Asymmetrical Force Sensor for Rowing Biomechanics

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Abstract

Collegiate rowers can suffer from injuries pertaining to the lumbar spine due to intense repetitive training and improper form [1]. Perfecting technique by minimizing leg force output asymmetry while rowing is essential to preventing such injuries and improving performance overall [2]. The UW Women's Rowing staff has tasked the team with creating a force sensing system to measure real-time biomechanical data in order to determine the presence of any lower extremity force asymmetries. The final design consists of a top footplate that translates vertically to transmit force to load cells that are housed underneath it. The device was evaluated through mechanical testing using a Mechanical Testing System (MTS) for accuracy and reliability, and human subject trials involving Division I collegiate rowers for validation.

Motivation

- Many members of the University of Wisconsin Rowing team have lower back pain, potentially due to asymmetric force output while rowing.
- Back injuries can be caused by consistently exerting force while the back is flexed, repetition of the rowing movement, and failure to properly adapt to the size of the ergometer or boat [3].
- Currently, UW Rowing coaches do not have a way to quantify asymmetry in rowers or correlate it with other risk factors.
- Existing products involve expensive and highly advanced equipment [3].
- With this device, UW Rowing staff will be able to measure and interpret rowers' force output to improve their technique, reduce injury risk, and assess injury recovery.

Background

- The rowing motion can be modeled as a deadlift with the athlete pushing their feet off the footplate and pushing their oar against the water.
- There are four phases of rowing:
  - Catch, Drive, Finish, Recovery
- Most in-season rower training occurs on an ergometer due to weather conditions.
  - Therefore, most technique deficiencies are developed on the ergometer, leading to injury.

Figure 1. Phases of the rowing stroke [3].

Design Criteria

- Must be compatible with Concept2 RowErg footstretcher and flexfoot
- Must not impede natural rowing motion
  - Device height < 2.54 cm to minimize difference in flexion angles
- Force capacity per footplate must be at least 900 N
- Data must be easily interpretable and stored for clinical use
  - Sample rate > 500 Hz
- Force magnitude measured within a margin of error of 5%
- Test-retest ICC > 0.75 for good statistical reliability [4]

Final Design

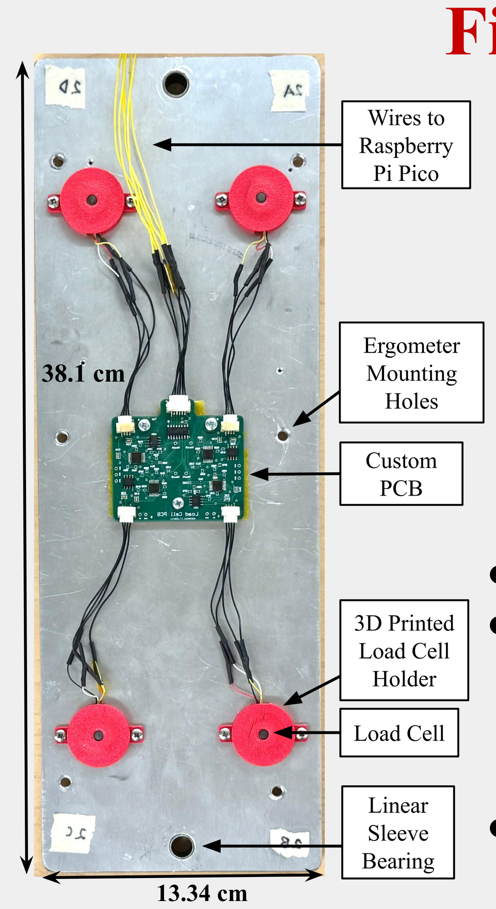

Figure 2. Top view of bottom plate with load cells and PCB.

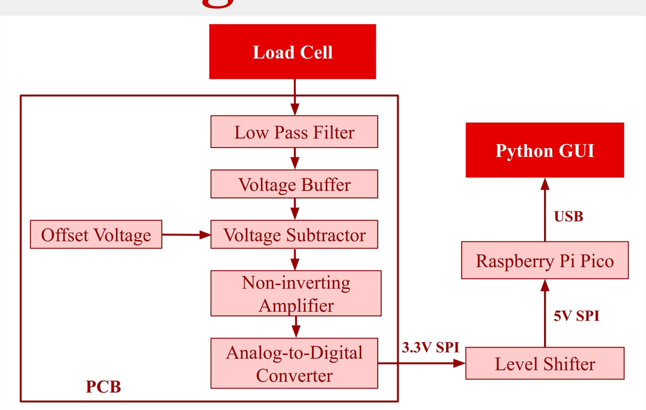

Figure 3. Hardware block diagram.

- CNC-milled ¼" aluminum plates
- Drilled holes for shoulder screws, bearings, set screws, load cell housings, ergometer mount, and flexfoot attachment
- Low friction linear motion via shoulder screw through sleeve bearing
- PCB processes load cell data and transmits via USB to laptop

Figures 4 and 5. Side view and front view of force plates on ergometer.

Testing

MTS Validation

- Load cells calibrated using MTS-applied forces and measured ADC values.
- Custom plywood fixture to hold force plate assembly in MTS
- Force plate MTS tests performed at center, anterior, and posterior with:
  - Cyclic compression (200–1200 N, 200 N steps) - 3 trials
  - Ramp-and-hold compression (200–1200 N, 200N steps) under constant shear (110, 150, 200 N)

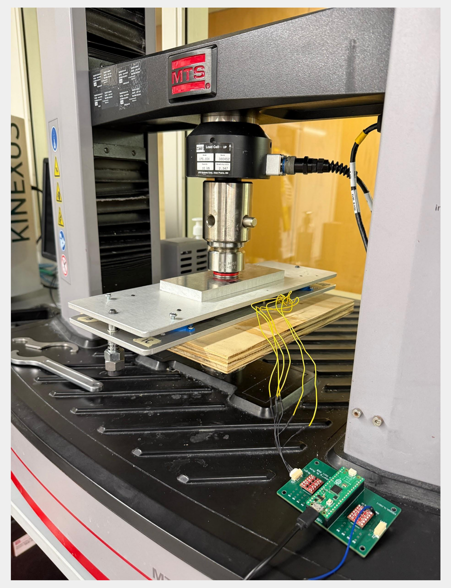

Figure 6. Normal compression loading test setup on MTS with plywood fixture.

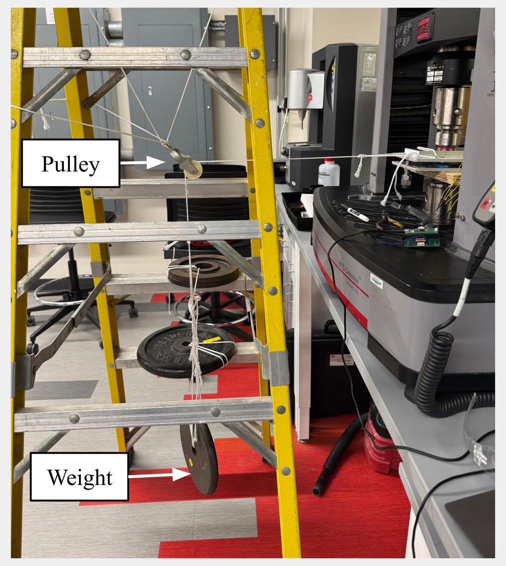

Figure 7. Pulley mechanism for shear loading during ramp and hold compression testing.

Athlete Testing - IRB Approved

- 27 UW rowers (24 female, 3 male) from the Lightweight, Openweight, and Men's teams participated.
- Subjects completed a 5-minute steady-state rowing session on the force plates following a warm-up.
- 11 rowers (10 female, 1 male) returned for repeat testing to assess device reliability.

Figure 8. UW Rower during athlete testing.

Results

MTS Data Analysis

- 3 points extracted at each plateau for MTS force and force plate force
- Mean absolute percentage error calculated for each position and shear loading condition (Figure 11)

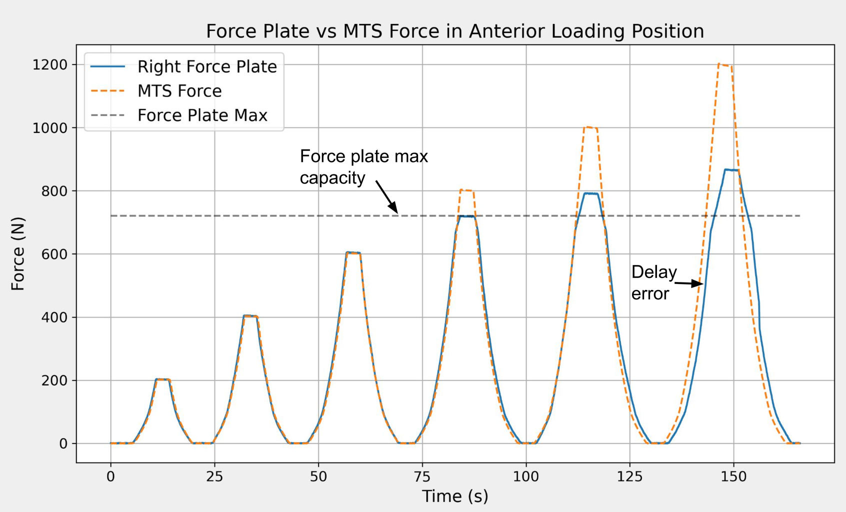

Figure 9. Force plate reading vs MTS reading with MTS loading in the anterior position with no shear load.

Figure 10. Loading positions.

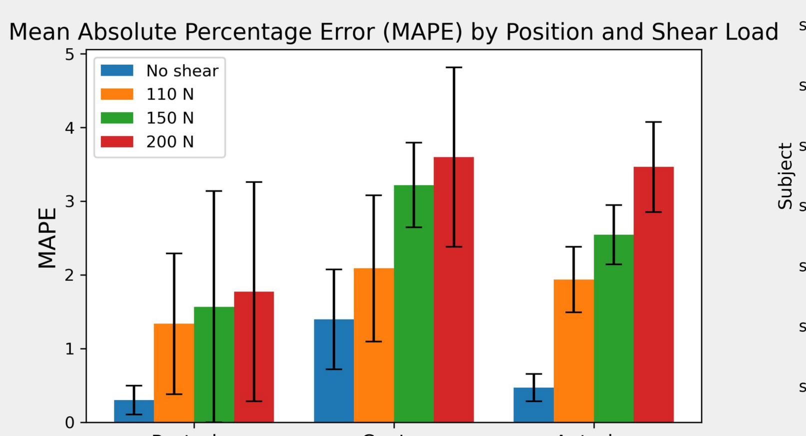

Figure 11. Mean absolute percentage error by loading position and shear load ± 1 SD.

Table 1. Intraclass correlation coefficients (ICC) for test-retest data using a two-way mixed absolute agreement model.

Metric	ICC	95% CI
Avg Left Peak	0.987	[0.949-0.997]
Avg Right Peak	0.872	[0.478-0.968]
Avg Peak Asymmetry Index	0.935	[0.751-0.984]

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

Equation 1. Asymmetry Index formula. Positive values correspond to right emphasis and negative values correspond to left emphasis.

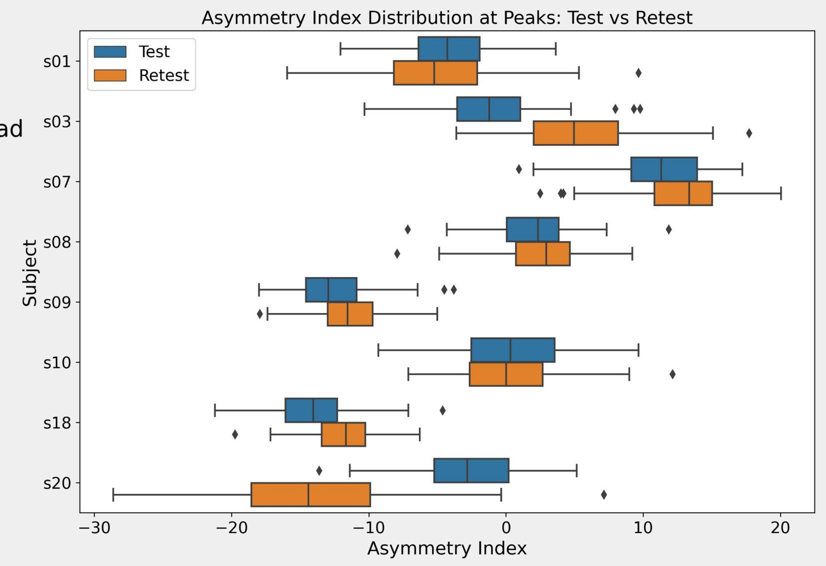

Figure 12. Boxplots of asymmetry index at peak forces for test and retest of 8 different rowers.

Athlete Testing Analysis

- Generated ICCs using test and retest data to determine force plate reliability
- Collected information on rower height, weight, experience level, side of boat, and injury history

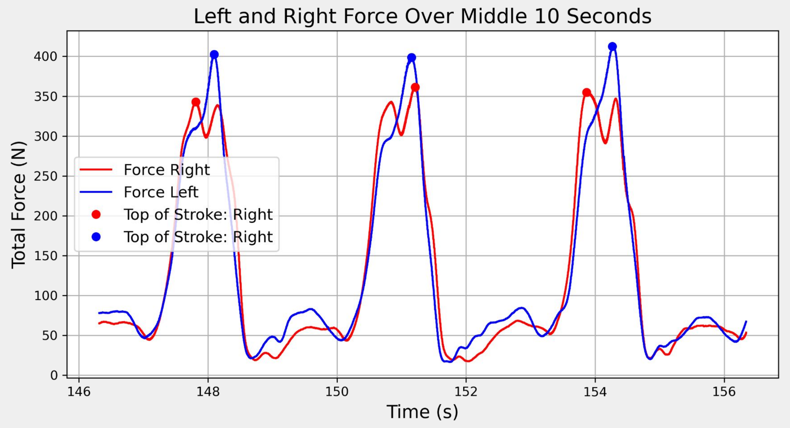

Figure 13. 10-second sample of data collection from a rower. Dots indicate peak of force of each stroke.

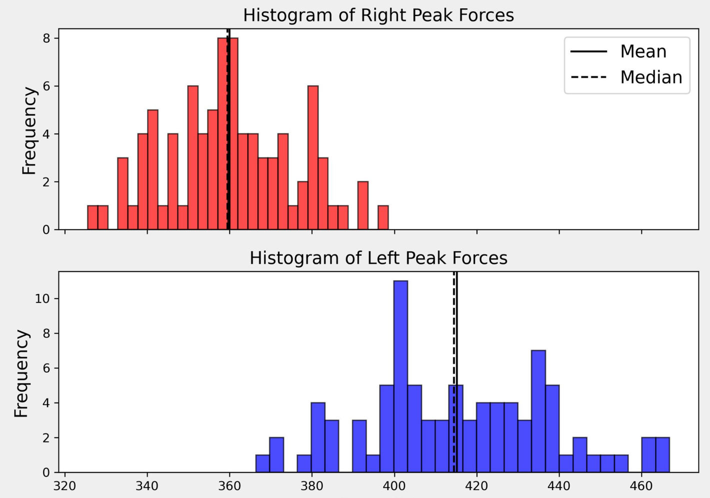

Figure 14. Histograms of right and left peak forces of a rower for 5 minutes of at steady state, excluding first and last 15 seconds.

Discussion and Future Work

Sources of Error

- Friction between shoulder screw and sleeve bearing
- Bending of aluminum plates
- Load cell non-linearity and hysteresis
- Ergometer movement and plasticity
- Load cell calibration errors
- Electrical noise, capacitor charging delays

Device Reliability and Accuracy

- All ICCs were greater than 0.75, demonstrating reliability in measuring peak force magnitude between test and retest.
- MAPE falls within PDS criterion of 5% error for all loading conditions.
- Error increases with shear load.
- Error greatest when loaded in the center - maximum bending
- Phase delay likely caused by time taken to overcome static friction between sleeve bearing and shoulder screw.

Initial Rower Data Analysis

- Device is functional in a collegiate athlete testing environment.
  - Easy assembly and setup
  - Real-time data collection and fast on-site analysis
  - No rowing technique alteration due to device
- Device is capable of correlating patient history with force output.
  - Leg length asymmetries → Increased asymmetry index
  - Pain onset between tests → Increased asymmetry index

Future Work

- Replace sleeve bearings with linear ball bearings
- Increase sample size of rowers
- Calculate and analyze other relevant force metrics for each rower:
  - Power
  - Delay between peak force at handle and peak force at feet
  - Phase delay between feet
- Further analyze and assess correlations between force-derived metrics and patient demographics:
  - Weight class
  - Height
  - Side of boat

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References

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