-ra8875

[18] “Amazon.com: HMTECH 7 Inch Raspberry Pi Screen 800x480 HDMI Portable Monitor IPS LCD Display for 4/3/2/Zero/B/B+ Win11/10/8/7 (Non-Touch) : Electronics.” Accessed: Feb. 15, 2024. [Online]. Available:
https://www.amazon.com/HMTECH-Raspberry-Pi-Monitor-Non-Touch/dp/B09MFNLRQQ/ref=sr_1_19?dib=eyJ2IjoiMSJ9.JljCE6ZRSG1UmXHLKVQsTOSOmjI2S16fBwawIM1SDQRNVtbzmzl-6l7jyv2WHEojn4_1fbdMrEjKJ2N6DlsOS1S_Odm7h1-hBHR_KRP25WLqzWjlOatBBV7izS9VySslppkzQ4jryYsL0anQ2avrjYf9gJTRyXicPuQSfz9uBG2eun_A0KELnkxx9iVoREpdLerDFL5Rl9ThR3gxpcvZLfQ9YadTlFqWjRwGeqxuUf8.kQ79bh655y4aHZHnCJ-wXuJp5K62rAR-7L7UOblNRmo&dib_tag=se&keywords=raspberry%2Bpi%2Bscreen&qid=1707866592&sr=8-

19&th=1

[19] R. P. Ltd, “Buy a Raspberry Pi 4 Model B,” Raspberry Pi. Accessed: Feb. 15, 2024. [Online]. Available: https://www.raspberrypi.com/products/raspberry-pi-4-model-b/

[20] “Grainger.com.” Accessed: Feb. 22, 2024. [Online]. Available: https://www.grainger.com/category/group/fasteners-hardware-raw-materials

[21] D. Bell, (2024), “Reliability and Validity of the ERG: A Pilot Study” [PowerPoint slides], University of Wisconsin-Madison.

[22] SparkFun Electronics, "24-Bit Analog-to-Digital Converter (ADC) for Weigh Scales," SEN-13230 datasheet, https://www.digikey.com/htmldatasheets/production/1836471/0/0/1/hx711.html?utm_adgroup=Integrated%20Circuits&utm_source=google&utm_medium=cpc&utm_campaign=Dynamic%20Search_EN_Product&utm_term=&utm_content=Integrated%20Circuits&utm_id=go_cmp-120565755_adg-9159612915_ad-665604606683_dsa-92304664120_dev-c_ext-_prd-_sig-CjwKCAiAi6uvBhADEiwAWiyRdhZfv3KMuEI_wsFyIUptImOAoQG1cAeTXiLCgTKzBZTvR7qe7oCyCRoCSkIQAvD_BwE&gad_source=1&gclid=CjwKCAiAi6uvBhADEiwAWiyRdhZfv3KMuEI_wsFyIUptImOAoQG1cAeTXiLCgTKzBZTvR7qe7oCyCRoCSkIQAvD_BwE.

[23] “Legislative Services Database - LSDBi.” Accessed: Oct. 11, 2023. [Online]. Available: https://web3.ncaa.org/lsdbi/search/bylawView?id=11561

[24] “Legislative Services Database - LSDBi.” Accessed: Oct. 11, 2023. [Online]. Available: https://web3.ncaa.org/lsdbi/search/bylawView?id=9024

[25] “Health Insurance Portability and Accountability Act of 1996,” ASPE. https://aspe.hhs.gov/reports/health-insurance-portability-accountability-act-1996 (accessed Sep. 21, 2023).

X. Appendix

Appendix A: Product Design Specifications

PRODUCT DESIGN SPECIFICATIONS: FORCE PLATES FOR ROWING BIOMECHANICS

BME 300/200, Section 303

Clients: Dr. Jill Thein-Nissenbaum and Ms. Tricia De Souza

Advisor: Dr. Joshua Brockman

Team Members:

Team Leader: Neha Kulkarni

Communicator: Simerjot Kaur

BSAC: Emily Wadzinski

BWIG: Bryan Topercer and Orla Ryan

BPAG: Simret Bhatia

Function:

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

Client Requirements:

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

Design Requirements:

1. **Physical and Operational Characteristics:**

a. Performance Requirements:

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

b. Safety:

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

c. Accuracy and Reliability:

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

d. Life in Service:

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

e. Shelf Life:

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

f. Operating Environment:

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

g. Ergonomics:

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

h. Size:

- The client has expressed a main interest in placing such a device in practice ergometers as well as practice rowing tanks.
- After determining the brand of ergs used by the client both for conditioning and in tanks to be Concept2, it is noted that the width of the machine is 60.96 cm [9] so the device should fit within those constraints.

i. Weight:

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

k. Materials:

- Current force sensors are typically constructed of silicone rubber elastomer with magnetic powders or particles used in calculations [10].

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

l. Aesthetics, Appearance, and Finish:

- At this moment, without an idea of specific materials that will be purchased, measurements for target placement of the device, and other necessary parameters, it is difficult to say exactly what the desired finish will be. Given that current practice ergometers used by the client are finished using a powder coat, and the devices’ legs are made of both aluminum and steel, these materials can be kept in mind when considering aesthetics [9].
- Overall, the team aims to produce a product that seamlessly fits into a rowing boat or ergometer, prioritizes comfortable foot placement for rowers, and does not interrupt users’ technique with any added bulkiness.

2. Product Characteristics:

a. Quantity:

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

b. Target Product Cost:

- The budget for this design project is between \$100-\$500 . The budget may be increased with approval from the UW Athletic Department.
- The competing designs listed in part 3d of the PDS have costs significantly greater than our budget. BioRow’s 2D Flat stretcher force plate costs over \$2000. Small-sized multi axis load cells

can range from $300-$500 [14]. In order to make a product within our target, load cells are more cost efficient.

3. Miscellaneous:

a. Standards and Specifications :

- The device must not interfere with the construction of the Concept2 RowErg® such that it fails to comply with the ASTM Standard Specifications for Fitness Equipment (ASTM F2276 − 23) [15].
    - Specifies that edges should be free of burrs and sharp edges, and corners should be chamfered
    - Specifies that the ergometer should withstand 1560 on/off cycles
    - Specifies that the footplate should be slippage-resistant
    - Specifies that the ergometer should be able to withstand 136 kg or the maximum user weight, whichever is greater
- The device must also comply with the ASTM Standard Specification for Universal Design of Fitness Equipment for Inclusive Use by Persons with Functional Limitations and Impairments (ASTM 3021-17), such that rowers with functional limitations and impairments can use the device [16].
    - Specifies that color contrast on any visual display must be greater than or equal to 70%
    - Specifies that font size should be at least 10 mm
    - Specifies that the display should continue to display visual feedback at least 5 seconds after exercise has stopped.

b. Customer:

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

  - The footrests should remain adjustable, and the wheels and upright storage capabilities should be unimpeded [8].

c. Patient-Related Concerns:.

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

d. Competition:

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

References:

[1] G. Treff, L. Mentz, B. Mayer, K. Winkert, T. Engleder, and J. M. Steinacker, "Initial Evaluation of the Concept-2 Rowing Ergometer's Accuracy Using a Motorized Test Rig," *Frontiers in Sports and Active Living*, vol. 3, Jan. 2022, doi: https://doi.org/10.3389/fspor.2021.801617.

[2] "Sizes - Wintech Racing," *wintechracing.com*. https://www.wintechracing.com/technology/sizes/ (accessed Sep. 22, 2023).

[3] S. Arumugam, P. Ayyadurai, S. Perumal, G. Janani, S. Dhillon, and K. A. Thiagarajan, "Rowing Injuries in Elite Athletes: A Review of Incidence with Risk Factors and the Role of Biomechanics in Its Management," Indian J Orthop, vol. 54, no. 3, pp. 246–255, Jan. 2020, doi: 10.1007/s43465-020-00044-3.

[4] "Site Home - Global Site," *Stanford.edu*, 2017. https://simtk-confluence.stanford.edu:8443/ (accessed Sep. 22, 2023).

[5] "How should I clean or disinfect the Force Plate?," *success.spartascience.com*. https://success.spartascience.com/en/knowledge/how-should-i-clean-or-disinfect-the-force-plate (accessed Sep. 22, 2023).

[6] Q. Liu, Y. Dai, M. Li, B. Yao, Y. Xin and J. Zhang, "Real-time processing of force sensor signals based on LSTM-RNN," *2022 IEEE International Conference on Robotics and Biomimetics (ROBIO)*, Jinghong, China, 2022, pp. 167-171, doi: 10.1109/ROBIO55434.2022.10011703.

[7] R. Taylor, "How to Become an Olympic Rower: Our Ultimate Guide from an Olympian," *www.rowingcrazy.com*, Apr. 27, 2023. https://www.rowingcrazy.com/how-to-become-an-olympic-rower/ (accessed Sep. 22, 2023).

[8] "Climate & Weather Averages in Madison, Wisconsin, USA," *www.timeanddate.com*. https://www.timeanddate.com/weather/usa/madison/climate

[9] David, "RowErg," *Concept2*, May 09, 2012. https://www.concept2.com/indoor-rowers/concept2-rowerg

[10] J. D. Miller et al., "Novel 3D Force Sensors for a Cost-Effective 3D Force Plate for Biomechanical Analysis," Sensors (Basel), vol. 23, no. 9, p. 4437, May 2023, doi: 10.3390/s23094437.

[11] W. Zhou, Y. Yu, S. Bai, and A. Hu, "Laser direct writing of waterproof sensors inside flexible substrates for wearable electronics," Optics & Laser Technology, vol. 135, p. 106694, Mar. 2021, doi: 10.1016/j.optlastec.2020.106694.

[12] "Rowing Glossary," *Dallas United Crew*. https://www.dallasunitedcrew.org/rowingglossary#:~:text=Octuple%20(8x)%3A%20A%20shell (accessed Sep. 22, 2023).

[13]]"Facilities - Porter Boathouse," *Wisconsin Badgers*. https://uwbadgers.com/sports/2015/8/21/GEN_2014010131.aspx

[14] "3 axis load cell, 3 axis load cell Suppliers and Manufacturers at Alibaba.com," *www.alibaba.com*. https://www.alibaba.com/showroom/3-axis-load-cell.html (accessed Sep. 22, 2023).

[15] “Standard Specification for Fitness Equipment” https://www.astm.org/f2276-23.html (accessed Sep. 20, 2023).

[16] “Standard Specification for Universal Design of Fitness Equipment for Inclusive Use by Persons with Functional Limitations and Impairments” https://www.astm.org/f3021-17.html (accessed Sep. 20, 2023).

[17] “Health Insurance Portability and Accountability Act of 1996,” ASPE. https://aspe.hhs.gov/reports/health-insurance-portability-accountability-act-1996 (accessed Sep. 21, 2023).

[18] “Force Plates,” Bertec. https://www.bertec.com/products/force-plates (accessed Sep. 13, 2023).

[19] “2D_Stretcher,” Biorow. https://biorow.com/index.php?route=product/product&path=61_115&product_id=109 (accessed Sep. 21, 2023).

Appendix B: Materials and Expenses

Item	Description	Manufacturer	Mft Pt#	Vendor	Vendor Cat#	Date	QTY	Cost Each	Total
Wire terminal	Connector for al	Multicomp pro	MC29391	Newark	34P2159	10/11/2023	$5.00	$0.08	$0.40
Fuse	1 A, 125 V, 5mm	Littlefuse	26K7739	Newark	26K7739	10/11/2023	1	$0.89	$0.89
Wire - Black	16 AWG hook-up	Multicomp pro	24-15050	Newark	44AC9035	10/11/2023	0.005	$17.09	$0.09
Wire - White	16 AWG hook-up	Alphawire	461626 WH005	Newark	98B9507	10/11/2023	0.005	$38.32	$0.19
Wire - Green	20 AWG solid wi	Alphawire	422001 GR005	Newark	28Y5639	10/11/2023	0.005	$24.48	$0.12
Wire - Blue	22 AWG solid ho	Multicomp pro	24-15416	Newark	68X4805	10/11/2023	0.04	$2.49	$0.10
Wire terminal	Connector for 22	AMP-TE Connect	61048-1	Newark	07AH7925	10/11/2023	2	$0.36	$0.72
Arduino Uno Rev	Microcontroller/	ARDUINO	A000066	Arduino	76300492	10/11/2023	1	$24.00	$24
Force Sensitive R	Sensing area tha	Sparkfun	no part number	Sparkfun	no part number	10/11/2023	4	$7.50	$30