VALIDITY AND RELIABILITY OF A FORCE SENSOR FOR ROWING BIOMECHANICS

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Abstract

Rowing athletes face an increased risk for lower back and hip injuries due to repetitive asymmetrical force outputs through the lower extremities. Current training methodologies primarily rely on qualitative assessment techniques, which lack precision in identifying biomechanical imbalances. This study aims to validate a cost-effective, ergometer-mounted force plate system capable of providing real-time data acquisition and feedback to measure lower extremity force asymmetry in rowing athletes. The device was evaluated through mechanical testing using a Mechanical Testing System (MTS) Criterion Model C43 (MTS Systems, Eden Prairie, MN, USA) for accuracy and reliability, and human subject trials involving Division I collegiate rowers for test-retest analysis. Results indicate that the device accurately quantifies force asymmetries within a ± 5.7% margin of error. The device also produces intraclass correlation coefficients (ICC) demonstrating good to excellent test-retest reliability in measuring peak force per leg and asymmetry index. Real-time feedback from the system enables athletes to make immediate adjustments, showing potential for injury prevention and performance optimization. The findings support the feasibility of this force plate system as a practical and accessible tool for biomechanical assessment.

Keywords: rowing, kinetics, biokinetics, Concept2

Word Count: 3144

Introduction

Rowing is a highly demanding exercise that commonly leads to lower back and hip injuries, particularly among female athletes. Rowers report more injuries during the offseason winter months[1], and injury can be significantly linked to ergometer rowing[2], so analyzing rowing mechanics specifically on the ergometer will be informative for both injury prevention and recovery. Bilateral asymmetry of force output at the foot stretchers have been observed to significantly influence lumbar-pelvic kinematics and pelvic twisting, which could be causal factors for lumbar spine injury[3]. These injuries could be a result of repetitive asymmetrical force output exerted by the lower extremities during the rowing motion, causing misalignment of the hips inducing stress on the lumbar spine. Currently, coaching staff and athletic trainers at the University of Wisconsin-Madison primarily rely on qualitative, visual analysis of athlete performance during ergometer training to identify and correct asymmetrical movements. Return-to-sport decisions in rowing are also primarily symptom- or time-based, rather than quantitatively evaluated[4]. However, such qualitative assessments are subjective and inadequate for precisely identifying biomechanical imbalances that can lead to injury or affect recovery.

Advancements in biomechanics have introduced force measurement systems capable of quantifying force asymmetries[5]. However, existing commercial solutions such as force platforms and instrumented rowing ergometers are often cost-prohibitive, too complex to integrate into training environments, and lack real-time quantitative feedback capabilities. These limitations prevent widespread adoption, leaving a gap in accessible and affordable technology for rowers and their staff.

The purpose of this study is to develop and evaluate an affordable, adaptable force plate system capable of real-time data acquisition with visual feedback to quantify lower extremity force asymmetry while rowing on a Concept2 Model D ergometer (Morrisville, VT, USA). The hypothesis for this research is that the designed footplate system will accurately and consistently measure forces exerted by rower's lower extremities normal to the surface of the plate within an acceptable margin of error of 5% and provide quantitative, real-time feedback.

Methods

Custom Force Sensor – Design and Construction

The force plate consists of four uniaxial compression load cells housed between two aluminum plates (Figures 1 and 2). The bottom plate is mounted to the Concept2 ergometer footplate base, while the top plate secures the rower's feet via the Concept2 Flexfoot. The top and bottom plates are connected by two shoulder screws passing through sleeve bearings press-fit into the bottom plate, reducing friction as the top plate translates in the normal loading direction. Ball-bearing tipped set screws in the top plate transfer force to the load cells, while compression springs on the shoulder screws preload the load cells by pushing the plates together, allowing measurement of both tension and compression.

Figures 1 (left) and 2 (right) — Front and side view of the force plate device mounted onto an ergometer.

The device uses 4 TE Connectivity load cells (FX292X-100A-0100-L, TE Connectivity Measurement Specialties, Grass Valley, CA, USA) per plate, which utilize a wheatstone bridge circuit configuration with a strain gauge. A Raspberry Pi Pico microcontroller (Raspberry Pi Ltd.), powered by a computer via USB, supplies 5 V to the load cells. Each analog differential output signal passes through a low pass filter (f_c = 7.23 Hz) and a unity gain voltage buffer (TLV274CPWR, Texas Instruments, Dallas, TX, USA) (LM358DR2G, Onsemi, Scottsdale, AZ, USA). The buffered differential signals are subtracted with an offset voltage of 104 mV and amplified (gain=23 V/V) by a non-inverting amplifier (TLV274CPWR). The amplified analog outputs are digitized by a 12-bit analog-to-digital converter (MCP3208, Microchip Technology Inc., Chandler, AZ), transmitted to the Raspberry Pi Pico digital pins via serial peripheral interface. A bi-directional level shifter (BOB-12009, SparkFun Electronics, Niwot, CO, USA) ensures compatibility between the 5 V ADC output and the Pico's 3.3 V GPIO pins. The Pico then transmits the data serially to the computer through the USB connection and a Python script calculates the total force on each plate and writes the data to a csv file.

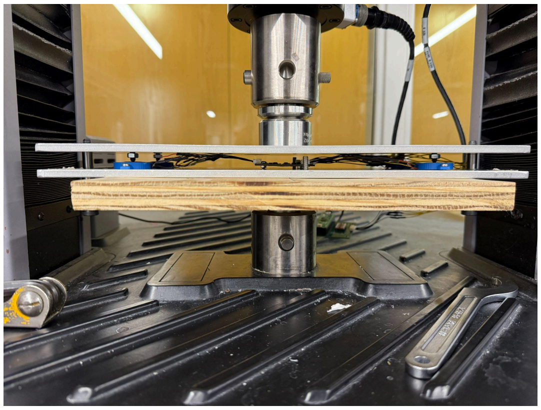
Load Cell Calibration – Protocol

Each load cell used on the device was individually calibrated to create a linear force-voltage curve. Calibration was conducted on the MTS fitted with a 1 kN load cell and its accompanying compression platen. The MTS applied a normal load on the load cell while the measured voltage from each load is recorded. Load was applied in a ramp-hold pattern, in which the MTS crosshead moves at a displacement rate of 0.02 mm/sec until it reached a 90 N load, held static at that load for 3 seconds, then ramped up to a 180 N load at 0.02 mm/sec, held for 3 seconds, and continued increasing the load by 90 N during each ramp and hold until it reached 450 N. After hitting 450 N, the load cell was fully unloaded at a displacement rate of –0.02

mm/sec. To determine the linear coefficient relating force to voltage for each load cell, a linear regression was performed using the average voltage reading from the middle 1 second of the 3-second static hold at each loading condition and the average of the applied force from the same time window.

Normal Load Compression Testing – Protocol

The fully assembled device was affixed to the MTS via a custom fixture attached to the 10 kN compression platen as seen in Figure 3. The MTS was programmed to apply a series of normal loads to the device in a ramp and hold pattern. Beginning with 0 N load, the applied load ramped to 200 N at a displacement rate of 0.02 mm/sec, held static for 3 seconds, and ramped back down to 0 N at a displacement rate of -0.02 mm/sec. Following another 3 second hold at 0 N, the applied load ramped to 400 N at a displacement rate of 0.02 mm/sec, held for 3 seconds, then ramped down to 0 N at a displacement rate of –0.02 mm/sec. This pattern (increasing ramp, hold, decreasing ramp, hold) was repeated at 600 N, 800 N, and 1000 N. This loading pattern can be visualized in Figure 4. Nine total trials were conducted with this loading pattern: three trials with load applied at the center of the top footplate, three trials with load applied at the approximate location of the rower's metatarsophalangeal joint (hereafter referred to as the "anterior" position), and three trials with load applied at the approximate location of a rower's heel (hereafter referred to as the "posterior" position). During load application, time and load data were recorded both by the MTS and the device. The device also recorded raw voltage values from each load cell.



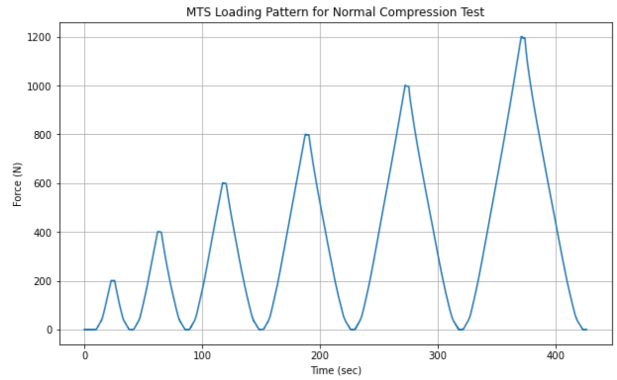
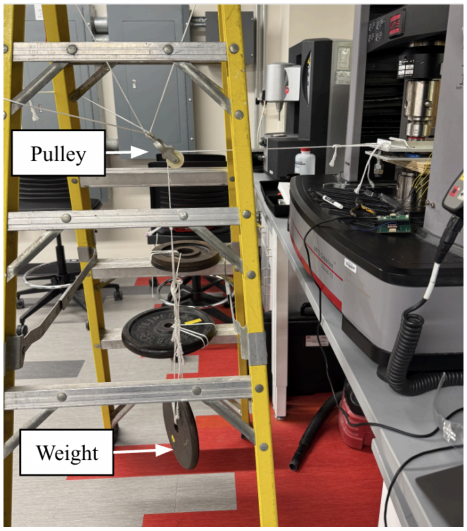
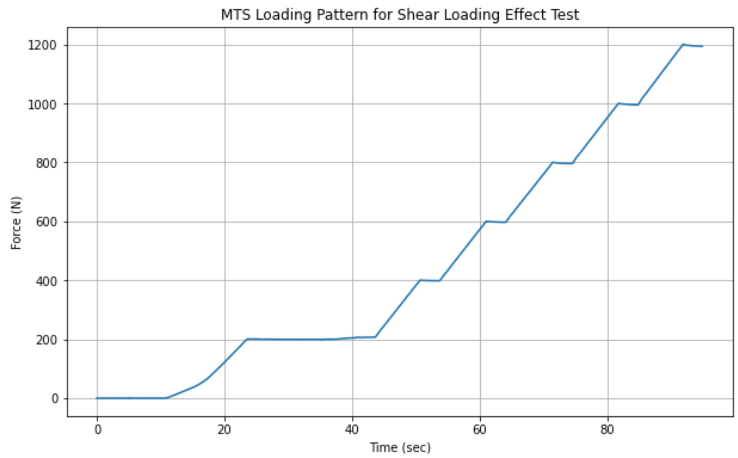


Figure 3 (left) and 4 (right) — MTS loading force (N) pattern for normal compression testing (left) and test setup using a plywood fixture bolted to the compression platen (right).

Shear Loading Effect Testing – Protocol

Rowers apply both shear and normal load through the feet during rowing[2]. The load cells utilized in the device are uniaxial compression load cells; therefore, testing was required to determine the effect of shear loading on their accuracy. Shear load was applied to the device through a pulley; a rope fixed flat to the footplate ran through the pulley and supported a hanging mass as shown in Figure 5. This pulley system converted the normal load of the hanging mass to a shear load on the device. During testing, the MTS was programmed to apply a 200 N load and hold static. Under these loading conditions, a 110 N, then 150 N, then 200 N mass was hung from the free end of the pulley to test the effect of increasing shear load on measured normal load. The MTS ramped from 200 N to 1200 N in 200 N increments, holding at each increment for 3 seconds. This loading pattern can be visualized in Figure 6. This process was repeated three times in each location on the plate (see "Normal Load Compression Testing - Protocol").





Figures 5 and 6 — MTS loading pattern for shear loading effect testing (left) and shear loading test setup using a pulley and hanging weight (right).

Compression Testing – Data Acquisition

During both normal and shear loading testing, time and force data were recorded both by the MTS Criterion and the load cell force plate. The MTS sampled data at a rate of 500 Hz, saving it to a JSON file, while the force plate device sampled at a rate of 1 kHz, passed it through a 20-point moving average filter, and saved it to a csv file.

Compression Testing – Data Analysis

Statistical analyses of compression testing were conducted using Python (Version 3.9.12). For each of the 9 normal compression tests and 9 shear effect compression tests, the force plate data and corresponding MTS data were first interpolated to unify their sampling rates, then digitally filtered by a 50-point moving average function. To ensure proper time alignment, their first derivatives were aligned via cross-correlation with the correlate function from the SciPy library (Scientific Library for Python, Version 1.7.3). The interpolated, unfiltered data were adjusted using this time alignment factor. Three force values from the time-aligned MTS and force plate data were pulled from each of the three second "holds" and used to calculate descriptive statistics relevant to device accuracy.

Device accuracy was evaluated according to ISO-5725-1 by the parameters of trueness and precision. Trueness, which describes systematic bias, is the mean of absolute percent errors between test results and true values. Precision, which assesses device consistency, is the standard deviation of the absolute percent error of repeated measurements. In addition, the absolute maximum error was calculated for each test case.

Human Subjects Testing – Subjects

IRB approval was obtained to test on human subjects for this study. The subjects were 27 Division I collegiate rowers who were all accustomed to rowing on the ergometer. The subject pool consisted of 3 female lightweight, 21 female open weight, and 3 male rowers. Subjects had varying injury history, which was recorded along with their age, height, and mass. All subjects gave their informed consent to take part in the study.

Human Subjects Testing – Protocol

The protocol began with the subject reading and signing a consent form. After this, the subject was asked a series of questions regarding rowing experience and injury history, then height and weight were recorded. The rower then proceeded to the warmup area where they first completed a 2000 m row at their steady-state rate (typically around 18–21 strokes/min) on a separate ergometer, followed by a series of dynamic exercises. After the warmup was complete, the subject moved to the data collection Concept2 Model D ergometer with the mounted force plates. The device was tared before each rowing session. Subjects were then asked to adjust the heel cup to their typical position according to their foot size and set the drag resistance for their steady-state row. Data collection was then initiated, and the subject rowed at their steady-state rate for roughly 5 minutes. Following this session of data collection, each subject was prompted with three survey questions for qualitative feedback on the device. Lastly, the subjects were asked to return for a second "retest" session of data collection. Rowers who were retested completed the same standard warm up followed by a 5 minute steady-state row.

Human Subjects Testing – Data Acquisition

All force data from human subjects was recorded by the right and left force plates. The device acquired data at a sampling rate of 1 kHz and saved it to a csv file (see Compression Testing-Data Acquisition for details). Deidentified anthropometric information of each rower, including height, weight, and rowing experience was collected via a form before the rowing session.

Human Subjects Testing – Statistical Analysis

All statistical analyses for human subjects testing was computed with the IBM SPSS statistical software. To assess the reliability of the force plate measurements across the first testing session and the second, retest session, intraclass correlation coefficients (ICC) and their 95% confidence intervals were calculated using a two-way mixed absolute agreement model. The metrics used to calculate the ICCs were mean peak left foot force, mean peak right foot force, and mean limb symmetry index which was calculated with the following equation.

$$Asymmetry\ Index\ (\%) = \frac{100 \times (Right - Left)}{0.5 \times (Left + Right)}$$

Results

The maximum absolute percent error of compression testing was 5.630%, occurring during a trial in the center of the force plate with 200 N of shear force applied (Table 1). The maximum mean absolute percentage error for any given trial was 3.599%, also occurring at the center position under 200 N shear. To provide a generalized measurement of trueness of the force plate, the mean absolute percent errors from each trial were averaged with equal weighting to a value of 1.975 ± 1.031%.

It should be noted that the repeated compression tests under 0 N shear were compiled into one trial with a larger population (n). Additionally, tests done on the anterior and posterior plate locations surpassed the capacity of the load cells at lower MTS magnitudes due to uneven force distribution, so the data points beyond these magnitudes were excluded.

Table 1 Compression Testing Accuracy Statistics

Position	Shear Force Applied (N)	Mean Absolute Percent Error (%)	SD Absolute Percent Error (%)	Max Absolute Percent Error (%)	n
Center	0	1.398	0.678	2.317	54
Center	110	2.089	0.993	3.105	15
Center	150	3.219	0.575	4.399	18
Center	200	3.599	1.220	5.630	18
Anterior	0	0.470	0.184	1.042	27
Anterior	110	1.937	0.443	2.676	9
Anterior	150	2.546	0.402	3.158	9
Anterior	200	3.464	0.612	4.065	9
Posterior	0	0.301	0.195	0.730	27
Posterior	110	1.337	0.956	2.966	9
Posterior	150	1.568	1.568	3.857	9
Posterior	200	1.771	1.486	3.947	9
	Mean ± SD:	1.975 ± 1.031			

All ICCs generated from test-retest rower force data were greater than 0.75, indicating good device reliability (Table 2). Rower force plots show strong visual correlation between test and retest plots in terms of shape and character (Figure 7). In some rowers, it is clear that they produce more force on one force plate than the other at the peak of each stroke in both the test and retest force profiles. Additionally, some rowers' force profiles were characterized by single peaks at every stroke, while others showed double peaks.

Table 2 ICCs for Test and Retest Rower Force Data

Metric	ICC	95% Confidence Interval
Mean Left Peak Force	0.987	[0.949-0.997]
Mean Right Peak Force	0.872	[0.478-0.968]
Mean Limb Symmetry Index	0.935	[0.751-0.984]

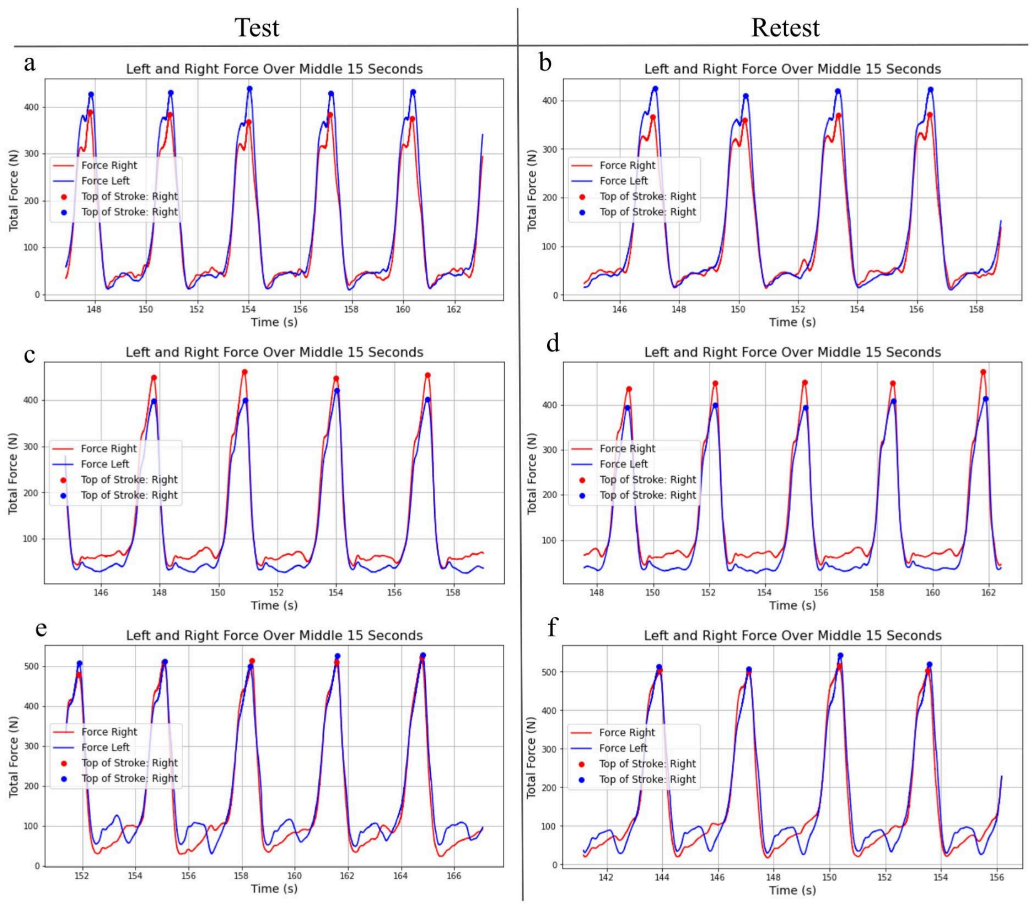


Figure 7 — Test and retest rower force profiles for three different human subjects. One human subject shows a double peak with left force dominance in both test and retest (a, b). The next

human subject shows single peaks with right force dominance (c, d). The last human subject shows single peaks with even force distribution between the right and left side, and their left force shows a dip before each peak (e,f).

Discussion

This study aimed to establish the validity and reliability of a custom, ergometer-mounted force plate that measures lower extremity force output during rowing. Mechanical testing and human subject testing indicate that the device shows sufficient validity and reliability to be used in a clinical or research setting to evaluate rowers' lower extremity force exertion during ergometer rowing.

Calibration revealed linearity in each load cell's force-voltage relationship with R^2 values above 0.999 for each load cell. Both normal and shear compression testing verify the force plate's validity and accuracy in measuring applied normal load within 5.7% error. The test setup provided controlled and repeatable loading conditions, and as shown in Table 1, the Mean Absolute Percent Error ranges from 0.301 ± 0.195% to 3.599 ± 1.220% depending on the loading condition. Our testing indicates that higher magnitudes of shear load applied on the plate induce greater error no matter the loading location. In most clinical settings, physicians make return-to-sport decisions based on the injured limb performing within 10-15% of the uninjured limb when assessing ACL recovery[6]. If this standard were to be assessed using our device, the percent error produced by shear loading is not significant enough to affect clinical evaluation of metrics such as peak force and asymmetry index. Mechanical testing also revealed increased error when the plate was loaded in the center; this is likely due a maximized bending moment induced by normal centric loading. However, rowers tend to apply more pressure on the forefoot[7] throughout the stroke so error induced by centric loading will be minimized during use.

Testing of the device with human subjects in an athletic environment revealed the device's test-retest reliability as well as its ability to capture clinically relevant data. ICCs calculated from extracting the average peak force per stroke from the right and left force plates, as well as average asymmetry index per stroke demonstrated good to excellent reliability. The high sampling rate of the device allows for detailed force profile analysis and the device's reliability allows for tracking of long-term athlete performance.

There are several limitations and sources of error in the device and test setups used in this study. The normal and compression loading test setup provided precise, repeatable loading conditions but failed to replicate the loading rate of typical strokes exhibited in rowing, limiting the scope of the accuracy analysis of the force plates. In addition, shear was only applied along the anterior-posterior axis of the device, despite the possibility of rowers applying shear to the plates along the medial-lateral axis. Finally, our results indicate a slight phase delay between external load application and the device's load measurement. This is likely due to the time taken to overcome static friction between the shoulder screw and sleeve bearing, but could be addressed by applying bearing grease to the assembly. From human subject testing, rowers were retested after varying periods of time, during which their training and racing was not monitored, so they could have developed changes in technique due to pain onset that would be reflected in the reliability data collected by the device.

Overall, validation and verification testing through the MTS and human subjects ensured the device is both accurate and reliable. The device will be able to provide the collegiate rowing teams with short term and long-term data outputs that will allow them to monitor athletic performance. This device will be able to function as a risk stratification and assessment tool by determining if an athlete meets appropriate asymmetry index for return-to-sport, and as a risk mitigation tool where athletes can receive feedback on how to optimize form for injury prevention.

Acknowledgments

The authors gratefully acknowledge the Jill Thein-Nissenbaum, Tricia de Souza, Dr. David Bell, Dr. Kreg Gruben, Dr. David Appleyard, and the University of Wisconsin-Madison Rowing Team for their support.

Data Statement

The MicroPython code to program the Raspberry Pi Pico, the Python script to save the data to a csv, and the Python data to analyze test results will all be uploaded to a public github repository. Printed circuit board project files (Altium) and CAD files (SolidWorks) as well as a bill of materials are publicly available on a public repository.

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Final Report Appendix

BME 402

1. Design Updates

Software Updates

A data collection GUI was designed to create a user-friendly interface for both MTS testing and human testing (Figure 1). The data collection GUI has a file dialog that prompts a user to select a file location and file name for a csv. Then, the user toggles between two modes: continuous and on-demand. Continuous mode allows the user to press “Start Data Collection” and then “Stop Data Collection”, and data will be sampled continuously between those two commands and saved to a csv. Alternatively, the user can toggle on-demand mode and use the “Measure Now” button to take one measurement at a time. The columns of the csv include local timestamp (precise to 1 ms), calculated left and right force data (lbs), channel by channel force data (lbs), channel by channel ADC data, and the most-recent tare values.

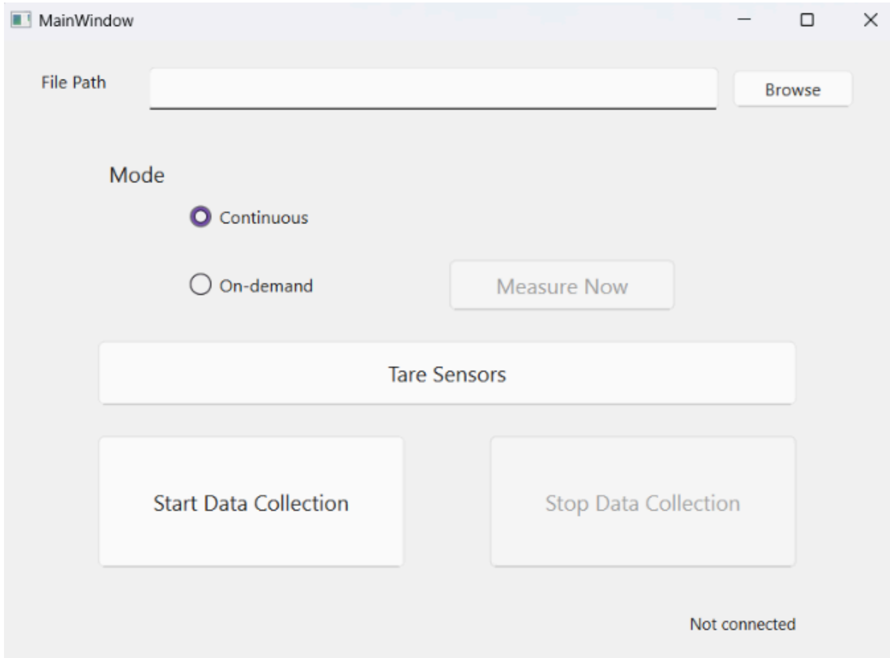

Figure 1: Data collection GUI window.

Hardware Updates

New load cell printed circuit boards (PCBs) were designed and ordered with the intention of improving the signal integrity of the boards with intentional board layout considerations, and conversion to surface mount (SMD) components to consolidate the size of the board (Figure 2).

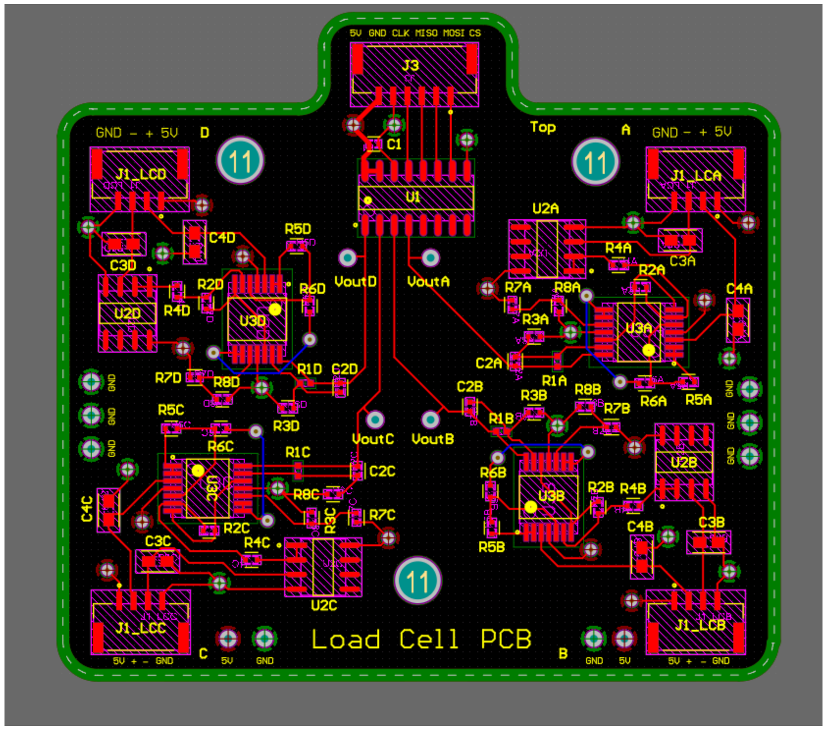

Figure 2: Updated load cell PCB layout (dimension: 63.2mm x 58.2mm).

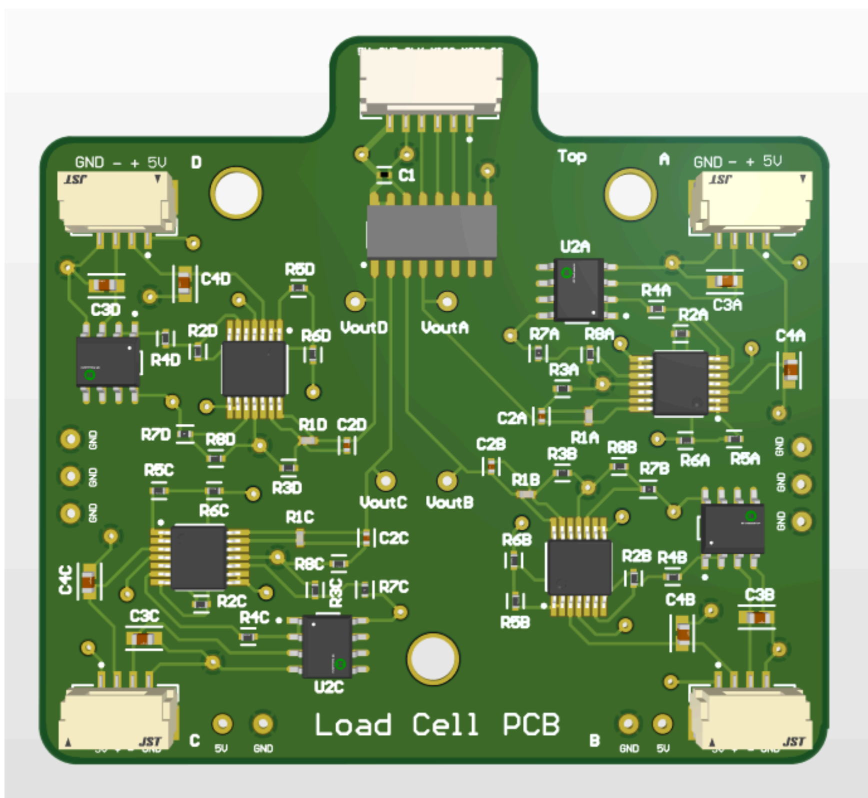

Figure 3: 3D view of updated load cell PCB.

Additionally, a PCB was designed to interface with the raspberry pi pico (Figures 4 and 5).

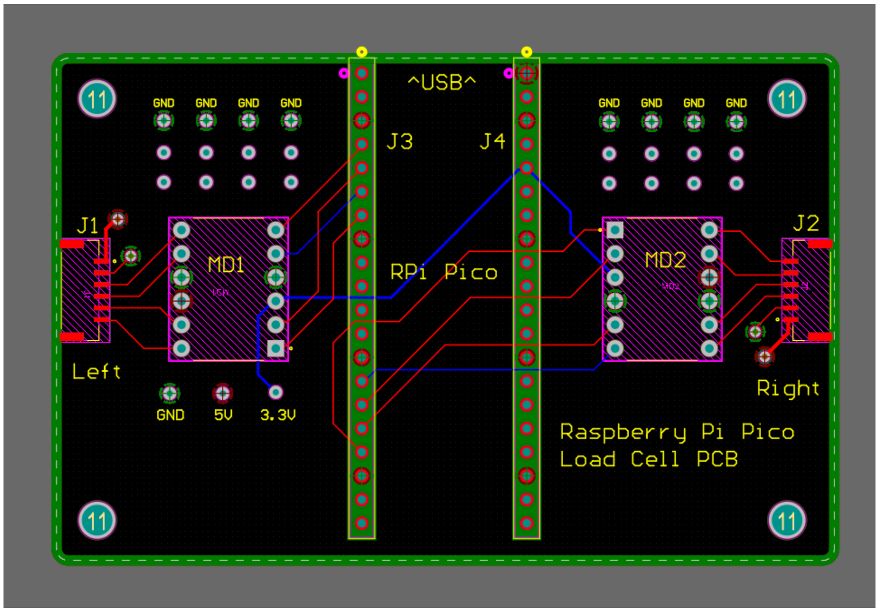

Figure 4: Raspberry Pi Pico PCB layout (dimensions: 84.7mm x 54.7mm)

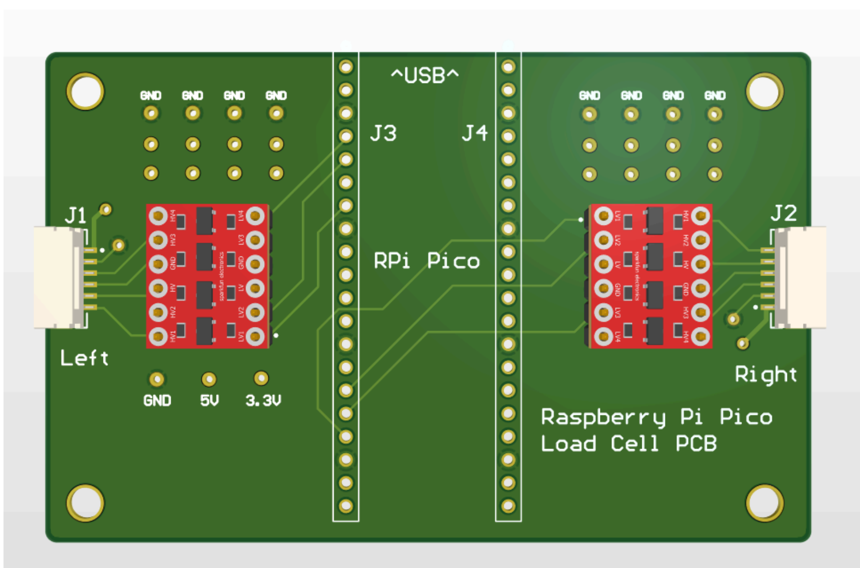

Figure 5: 3D view of Raspberry Pi Pico PCB.

Mechanical Updates

Ball-point tipped set screws (to replace the current load pin set screws) were ordered to reduce shear loading of the load cells.

Figure 6: JW Winco GN 605 Socket Screws.

2. Other Updates

IRB Submission

With the assistance of Dr. David Bell, the team has submitted an application to the IRB to perform research with human subjects. With permission from the IRB, we will be able to gather and publish data from college athlete rowers using this force measurement device.

THE UNIVERSITY of WISCONSIN MADISON

Product Design Specifications: Asymmetrical Force Sensor for Rowing Biomechanics

BME 402

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

Advisor: Dr. David Appleyard

Team Members:

Team Leader: Allicia Moeller

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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.

<u>Design Requirements:</u>

1. Physical and Operational Characteristics:

a. Performance Requirements:

- The product must track the degree to which rowers are exerting symmetric force through their entire lower extremity, to track any asymmetry present.
  - The device should quantify the degree of asymmetry using the magnitude of relative force between limbs 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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