Preliminary Report: Asymmetrical Force Sensor for Rowing Biomechanics

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BME 400

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Abstract

Elite rowers that engage in a high volume of training can suffer from a variety of injuries, the most common occurring in the lumbar spine [1]. As rowing is a full-body movement, perfecting technique and maintaining proper form is essential to preventing such injuries and improving performance overall [2]. The UW-Madison Women's Rowing Team is seeking a way to measure force output from rowers' lower extremities in real-time to determine the presence and cause of any 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, accurate, and ergonomic alternative, several designs were considered. The design that was deemed most suitable is the Stationary Force Plate design with a load cell at each corner of the plate on the right and left footplates. The signal from each of the eight load cells will be sent to a Raspberry Pi, which will handle the data processing and generate a graphical user interface (GUI) that updates with real-time data, allowing the users to easily track trends during training. 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 Concept2 Ergometer, testing will be performed to evaluate the device's capabilities and performance, after which the design will either be revised or 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 training. In rowing, a slight change in body angle or stroke sequence can significantly impact joint positioning and stresses placed on the lower back [4]. 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]. Despite this, current methods do not involve a way to quantitatively assess asymmetry in rowers. The University of Wisconsin Women's Rowing coaching staff is looking for a device to measure the force output female collegiate athletes produce while rowing. They want this device to be mounted on an ergometer, because most in-season training sessions, and therefore most injuries, occur on the ergometer. 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. These assessments primarily occur during rowing on an ergometer. 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. The ergometer's screen displays a live force-time curve for each stroke and rowers are adept at interpreting this graphical representation. 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 varying 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 force sensor system on the ergometer that will capture force output during time of use and will assess lower extremity asymmetry to establish risk stratification. Additionally, the team aims to connect the force plate system to a user-friendly interface that will enable coaches and athletes to understand essential biomechanical 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. 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.

The prospective design must be able to be installed on the Concept2 RowErg, which is the type of ergometer used by the UW Rowing Teams. The UW Rowing Teams use two different models of the Concept2 RowErg, whose footplates are shown in Figures 2 and 3, and the device should be modular such that it can be installed on either model. The model shown in Figure 2 is a newer model and is more commonly used during training. The model shown in Figure 3 is configured in the tank in the UW Boathouse. The tank houses 12 bases of the Concept2 RowErg lined up in a row to simulate a shell configuration, as shown in Figure 4. It is imperative that the device can be transferred to this setup to assess asymmetry during sweep rowing as well as ergometer rowing.

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 2 (left) and Figure 3 (right). Footplate of two different Concept2 RowErg models used by UW Rowing Teams.

Figure 4. Concept2 RowErgs (older models) lined up to simulate a shell during sweep rowing in the UW Boathouse tank.

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 [10]. 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 [11].

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 both Concept2 RowErg models that are used by the UW-Madison Rowing Teams. This will entail taking certain dimensions into consideration, such as the standard ergometer 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 alter the shape of the ergometer footplates. The main goal of the design is to provide real-time, accurate measurements of rowers' magnitude of force so that any asymmetries can be corrected in the moment. As such, the device should have a maximum load capacity of 900 N [12] and the force magnitude must be measured within a limited margin of error of 5% [13]. The display component of the design should have at least a 24 Hz frame rate and no more than a 0.5 second delay to provide real-time visual feedback at least once per stroke [14, 15]. The product should be engineered to last a service life of around 10-12 years, approximately the length of an average rower's career [16]. The product should also be reproducible, with the end goal of developing 8 devices that can be positioned on the ergometers to gather data. The full Product Design Specifications (PDS) are outlined in Appendix A.

III. Preliminary Designs

Stationary Force Plate

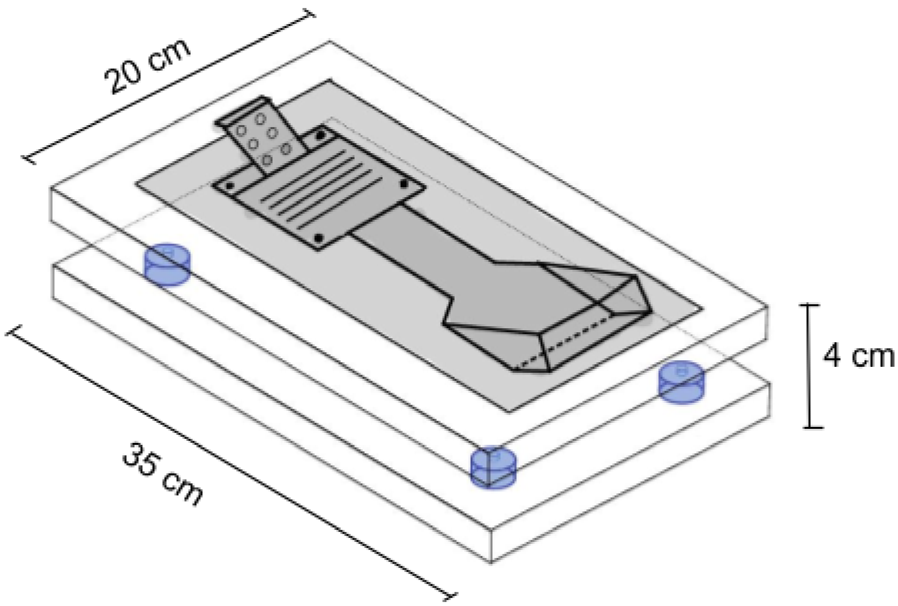


Fig 5. Stationary Force Plate Design.

The Stationary Force Plate Design consists of two aluminum plates. The bottom plate is screwed into the ergometer in place of the original ergometer's footplate. Four single-axis, button load cells are secured into the corners of the bottom plate with screws. The second plate rests on top of the load cells, with divots that align to each load cell button. Foam or springs with negligible spring constants may be secured in between the plates to keep them together. The FlexFoot from the ergometer will be screwed back onto the top plate to maintain adjustability between different foot sizes.

Membrane-Bound Force Plate

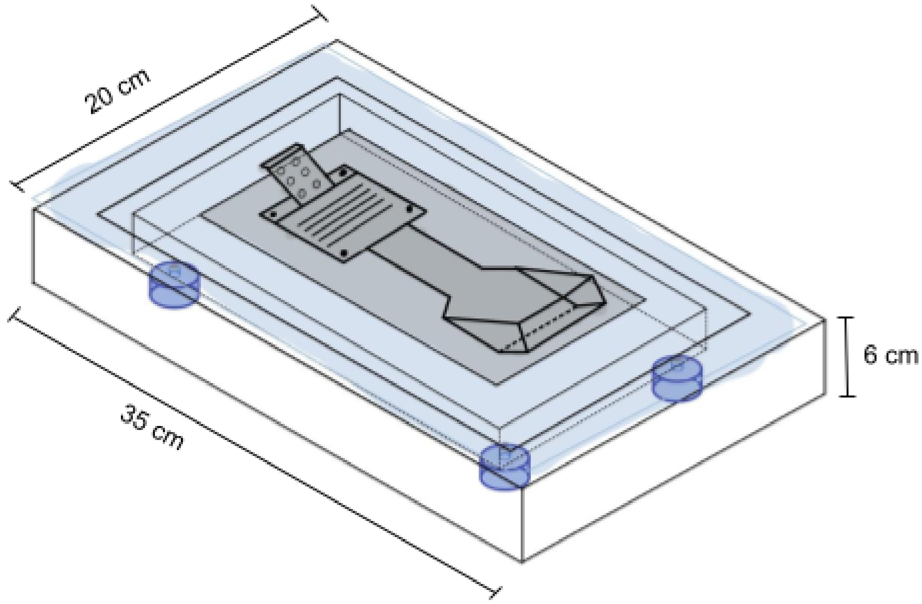


Figure 6: Membrane-Bound Force Plate Design.

The Membrane-Bound Force Plate Design combats potential off-axis loading with a reactionary tensile force produced by a fabric membrane. The design consists of an inner and outer aluminum plate with a slight gap between them. The outer plate will be screwed into the ergometer, with four load cells secured on top of the corners. Ball bearings will be placed on the points of the load cells to reduce friction between the load cells and inner plate. A fabric membrane will be glued to both plates and situated on top of the bearings. If the rower were to apply a force in the plane of the fabric, the fabric creates a reactionary force in the opposite direction to prevent the inner plate from moving and cancels any directional forces not normal to the plate when the athlete is rowing. The FlexFoot is also fixed to the top of the inner plate over the fabric to retain adjustability.

Bearing-Guided Force Plate Design

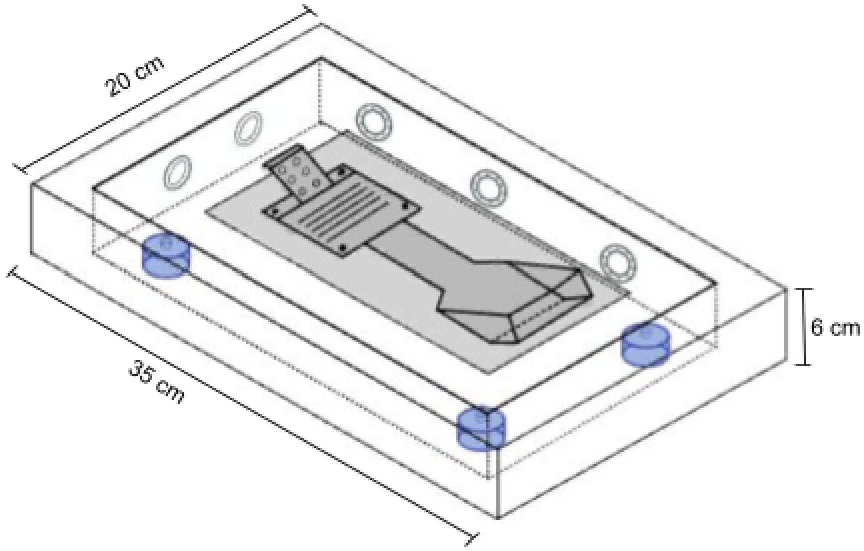


Figure 7: Bearing-Guided Force Plate Design.

The Bearing- Guided Force plate design safeguards against off axis loading through the use of bearings placed on the sides of the footplate of the ergometer. The design consists of an inner and outer aluminum plate that are separated by frictionless bearings which allow for smooth movement while canceling out the horizontal and vertical force components. Outer plate will be mounted to the ergometer, and the inner plate will be placed on top of the load cells at each corner with ball bearings. The ball bearings minimize friction and ensure the inner plate only deflects normal to the ergometer footplate plane. This shields the load cells from any off-axis loading.

Graphical User Interface and Display

The chosen footplate design will be connected to a GUI that displays rowers' force output in real time. The user interface will allow users to choose between four graphical representations of force output. The four options consist of either the rower's pure force output or the force difference between legs on a bar graph or a line graph, as shown in Figures 8-11 below. Rowers will interpret these graphical representations of their force and adapt their technique.

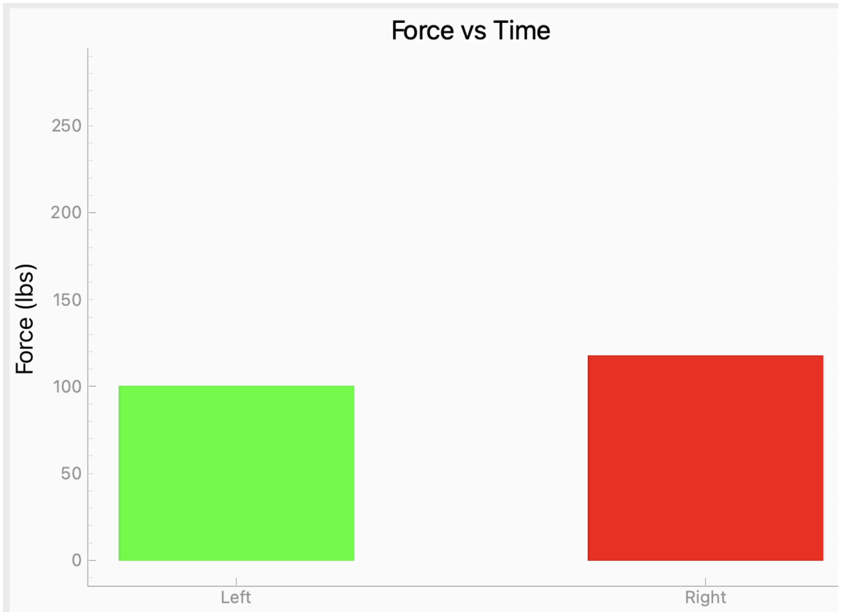


Figure 8. Absolute force output bar graph GUI design. The bar representing the leg with more force output turns red; the rower's goal is to press evenly so both bars are green.

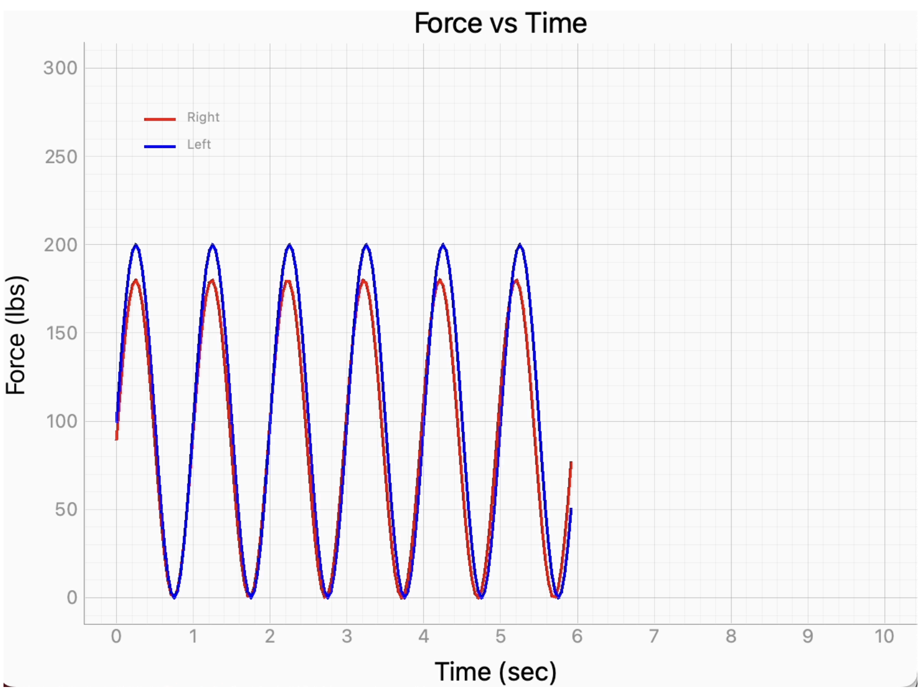


Figure 9. Absolute force output line graph GUI design. The rower's goal is to press evenly tso the red and blue curves for each leg overlap.

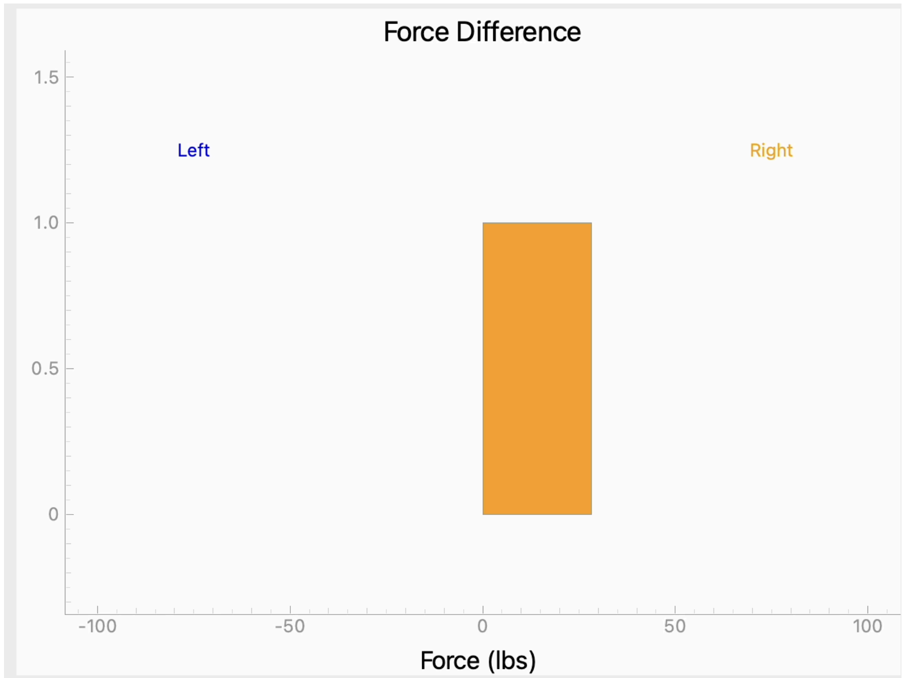


Figure 10. Force difference bar graph GUI design. The bar moves towards the leg with more force output. The rower's goal is to press evenly such that the bar does not appear.

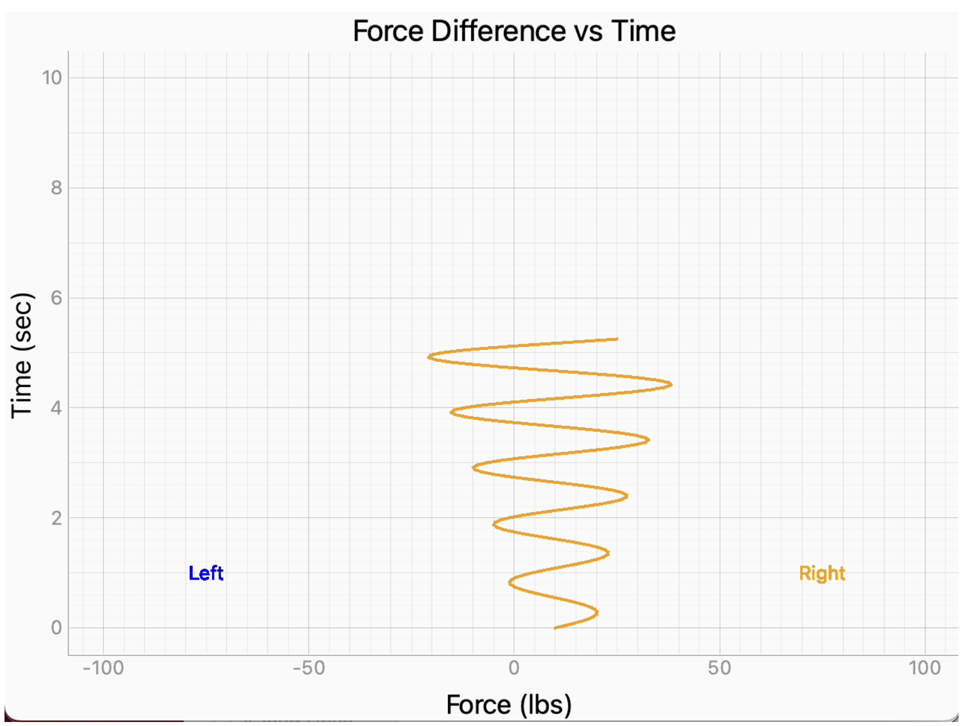


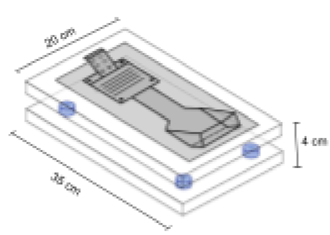
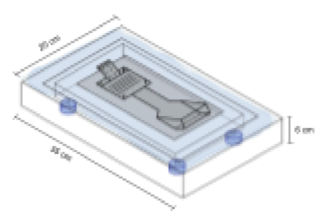
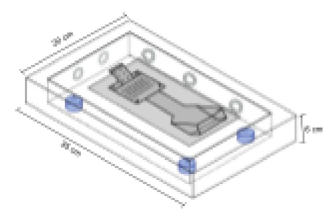
Figure 11. Force difference line graph GUI design. The line moves towards the leg with more force output. The rower's goal is to press evenly such that the line remains vertical.

The graphical user interface will be implemented using a Python script, designed using PyQt5. Python was chosen as the implementation method because it is easily accessible, highly adaptable to the client's needs, and allows for easy data storage. Because the GUI will be run in Python, a laptop will be required and will be used as the display screen. However, this laptop can be connected to a TV monitor or tablet for more convenient viewing per the user's preference.

IV. Preliminary Design Evaluations

Design Matrix

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 Force Plate 		**Membrane-Bound Force Plate** 		**Bearing-Guided Force Plate** 	
Criteria	**Weight**	Score (5 max)	Weighted Score	Score (5 max)	Weighted Score	Score (5 max)	Weighted Score
Reliability	25	2	10	4	20	5	25
Ergonomics	25	5	25	4	20	4	20
Cost	20	3	12	2	8	1	4
Ease of Fabrication	15	4	12	3	9	2	6
Ease of Maintenance	15	4	12	3	9	2	6
Sum	**100**	**Sum**	**71**	**Sum**	66	**Sum**	61

Design Evaluations

Load Cell Housing Matrix Category Descriptions:

The design matrix to determine the best housing device includes the following criteria: Reliability, Adjustability, Cost, Ease of Fabrication, Ease of Maintenance, and Ergonomics. Reliability refers to how accurately the device collects data despite off-axis loading, and the repeatability of collected data. Cost is a criterion to ensure that we are taking into account the budget constraints before moving forward with a design and location. The Ease of Fabrication category is how easily the design can be implemented to the Concept2 ergometer and how easily the load cell housing can be fabricated. The Ease of Maintenance criterion is a measure of the services required to maintain the device, such as calibration, cleaning, and replacement of parts. Lastly, the Ergonomics criterion refers to how the design may possibly hinder the rowing motion of the athlete. The goal of the design is to not inhibit the athletes natural rowing motion.

Footplate Score Distributions:

The first design, The Stationary Force Plate, ultimately scored the highest out of the three with a score of 71. The stationary plate is the most simplistic design, and therefore easiest to fabricate, maintain, use, and is the least costly. However, in the Reliability category, the design scored the lowest. Due to the design's lack of off-axis load prevention, the accuracy of the data collected would be poor. In addition, with varying accuracy, the repeatability of the data would be inconsistent. In contrast, the design scored a 5/5 in Ergonomics, as it has the lowest profile and is the least obstructive to the rower since there's only a flat plate. In terms of Cost, the design was given a 3/5. Though the design requires less materials than the others, it still requires numerous costly load cells. In the Ease of Fabrication category, the stationary footplate's simple components allow for easier assembly than the others with added components. Lastly, for similar reasons, the design's Ease of Maintenance scored highly as it has fewer parts to preserve and would only require the occasional calibration. The footplate is also fully enclosed so it would not require any internal cleaning.

The second design, the Membrane-Bound Force Plate, ranked second with an overall score of 66. In terms of Reliability, the design scored moderately with a 4/5. This design provides improved accuracy in data collection over the Stationary Plate, due to its ability to limit off-axis loading. However, its complexity could still lead to some reliability concerns and is dependent on the material chosen to create the “membrane”. For Ergonomics, the design scored a 4/5. While slightly more intrusive than the Stationary Plate, its overall impact on the rower’s natural motion remains minimal, which is due to the membrane structure maintaining a low profile. For Cost, this design received a score of 2/5, primarily due to the additional materials and components needed like fabric and adhesive, which drive up expenses. The Ease of Fabrication category yielded a score of 3/5, as the design, while not overly complex, is more intricate to manufacture than the Stationary Plate due to the membrane and attachment points. Similarly, for Ease of Maintenance, the design scored a 3/5, as the extra components mean there are more parts that require care, calibration, and potential replacement over time.

The third design, the Bearing-Guided Force Plate, ranked third with an overall score of 61. It scored the highest in Reliability, with a 5/5 main due to its accurate ability to minimize off-axis loading, ensuring more accurate and consistent data collection. However, this design was rated 4/5 in Ergonomics, similar to the Membrane-Bound Force Plate. While the bearings add some height to the system, they do not significantly interfere with the rower’s motion. For Cost, the Bearing-Guided Plate scored the lowest, with a 1/5. It's more sophisticated design and the materials required, specifically the bearings, make it the most expensive option. In Ease of Fabrication, the design also scored a 2/5, as the additional components and precision assembly required for the bearings make it difficult to manufacture. Finally, for Ease of Maintenance, this design again received a 2/5. The bearings and associated mechanisms would require regular cleaning and maintenance to ensure smooth operation, adding complexity to its upkeep.

Proposed Final Design

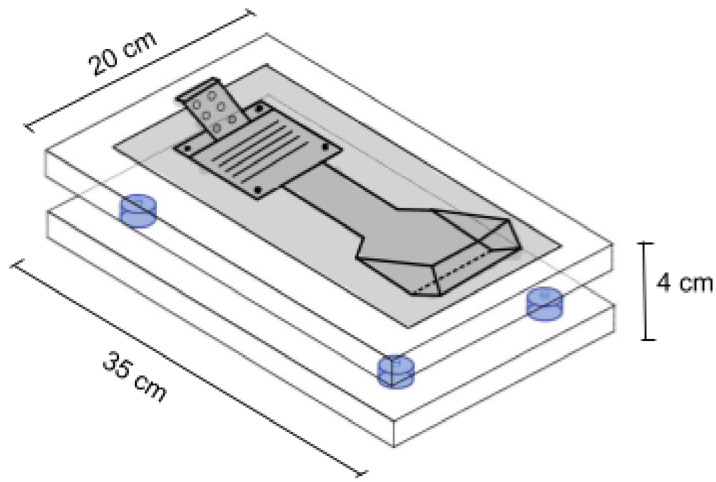


Figure 12. Drawing of Proposed Final Design.

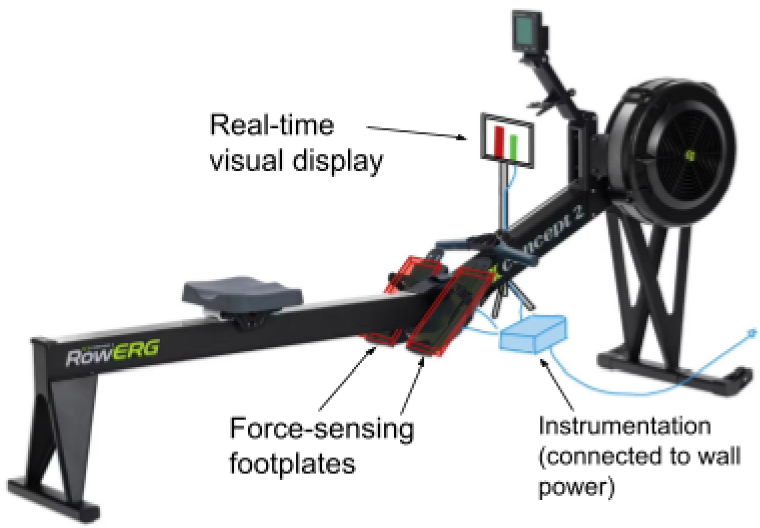


Figure 13. Placement and Integration of chosen footplate design, display, and instrumentation.

The proposed final design is the Stationary Force Plate design due to its overall simplicity and cost-effectiveness. While the design did not score particularly high in total points on the Design Matrix, its overall minimalism and core concept sufficiently provides an effective solution. The design saves expenses on additional components if off-axis loading proves to be negligible. Otherwise, the design's components are transferable to the other proposed designs, which allows for efficient iteration.

The force plates will be placed where the current footplates are located on the ergometer, as seen in Figure 13. The instrumentation hardware connected to the force plates will be compacted within a compartment below and connected to a wall power source. The display for the real-time data and storage will be joined to the instrumentation box and power source, and will sit on a stand or in a position for the athlete to see when rowing.

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, the top plate will be placed underneath the Flexfoot adjustable plate, which will be beneficial to ensure the rower's grip on the ergometer with the device included and further prevent technique impedance.

The team purchased the FX29 Compact Compression load cells from TE Connectivity, shown in Figure 14. The load cells have a capacity of at least 900 N and be at most 2.5 cm thick [17] so they are thin enough to be housed within an aluminum plate.

Figure 14. TE Connectivity FX29 100 lb load cell. [17]

Hardware:

The microcontroller used to process the signal from the load cell will be the Raspberry Pi 4 Model B because its microHDMI port allows for connection to a robust visual display. A signal processing circuit will be fabricated using LM358 op amps to buffer and amplify the voltage output from the load cell, and the MCP3008 analog-to-digital converter to sample the amplified analog signal and send it to the Raspberry Pi via SPI communication. The hardware components will be soldered to a perf-board and placed in a plastic housing to keep them organized and protected.

Display:

The hardware described above will be connected to a laptop which will act as both a display screen for the GUI and a storage location for the data collected during rowing trials. A laptop is necessary because the GUI and data storage methods will be implemented using a Python script or application. However, for easier viewing, the laptop could be connected to a TV monitor or a smaller tablet, depending on the rowers' preference. The UW Boathouse has access to these display options if needed.

Methods

Footplate:

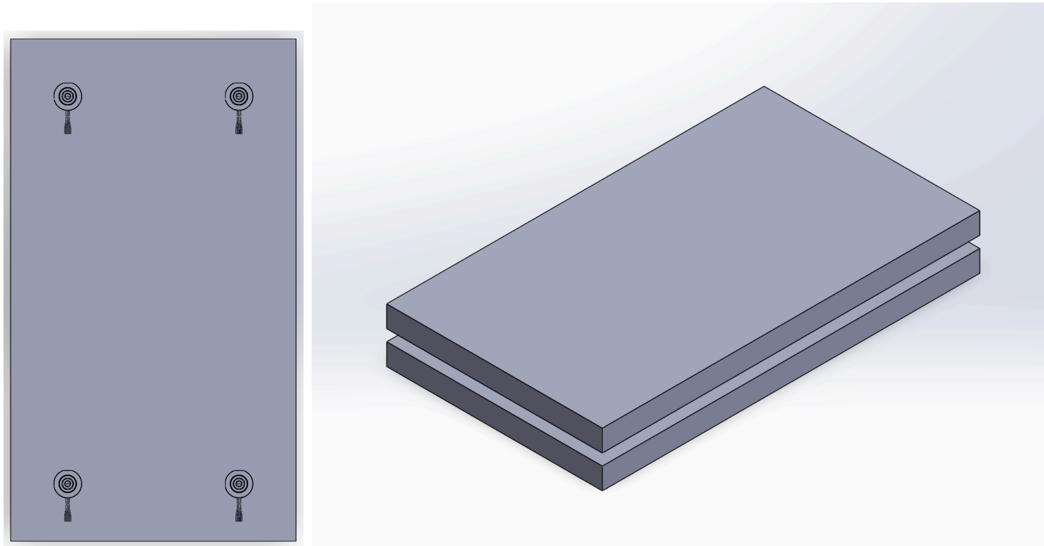


Figure 15: CAD Model of bottom plate with load cells and isometric assembly

The method of fabrication for the footplate requires using the power saws in the TeamLab, thus requiring the TeamLab Green Permit. The team must start by obtaining a square piece of aluminum and cut it to size (13cm x 30.5cm). The bottom aluminum plate must then have circular features milled out to house the load cells. Figure 15 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 right and left footplates.

Hardware:

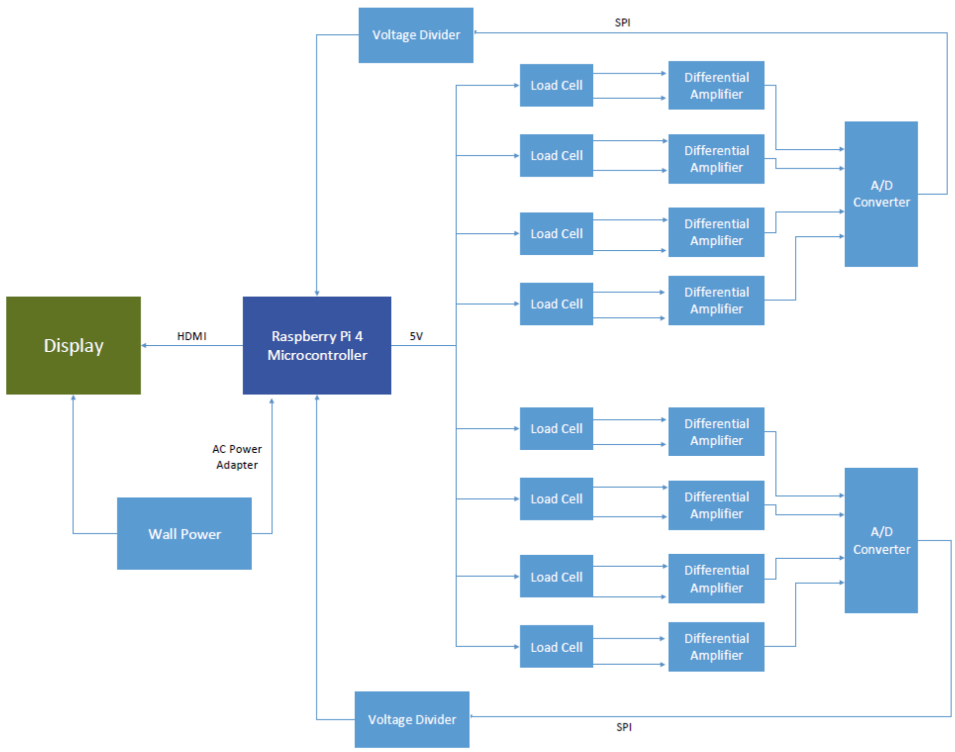


Figure 16. Hardware block diagram.

Figure 16 outlines the entire signal processing methodology to be utilized. The load cells used to fabricate this design will be the TE Connectivity FX29 100 lb load cells, which use a wheatstone bridge circuit configuration with a strain gauge, shown in Figure 17. The load cells have an operating voltage of 5V and their data output is the difference between the positive and negative output lines. To implement eight load cells into our design (four for each foot plate), the Raspberry Pi will draw wall power via an AC power regulator designed for use with Raspberry Pis, then the Pi will power each load cell from its 5V pin. The two output signals will be filtered with a low pass filter with a cutoff frequency of 7.23 Hz, buffered, subtracted, and amplified with a gain of 50 by a differential amplifier shown in Figure 18. The analog outputs of the differential amplifier will be connected to the MPU3008 analog to digital converter which will send the data sequentially to the Raspberry Pi digital pins via SPI communication. Because the operating voltage of the Raspberry Pi GPIO pins is 3.3V, and the output of the ADC digital pins is 5V, a voltage divider will be used to shift the voltage down from 5V to 3.3V. The Raspberry Pi will run a Python-implemented GUI using data from the load cells that will be displayed on either a laptop, monitor, TV, or LCD display via HDMI cord.

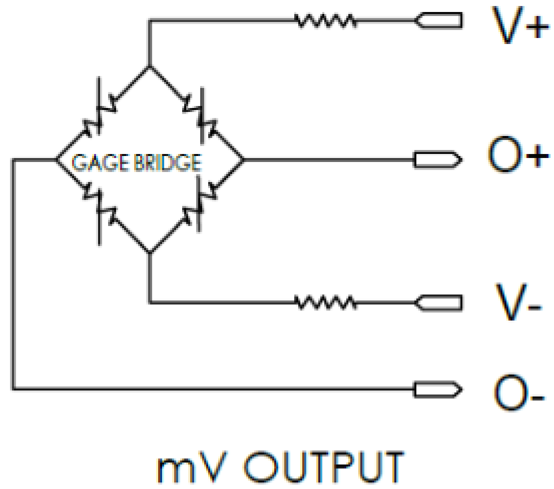


Figure 17. FX29 load cell circuit diagram. [17]

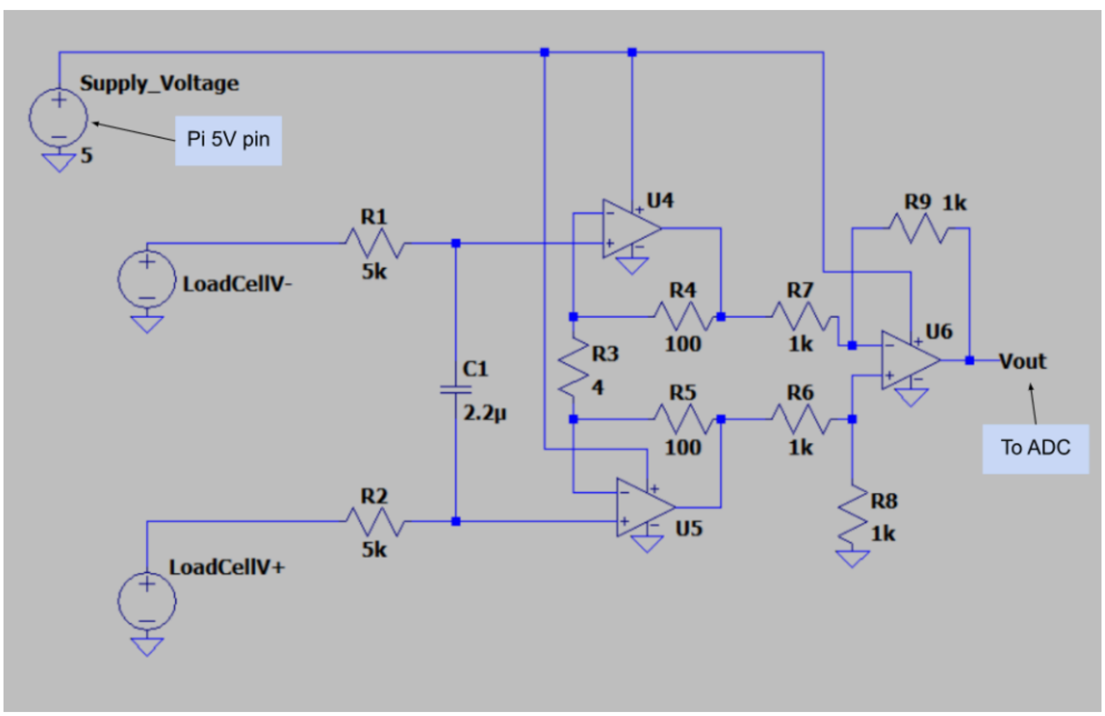


Figure 18. Differential amplifier subcircuit schematic.ll then be adhered to the ergometer using the existing screw holes in the ergometer footplate, which can be seen in Figures 2 and 3.

Display:

The fabrication of the display can be broken into 3 components: programming the GUI, integration of the physical display onto the ergometer, and data storage and post-processing. Programming the GUI will be done in Python, using the PyQt5 library. This library allows for easy design and implementation of a user interface, and will enable the team to make changes to the GUI design according to rower feedback during testing. Integration of the display with the ergometer will be done according to user needs based on the chosen display screen. The chosen screen will be placed on a stand or cart directly in front of the rower at eye level, so the rower can face forward during rowing as usual.

The raw force data from rower trials 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. A Python script will be written 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 user-friendly for physical therapists or trainers.

Final Prototype

The team does not yet have a final prototype.

Testing

Force Plate Calibration:

Each force plate will be calibrated as a whole including the four load cells to ensure accurate force measurements. We will begin by placing an object of known weight at different positions on the plate, recording the total output from the system, and adjusting a scaling factor based on the ratio of the known weight to the output weight. Once the appropriate scaling factor is determined for the entire force plate, we will verify the calibration by testing with five different objects of known weight and comparing their values to the plate's output. The goal is to ensure that the system consistently outputs weights within a 5% margin of error. After the calibration is verified, we will tare the system to exclude the weight of the plate itself. Lastly, we will place the known weights on different areas of the plate and compare the measured weights to verify that the system remains accurate. If the combined output from the force plate deviates by more than 5% from the known weights, we will adjust the design to improve measurement accuracy and minimize signal distortion.

Accuracy Testing:

To determine whether our prototype meets our criteria of quantifying accurate and repeatable vertical force values regardless of off-axis loading, accuracy testing will be performed. The two force plates will be assembled and connected to their required circuitry, but not mounted to the ergometer. They will be placed on a table to better control the angle of applied force.

- Centric loading test:

First, 5 kettlebell weights of different weights ranging from 5 pounds to 100 pounds (using multiple kettlebells if necessary) will be weighed on a trusted scale and their known force readings will be recorded.

- Eccentric loading test:

Next, a kettlebell of known weight will be placed on each force plate in 5 different locations (center and four corners) and the force outputs will be recorded. This will be repeated with 2 more kettlebells of different weights.

- Off-Axis loading test:

To test how shear components of force affect the normal force reading of the force plate, an object of known weight will be attached to a rope and hung off the side of the table. The other end of the rope will be placed across the top of the force plate and a kettlebell will be placed on top of it to hold it in place. This will apply a shearing force to the plate. This will be repeated for 4 different hanging objects of known weights. The entire process will be repeated with the rope laid across the force plate in the orthogonal direction so that shearing force in the x and y direction is considered.

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, there is a possibility that the results of the test for off-axis loading described above reveal that off-axis loading severely affects the accuracy of the device. If the test results show that off-axis loading induces an error outside of the 5% specified in the PDS, the team will iterate the design to either the Membrane-Bound or Bearing-Guided designs. Because the components of the chosen Stationary Footplate design are included within the other designs, this iteration will be efficient and cost-effective while addressing the error that off-axis loading introduced in the Stationary Footplate Design.

Another potential source of error stems from the sensitivity of the load cell and resolution of the signal. The load cells have a nonlinearity of 1% [17], meaning they could deviate up to 1 lb. Each individual load cell is within the 5% error specification of the PDS; however, the device incorporates four load cells on each of the right and left footplates, so this error could compound up to 8% for the device as a whole. This error will be addressed through extensive calibration as outlined, as well as some compensation in the signal processing code.

The resolution of the load cells is also limited by the Analog-to-Digital Converter (ADC) employed in the circuit. The team will use a 10-bit ADC, limiting the resolution of each load cell to 0.1 lb. The clinical metrics we aim to extract from our device are peak force, time to peak force, and percent difference in force between legs. Typically, the return to injury threshold for athletes with lower leg injuries is a 90% difference in force output between the injured and non-injured leg. A resolution of 0.1 lb should be sufficient to meaningfully make this assessment using our device. However, a 12- or 14-bit ADC can be substituted into the circuit to increase the resolution if the clients deem necessary.

The team has also considered ethical considerations in its design. The design does not infringe on Bylaw 10 in NCAA Division 1 Legislation [18] 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 [19]. 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 [20]. 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 can contribute to lower extremity injuries among competitive, collegiate rowers. Our objective is to design a low-cost force plate that provides real-time force data for the UW-Madison Rowing Team as the athletes train on the ergometer. Our chosen design, the Stationary Force Plate Design, consists of two aluminum plates. The bottom plate will be securely screwed into place, with four single-axis button load cells mounted at each corner. The upper plate, resting on top of the load cells, features divots that align with each load cell point. To hold the plates together, foam or springs with negligible spring constants will be adhered between them. The FlexFoot from the ergometer will be reattached to the top plate, allowing for adjustability to accommodate different foot sizes. As force is applied through the foot, the load cells will generate a signal to the Raspberry Pi microcontroller, which will relay the data to a display screen via HDMI connection showing a detailed GUI. This design will be installed in the ergometers at the UW-Madison Porter Boathouse, enabling athletes and coaches to visualize and analyze real-time data through a graphical user interface. Additionally, raw data will be accessible from an SD card or USB hard drive connected to the microprocessor. In the future, we plan to develop eight of these sensors allowing for more data gathering to further support the athletes' training and performance.

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X. Appendix

Appendix A: Product Design Specifications

PRODUCT DESIGN SPECIFICATIONS: ASYMMETRICAL FORCE SENSOR FOR ROWING BIOMECHANICS

BME 400, Section 304

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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 rowing is often difficult to obtain in non-clinical settings and may be very expensive to implement, especially due to environmental and equipment-related constraints. 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 difficult to quantify visually, and current methods include using stationary rowing simulation machines that underestimate the mechanical power required against water currents [2]. Specifically, these current methods of evaluating rowing form focus mainly on upper body metrics such as stroke power and involve studies outside of the rowing environment. Our design aims to provide accurate real-time data of rowers' lower extremities by integrating a force sensor system on an ergometer base to transduce force measurements that can be viewed while rowing against current in a tank or on the stationary ergometer. The application of our design will allow athletes and coaches to assess and adapt athlete performance, identify risk factors for injury, and assess return to injury metrics.

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 transmitted through each leg and translate the data to an interface that provides real-time data viewing while rowing.
    - The device must display real-time data on the amount of force transmitted by the toe and heel (separately) of each foot onto the tank footplate.
    - The device must store relevant performance metrics from a trial, such as peak force per stroke and time to peak force.
- The frequency and duration of force data storage during rowing sessions must be adjustable.
- The client desires an easily integrated force measuring system that should operate without requiring change in rowing technique or excessive modification of current rowing equipment.
- The device must alert the rower when force exerted by the right and left foot are asymmetrical.

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 device should quantify the degree of asymmetry using the magnitude of relative force between limbs in Newtons.
- The product should display real-time data during a rower's trial so they can monitor any fluctuations as they occur.
  - The real-time display must be easily interpretable by the user(s) using simple visual cues like colors, lights, figures, and text.
- The product should be able to store data so coaches and rowers can see the data in real time and analyze it later.

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, as well as ergometers in the training room, which exist in 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 will be mounted flat onto the existing ergometer footplate.
  - The force plate must be compatible with different foot sizes.

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 [12][13]. 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 [14]. 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. [15]
- 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. [16]
- A display screen such as a TV monitor, tablet, or laptop will be used to display rowers' data, as these screens are readily available in the UW Boathouse.

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 [17].

- 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 $500. 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) [18].
  - 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 [19].
  - 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 [20].
  - 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, as well as between different models of ergometers.

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 [19].
  - 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 [21].
  - 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 [22].
  - 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
Sensors	Load Cells	TE-Connectivity	FX292X-100A-0100-L	Mouser	824-FX292X-100A0100L	9/26	8	$27.72	$221.76	mouser_load_cells
Raspberry Pi	Microcontroller	Raspberry Pi	Raspberry	Adafruit	4292		1	$45	$45.00	rpi4

			Pi 4 Model B - 2 GB RAM							
ADC	MCP3008 ADC	Bridgold	MCP3008 -I/P	Amazon		4/11	1	$13.99	$13.99	mcp3008
								TOTAL:	**$280.75**	