VALIDITY AND RELIABILITY OF A FORCE SENSOR FOR ROWING BIOMECHANICS

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Abstract

Rowing athletes are at 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 develop and validate a cost-effective, adaptable 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 validation. Results indicate that the device accurately quantifies force asymmetries within a ±5% margin of error, demonstrating high repeatability across trials. Additionally, 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: 2767

Introduction

Rowing is a highly demanding exercise that commonly leads to lower back and hip injuries, particularly among female athletes. 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[1]. 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. However, such qualitative assessments are subjective and inadequate for precisely identifying biomechanical imbalances that can lead to injury.

Advancements in biomechanics have introduced force measurement systems capable of quantifying force asymmetries. 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 X and X). 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 of prototype config)

Figure X outlines the entire signal processing methodology of the device. The device uses TE Connectivity load cells (FX292X-100A-0100-L, TE Connectivity Measurement Specialties, Grass Valley, CA, USA), 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 5V 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 5V ADC output and the Pico's 3.3V 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.

(circuit block diagram)

Load Cell Calibration – Protocol

Each load cell used on the device will be individually calibrated to create a linear force-voltage curve. Calibration will be conducted on the MTS fitted with a 1 kN load cell and its accompanying compression platen. The MTS will apply a normal load on the load cell while the measured voltage from each load is recorded. Load will be applied in a ramp-hold pattern, in which the MTS crosshead moves at a displacement rate of 0.002 mm/sec until it reaches a 50 N load, holds static at that load for 3 seconds, then ramps up to a 100 N load at 0.02 mm/sec, holds for 3 seconds, and continues increasing the load by 50 N during each ramp and hold until it reaches 400 N. After hitting 400 N, the load cell will be fully unloaded at a displacement rate of –0.02 mm/sec. To create the force-voltage curve, the average voltage reading from the middle 1 second of the 3-second static hold at each loading condition will be plotted against the applied force.

Normal Load Compression Testing – Protocol

The fully assembled device will be affixed to the MTS via a custom fixture attached to the 10 kN compression platen. The MTS will be 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 will ramp to 100 N at a displacement rate of 0.02 mm/sec, hold static for 3 seconds, and ramp 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 will ramp to 200 N at a displacement rate of 0.02 mm/sec, hold for 3 seconds, then ramp down to 0 N at a displacement rate of –0.02 mm/sec. This pattern (increasing ramp, hold, decreasing ramp, hold) will repeat 10 total times per trial with the amplitude of the peaks increasing in 100 N increments until the peak reaches 1000 N. Nine total trials will be 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, and three trials with load applied at the approximate location of a rower's heel. During load application, time and load data will be recorded both by the MTS and the device. The device will also record raw voltage values from each load cell.

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 is required to determine the effect of shear loading on their accuracy. Shear load will be applied to the device testing through a pulley; a rope fixed flat to the footplate will be run through a pulley and have a mass hanging on the end. This pulley system converts the normal load of the hanging mass to a shear load on the device. During testing, the MTS will be programmed to apply a 200 N load and hold static. Under these loading conditions, a 50 N, then 100 N, then 150 N mass will be hung from the free end of the pulley to test the effect of increasing shear load on measured normal load. This process will be repeated for three additional trials in which the MTS applies a 400 N load, a 600 N load, and 800 N load.

Compression Testing – Data Acquisition

During both normal and shear loading testing, time and force data will be recorded both by the MTS Criterion and the load cell force plate. The MTS will sample data at a rate of 5 kHz, saving it to a JSON file, while the force plate device will sample at a rate of 1 kHz, passing it through a 20-point moving average filter, and saving it to a csv file. A cross-correlation of the data output by the force plate and the MTS will be performed to identify and correct time lag before accuracy and repeatability analyses.

Compression Testing – Data Analysis

Device accuracy will be assessed according to ISO-5725-1 by the parameters of trueness and precision. Trueness is the mean of absolute errors between test results and true values and describes systematic bias, whereas precision is the standard deviation of repeated measurements and describes the agreement of independent test results. The absolute maximum error will be calculated as well as the 95th and 99.5th percentiles. All accuracy metrics will be reported as force values (Newtons) as well as percentages of full-scale, normalized by the combined maximum rated load of the four load cells (1780 N).

A comparison of test data over the nine trials will be used to quantify repeatability. The repeatability of the device, according to ISO-5725-1, measures the dispersion of test results under repeatability conditions. In this case, repeatability will be characterized by the mean of the coefficient of variance of test results across the nine trials as well as the maximum coefficient of variance across trials. ICC estimates and their 95% confident intervals will be calculated using Pingouin statistical package version 0.5.1 based on a single measure, absolute-agreement, 2-way mixed-effects model.

Human Subjects Testing – Subjects

The subjects were [X] Division I collegiate rowers who were all accustomed to rowing on the ergometer. The subject pool consisted of [X] female lightweight, [X] female open weight, and [X] male rowers. Their mean age, height, and body mass are [X] years, [X] cm, and [X] kg, respectively. Subjects also had varying injury history, which was recorded. All subjects gave their informed consent to take part in the study.

Human Subjects Testing – Protocol

With the device mounted on the Concept2 Model D ergometer, each subject will be asked to adjust the Flexfoot to their typical position according to their foot size and perform a standard warmup of 2 minutes at a low-intensity stroke rate and resistance of their choice. After the warmup, the subject will be asked to hold the handlebar in a neutral position as if they were to begin rowing.

The device will be tared with the rower in this position. Then, the subject will row 2000 m (roughly 5-8 minutes) at their "steady state" stroke rate (typically 22-24 strokes/min). The subject will then dismount the ergometer and rest for two minutes before repeating the same 2000 m row at their steady state stroke rate. The device will be re-tared once again before the second trial while the rower is in the neutral position. Following this session of data collection, each subject will return for a second session of data collection 3-5 days later. The second session of data collection will be conducted exactly the same as the first, consisting of a warmup, 2000 m row, 2 minute rest, 2000 m row.

Human Subjects Testing – Data Acquisition

All force data from human subjects will be recorded by the load cell force plate. The device will acquire data at a sampling rate of 1 kHz and save it to csv file (see Compression Testing-Data Acquisition for details). Deidentified anthropometric information of each rower, including height, weight, and rowing experience will be collected via a form before trials begin.

Human Subjects Testing – Statistical Analysis

To assess the reliability of our force plate measurements, the Coefficient of Variation (CV) will be calculated to compare accuracy variability across trials and conditions. The CV is the percentage of the mean and used in biomechanics for repeatability and reliability of force data measurements. A lower CV value corresponds with more consistent accuracy. A CV threshold of less than 10-12% is deemed acceptable for human force variability during rowing trials[3].

To determine if the total force production and force asymmetry remained consistent across trials, a paired t-test will be performed at single-point comparisons. Analyses will be performed to compare left and right leg forces, as well as force measurements between Day 1 and Day 2. Repeated measures ANOVA will also be applied for multiple time points within a session to compare force over various rowing strokes. A Bonferroni correction will be applied to the ANOVA test for multiple comparisons to reduce false positives. A significance threshold of $p<0.05$ for both tests will be used, following standard statistical guidelines[4]. ANOVA effect size will also be calculated to determine the practical significance of the difference between groups. An effect size less than 0.06 indicates the difference might not be meaningful[5].

To examine the relationship between rower characteristics and force output, Pearson's correlation coefficient (r) will be used to measure the linear relationship between continuous variables. If normal distribution assumptions are violated, Spearman's rank correlation (ρ) will be applied to access consistently increasing or decreasing trends.

Results

No results to analyze yet.

Discussion

The MTS machine testing and the human subjects testing will provide sufficient evidence that the adaptable force plate system will be capable of providing real-time data acquisition and visual feedback to quantify lower extremity force asymmetry in rowing athletes. The MTS machine testing will be essential for verifying and validating the reliability of the force plate because it is able to provide controlled and repeatable mechanical loading conditions. Although it will not be able to perfectly simulate a rowing stroke, the function implemented on the MTS will be able to mimic the gradual increase and decrease in force with the peak force being held for a few seconds. Additionally, the MTS ensures accuracy when loading the load cells and is easily repeatable.

Human subjects testing will be the other crucial method for validating the reliability of the rowing force plates, as it ensures the sensor performs accurately and consistently in real-world applications. While lab-based verification methods like MTS machine testing confirm the sensor's accuracy under controlled conditions, human subjects testing assesses how it responds to actual user interactions, including variations in force application. The human subjects will also range from healthy to non-healthy rowers in different weights classes in order to get a more comprehensive test. This testing helps validate that the sensor maintains accuracy despite biomechanical differences, positioning inconsistencies, and dynamic loading conditions inherent to human use. Additionally, it will identify potential usability issues, such as discomfort, responsiveness, or integration challenges, that may not be apparent in machine-based testing. The human subjects testing will also provide qualitative feedback on comfort, ease of use and GUI preferences for the device. By combining controlled verification with real-world validation through human subjects testing, the team can ensure the force sensor meets both technical and practical performance expectations.

Both MTS machine testing and human subjects testing have limitations when validating the reliability of a force sensor. MTS machines provide precise, repeatable loading conditions, but it lacks real-world variability, failing to account for dynamic human interactions. Additionally, MTS testing can be complex to set up as it will require the creation of a new program. While the MTS excels in static and fatigue testing, it will not fully capture the unpredictable nature of human-applied forces. On the other hand, human subjects testing introduces real-world variability but comes with challenges such as inconsistent force application, subject fatigue and limited reproducibility due to individual biomechanical differences. While the MTS testing will ensure controlled verification, human subjects testing provides critical real-world validation and combining both approaches helps achieve a more comprehensive assessment of a force sensor’s accuracy and reliability.

Additional sources of error pertaining to hardware and design of the device could also affect accuracy of results from the MTS and human subject's test. One potential source could be non-linearity and hysteresis (up to 1%) inherent to the load cells, as specified by the manufacturer. Although calibration curves show a highly linear relationship between applied force and output, these factors remain relevant as the load cells are dynamically loaded during rowing. Another potential source of error is electrical noise. Electrical noise in the load cells' analog output mitigated by low-pass filters, and minor signal delays caused by capacitor charging times are additional concerns. From previous testing, results showed that shear loads did have a significant effect on the accuracy of the normal force measurement (while remaining within 5% margin of error). Shear loads induced by the rowing motion could be a significant source of error, which is why extensive testing on the effect of shear loads on accuracy must be more thoroughly investigated. Finally, the friction between the shoulder screw and the sleeve bearing has the potential to distort the force readings by absorbing some of the applied force.

Overall, validation and verification testing through the MTS and human subjects will be able to ensure the device meets the product design specifications. Once validated, the device will be able to provide the UW Rowing Team 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 diagnostic tool by determining if an athlete meets the Limb Symmetry Index and as a risk mitigation tool where athletes can receive feedback on how to optimize form for injury prevention.

Acknowledgments

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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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Preliminary 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.

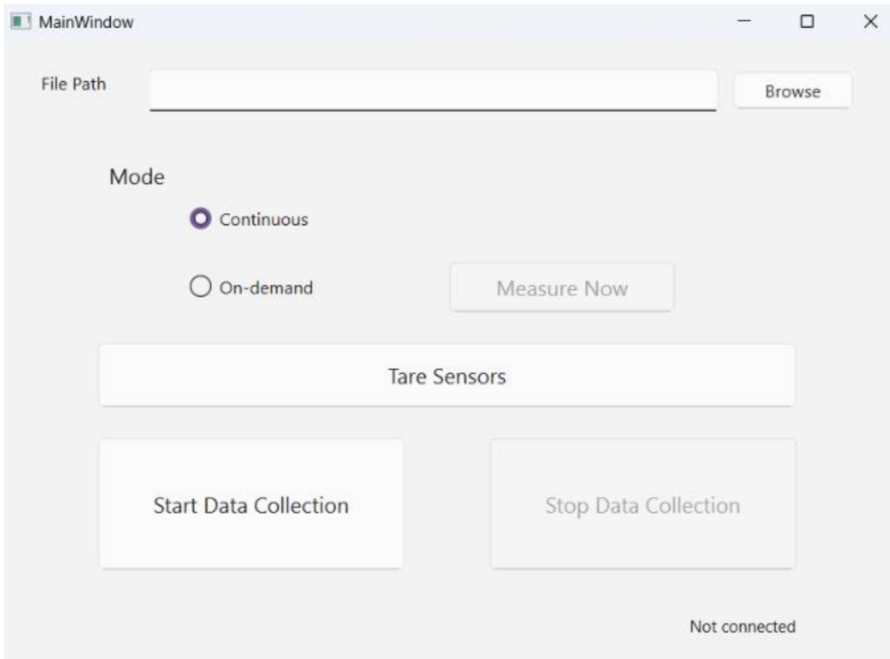

Figure 1: Data collection GUI window.

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).

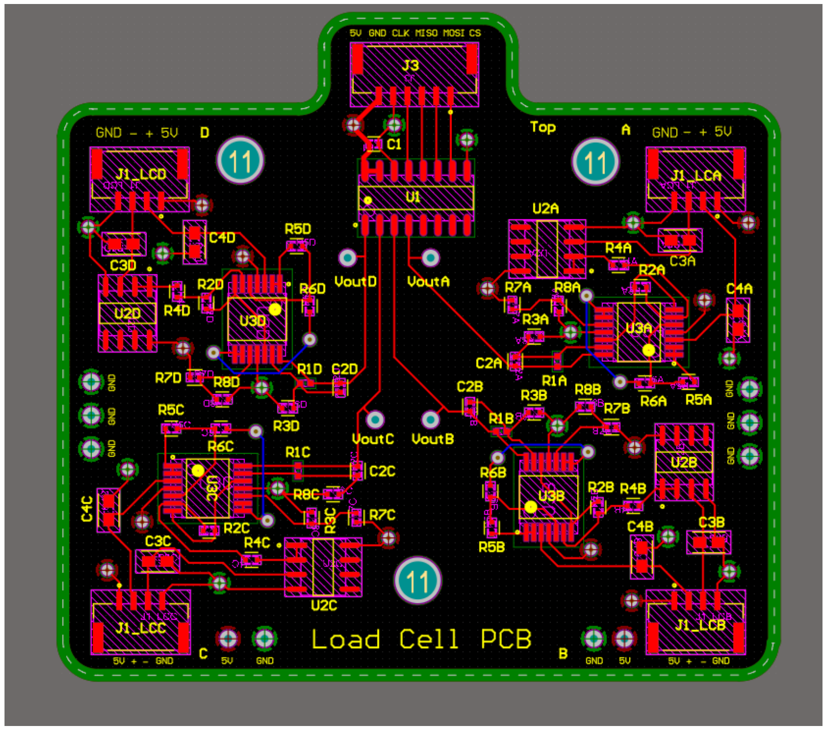

Figure 2: Updated load cell PCB layout (dimension: 63.2mm x 58.2mm).

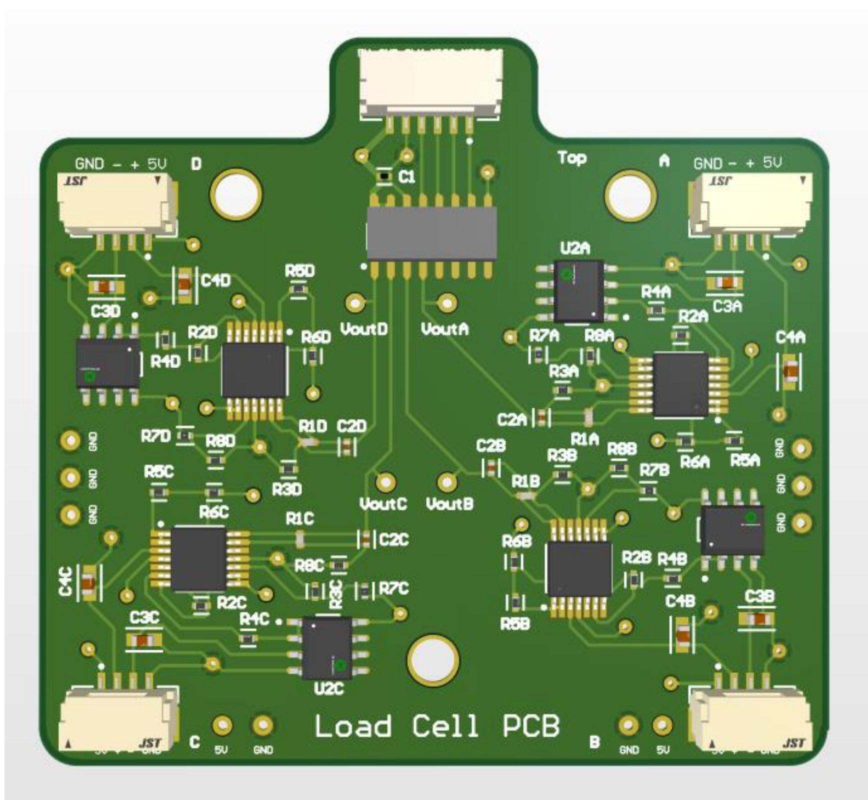

Figure 3: 3D view of updated load cell PCB.

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

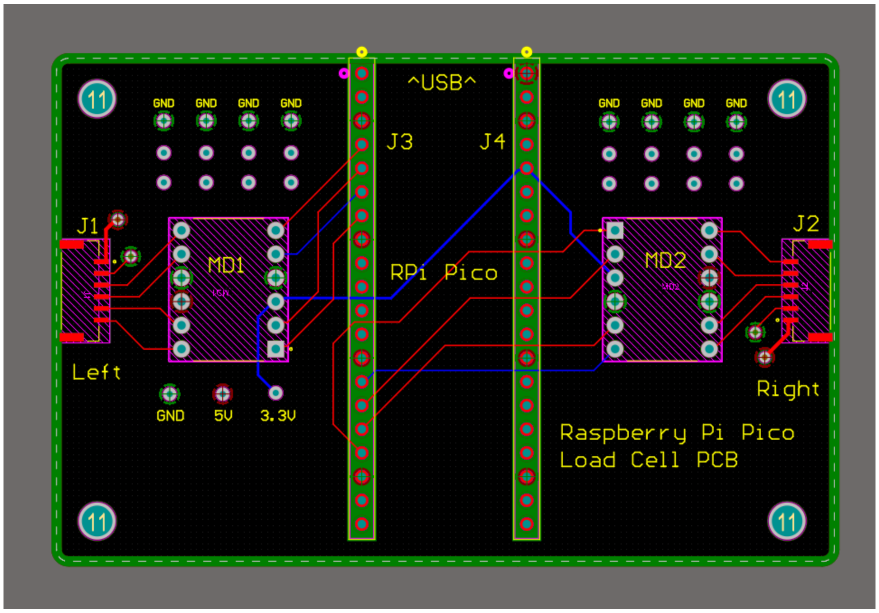

Figure 4: Raspberry Pi Pico PCB layout (dimensions: 84.7mm x 54.7mm)

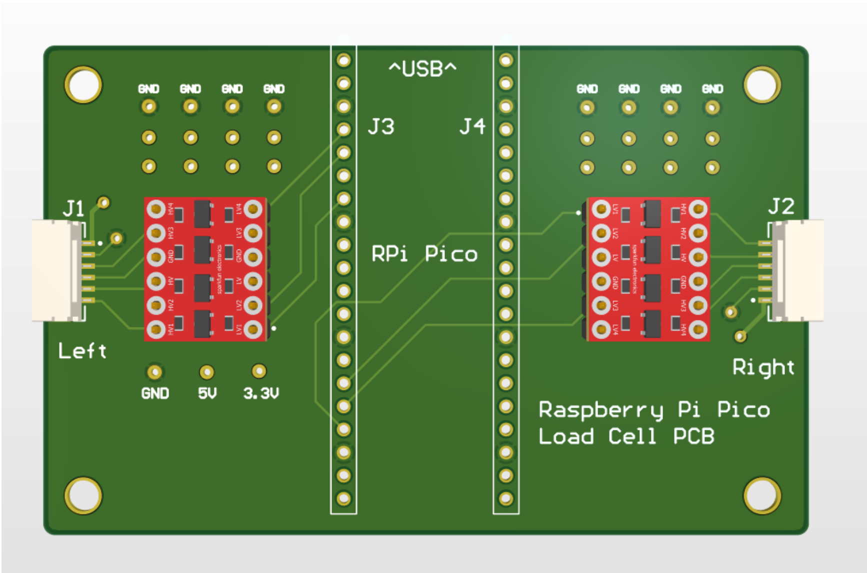

Figure 5: 3D view of Raspberry Pi Pico PCB.

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.

PRODUCT DESIGN SPECIFICATIONS: ASYMMETRICAL FORCE SENSOR FOR ROWING BIOMECHANICS

BME 402

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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.

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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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