

Development and Testing of a Novel Dual Lever Operated Rowing Ergometer using a Chebyshev Lambda Linkage

Adam Benaben, Chinmay Bharatia, Fred Carver, Diya Kalyan, Rohan McCall, Lukasz Regulski

Abstract

Functional Electrical Stimulation (FES) and rowing is used to strengthen lower body bone and muscle in people suffering from Spinal Cord Injuries (SCI) [1]. Conventional ergometers (such as the Concept2[2]) are adapted for the needs of SCI patients by securing the upper body with a rigid backrest, limiting trunk motion and reducing stroke length [3]. This restriction prevents full engagement of core and upper body muscles, which are essential for functional movement and rehabilitation.

To address these limitations, this study presents a novel dual-lever rowing ergometer featuring a Chebyshev “Lambda” linkage. Unlike traditional cable-resistance mechanisms, this design enables greater trunk engagement while maintaining stability, simulating water rowing more effectively. The system is instrumented with force and motion sensors to evaluate postural control and muscle activation.

Experimental trials were conducted on an able-bodied participant using motion capture and EMG data to assess trunk stability and muscle engagement. A Trunk Stability Score (TSS) was introduced, quantifying postural control by analysing the Zero Moment Point (ZMP) trajectory relative to the rower’s base of support. Results from Trial 15 showed a TSS of 0.7544, indicating moderate stability, with no time spent outside the support zone. EMG confirmed expected activation patterns in key muscle groups, including the rectus femoris, biceps brachii, and triceps brachii.

These findings demonstrate that the dual-lever mechanism improves postural control and upper body engagement compared to conventional ergometers. The system has potential applications in SCI rehabilitation, offering a quantifiable metric (TSS) for trunk stability assessment and enhanced muscle activation for functional training.

Key words

Rowing, Chebyshev Lambda, Trunk Stability, Biomechanics, EMG, Motion Capture, Muscle Activation, FES

Acknowledgements

Prof. Michael Chappell, Dr Neil Evans, Prof. Brian Andrews, Dr Panagiotis Tsakonas, Jim Flood

1 Introduction

FES rowing is a specialised exercise for individuals suffering from paralysis, usually because of spinal cord injuries. In FES rowing, electrical impulses are used to stimulate leg muscles such as the quadriceps and hamstrings to cause contraction. This has health benefits for quadriplegics and paraplegics who are at risk from diseases such as coronary heart disease, diabetes and obesity as well as increasing bone loading forces which can help prevent severe lower body fractures due to bone mineral density loss [3] [4].

Current FES rowing ergometers are adapted from traditional, 'Concept2 style' rowing ergometers with the FES patient's upper body held in place with a harness attached to a moving but rigid seat backrest [4]. Moving from a 'Concept2 style' machine to a lever-operated machine allows the upper body of FES patients upper body to remain unrestricted, offering a new type of stability training in the core trunk and upper limb muscles in the expectation that the skill training will carry over everyday activities of daily living involving weight transfers.

This study aims to establish the foundation for the development of FES rowing by introducing a lever-operated design that enables long-term health monitoring. To achieve this, the design integrates measurement sensors to assess key health parameters, including trunk stability and muscle activation, providing objective indicators of patient progress over time.

2 Context

There is currently no quantitative measure of distributed dynamic trunk stability for paraplegics and tetraplegics [5]. In clinical research the displacement trajectory of the centre of pressure is determined, for quiet sitting with the arms folded. The relative distance of the COP to the boundary base of support being graphically displayed. However, this only considers static forces during quiet sitting without any hand gripping onto a support. This research proposes a new metric to determine trunk stability, that could potentially be used clinically.

The Zero Moment Point (ZMP) is often used to control dynamic walking robotics and is the point on the ground where the horizontal moments and inertial forces become zero. This can also be used to assess hand supported stability. For a dynamic object to be stable, this point must be within the support base, the area bounded by the objects contact points with the ground, this makes ZMP stability a dynamic analogue to the ground projected Centre of Mass for static objects [6]. ZMP trajectory can be determined using motion capture data. This point can be compared to the position within the stable base over time [7].

In SCI patients with poor control of their trunk, new patterns of postural control might be trained based on the inclusion of non-postural muscles such as the latissimus dorsi, the shoulder girdle, and the upper arm to maintain and restore sitting balance [8]. We envisage that the

training of these muscles in a standardised and clinical exercise using the new ergometer may therefore be a useful tool for rehabilitation and establishing these patterns.

In cases of SCI of motor level C5 and below, patients are still able to control their deltoid and biceps even if otherwise tetraplegic [9]. Nerve and tendon transfer operations from the posterior deltoid to the triceps can be performed on these patients to restore active elbow tension providing some restoration of previous function and ability [10], [11]. It is envisaged that the cyclical exercise of rowing will enhance and accelerate the rehabilitative training in both strength and coordination of these muscles with minimal supervision for therapists. FES might also be incorporated in future developments to stimulate the latissimus dorsi, via thoraco-dorsal nerves and in some cases the erector spinae group and quadratus lumborum. The push and pull motion of a lever activated ergometer may provide useful rehabilitation for patients who undergo this procedure. Muscle activation data for a healthy subject using the designed ergometer have been collected to for these muscle groups to explore their use in rowing and provide a baseline. These data have been collected using surface EMG.

3 Mechanical Design

FES rowing has traditionally used cable ergometers, which restrict trunk movement and limit stroke efficiency [2]. While single-lever designs (Figure 1) allow for some trunk engagement, their circular handle trajectory does not accurately replicate the motion of rowing on water, leading to inefficient force distribution and restricted stroke length [12].

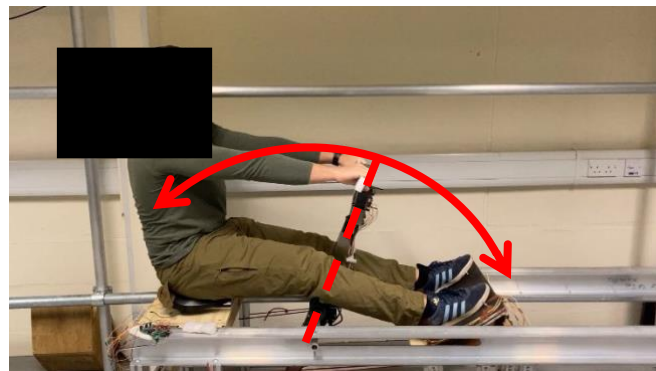


Figure 1 - Single Lever Operated Rowing Ergometer

To address these limitations, a dual-lever rowing ergometer with a Chebyshev “Lambda” linkage was developed. This mechanism enables a near-linear handle trajectory, improving stroke biomechanics, force application, and trunk stability for both able-bodied users and SCI patients.

3.1 Chebyshev Lambda Linkage

Traditional single-lever systems constrain handle motion to a circular arc, causing unnatural rowing mechanics and uneven force distribution [13]. The Chebyshev Lambda linkage (Figure

3) was chosen for its ability to convert rotational motion into near-linear motion, mimicking natural rowing (Figure 2). [14] Key benefits include: 1) near-linear handle movement, reducing unnatural motion and improving stroke mechanics 2) continuous force application, maintaining engagement in both drive and recovery phases 3) improved trunk engagement, promoting active postural control – crucial for SCI rehabilitation.

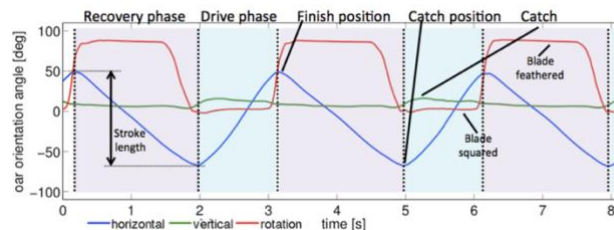


Figure 2 - Oar Orientation Angle Through Rowing Cycle [13]

3.2 Advantages of the Dual-Lever

The system further optimises rowing mechanics and stability: 1) Balanced load distribution unlike single-lever design, the dual-lever configuration ensured even force application 2) independent handle rotation (Figure 6), allowing natural wrist movement and reducing strain 3) Enhanced stability supporting postural control training. Combining the dual-lever system with the Chebyshev “Lambda” linkage, this design achieves a more natural and efficient rowing motion.

3.3 Comparison with existing designs

Table 1 Comparison of existin ergometer designs

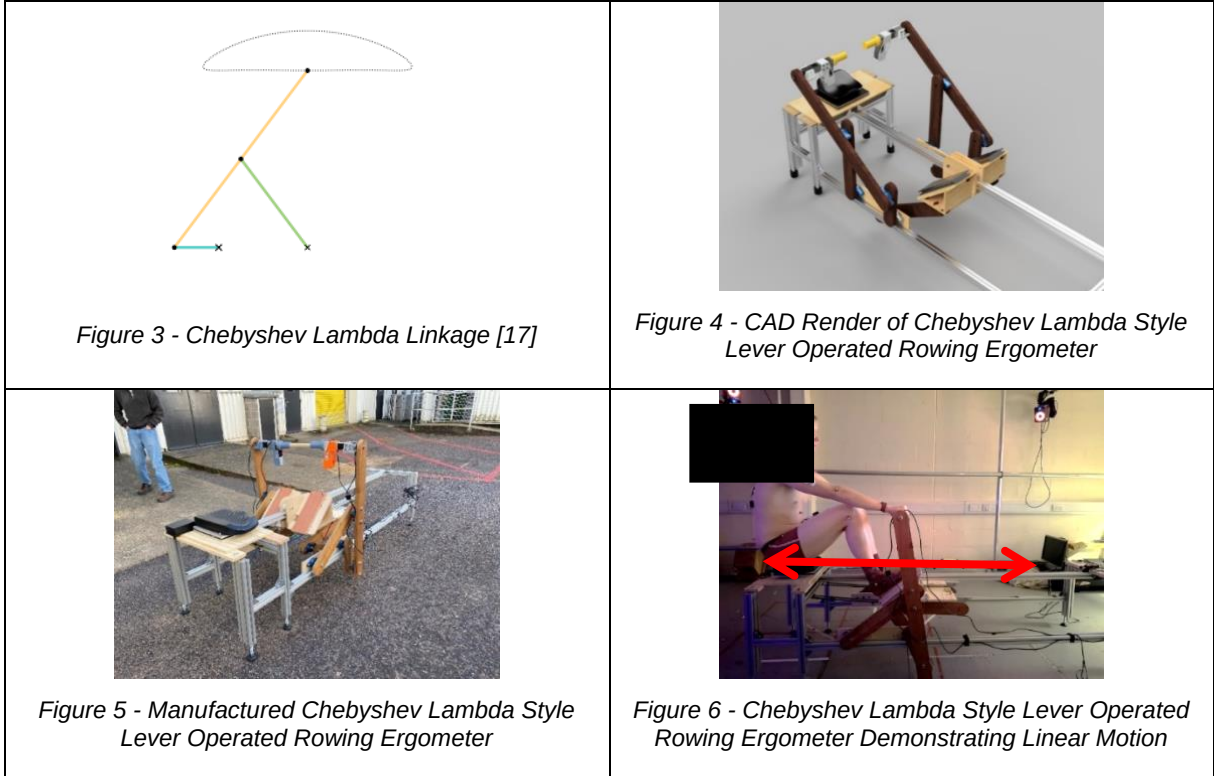
Feature	Cable-Based Erg [15]	Single-Lever [16].	Dual-Lever
Handle motion	Pull only	Arc-constrained	Near linear
Force Application	Pull only	Asymmetric push-pull	Continuous push-pull
Trunk Engagement	Minimal	Moderate	High (active stabilisation)
Load distribution	Asymmetric	Moderate	Balanced (dual lever)
Stroke length	Full	Moderate	Full, natural

The proposed system offers biomechanically superior alternative with enhanced stroke efficiency, continuous force application, and improved trunk control, making it effective for SCI rehabilitation and training.

4 Sensing System

Developing the ergometer required a sensor system to measure the forces in the handle to determine effectiveness of rehabilitation. This was done using four 100kg rated aluminium load cells. These were amplified and transmitted to the controller at a 50Hz frequency the biomechanics analysis. Four FX19 compression load cells were also placed in the seat.

Compression load cells in the footplate were replaced with bars held between brackets to measure forces in both directions.



A system to find the state (positions and velocity) was also developed. This used an inertial measurement unit (IMU) to find the angle of the linkages left pivot. The accelerometer data from the IMU were pre-processed to remove unwanted tangential and centripetal accelerations before being fused with the gyroscope and magnetometer using an extended Kalman filter (EKF).

From here the rotation of the other pivot could be derived. This was done using newtons method.

$$\phi_{\text{new}} = \phi_{\text{old}} - \frac{f(\phi_{\text{old}})}{f'(\phi_{\text{old}})} \quad (1)$$

It took 10 iterations to reach a close approximation (within $10^{-3}\%$) of the analytical solution.

Then coordinates for any other point in the linkage were calculated. This information was combined with the load cell forces to calculate power output.

A user interface, including a digital twin of the machine and gamification concept were developed, but remain in the proof-of-concept stage for future work.

5 Experimental Methodology

The study aimed to evaluate trunk stability and muscle activation during rowing using the dual-lever Chebyshev Lambda linkage ergometer. Experimental trials were conducted with an able-bodied participant to assess postural control, force application, and muscle recruitment patterns. Data collection integrated motion capture, load cells, and EMG sensors to quantify biomechanical performance.

5.1 Motion Capture and Trunk Stability Assessment

A Vicon Nexus motion capture system was used to track three-dimensional trunk, lower, and upper limb movement. Reflective markers were positioned at key anatomical landmarks, including the pelvis, sternum, shoulders, elbows, knees, and ankles, allowing for precise tracking of trunk displacement relative to the rowing seat.

The ZMP is the point where the sum of horizontal forces and moments equals to zero, ensuring dynamic stability. It is calculated as:

$$ZMP_x = \frac{\sum(M_{iy} + F_{iz}x_i)}{\sum F_{iz}}, ZMP_y = \frac{\sum(M_{ix} + F_{iz}y_i)}{\sum F_{iz}} \quad (2)$$

where M_i are moments, F_{iz} are vertical forces, and x_i, y_i are coordinates. The ZMP must remain within the support base for stable posture control.

ZMP trajectory was computed to determine postural stability, and a Trunk Stability Score (TSS) was introduced as a metric for quantifying deviations in trunk motion. TSS consists of two primary indicators: 1) Trunk sway in the mediolateral direction determined by calculating standard deviation of trunk centre's Y-coordinate and 2) Mediolateral handle force use, computed by using root mean square values from load cell data. TSS was calculated as follows:

$$TSS = \frac{1}{1 + \alpha(\text{trunk sway} + \beta * \text{handle ML use})} \quad (3)$$

where trunk sway (m) represents lateral trunk displacement. Handle mediolateral force (N) reflects stabilisation effort through the arms. A higher TSS indicates greater trunk stability (scored 0-1). The weighting coefficients ($\alpha = 0.5$ and $\beta = 0.1$) were selected. Trunk sway exerts a nonlinear influence on postural control, requiring a scaling factor (α) that prevents extensive penalisation of minor deviations while maintaining sensitivity to larger displacements. The β coefficient ensures that force values remain within a comparable magnitude to trunk displacement, converting Newtons to kg-equivalent terms for unit consistency. These parameters were initially determined empirically and will be further refined through data-driven optimisation techniques.

Motion capture data were recorded at 200 Hz, and force measurements were obtained via synchronised load cells embedded in the handles, seat, and footplate. Data alignment was achieved using piecewise cubic Hermite interpolation, ensuring consistent synchronisation across all measurement systems.

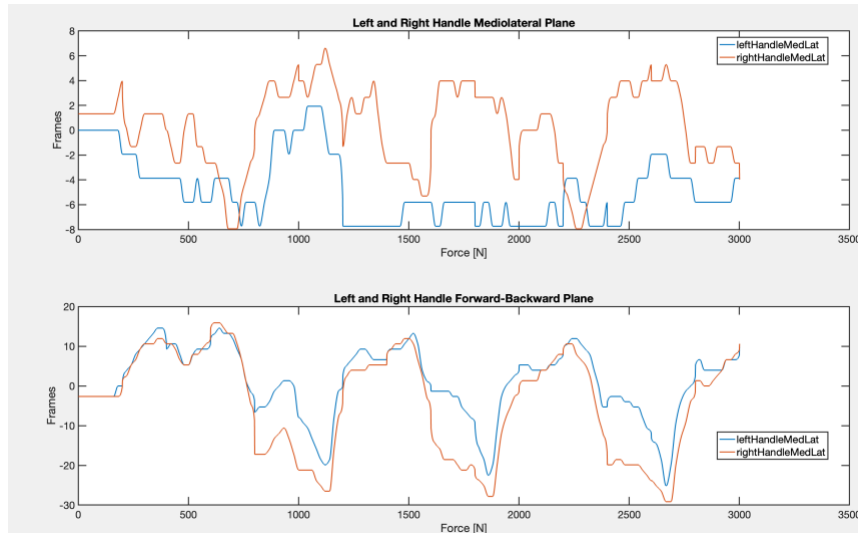


Figure 7 - Raw Data from load cells after interpolation

5.2 Muscle Activation Data Acquisition

To assess muscle engagement, surface EMG sensors were attached to key muscles involved in rowing, including the posterior deltoid, triceps brachii, rectus femoris, latissimus dorsi, and biceps brachii. Electrode placement followed SENIAM guidelines [18] to ensure accurate signal capture. EMG data were recorded at 1000 Hz. The signals underwent initial pre-processing, including the removal of NaN and infinite values, followed by bandpass filtering (10–500 Hz) using a fourth-order Butterworth filter to reduce motion artefacts. The rectified signals were then smoothed using a moving average and a 30 Hz low-pass Butterworth filter to facilitate clearer analysis. Finally, the data were normalised relative to each muscle's maximum voluntary contraction (MVC) to standardise muscle activation across trials. MVC was estimated by finding maximum amplitude of EMG readings of each trial [19].

5.3 Data Analysis

Collected data were analysed to 1) assess trunk stability using TSS and ZMP trajectory analysis 2) quantify muscle activation patterns by extracting normalised EMG data across a trial 3) evaluate force distribution through load cell measurements, correlating them with stability metrics

6 Results

The EMG signals for Trial 15 reveal distinct activation patterns of key muscle groups during rowing. The rectus femoris (QFR, QFL) showed high activation peaks during drive phase,

aligning with the expected role of the quadriceps in knee extension. The biceps brachii (BBR, BBL) exhibited concurrent activation. This suggests coordinated flexor engagement during the pull phase. In contrast, the triceps brachii (TBR, TBL) demonstrated a 180° phase shift, showing higher activity during the push motion when the arms extended forward. Signal irregularities were seen in the latissimus dorsi (LDR, LDL), due to cyclic noise from deeper back muscles. These findings confirm that the dual-lever system effectively engages key muscle groups across the stroke cycle, supporting its applicability in upper-body training and postural control (Figure 9).

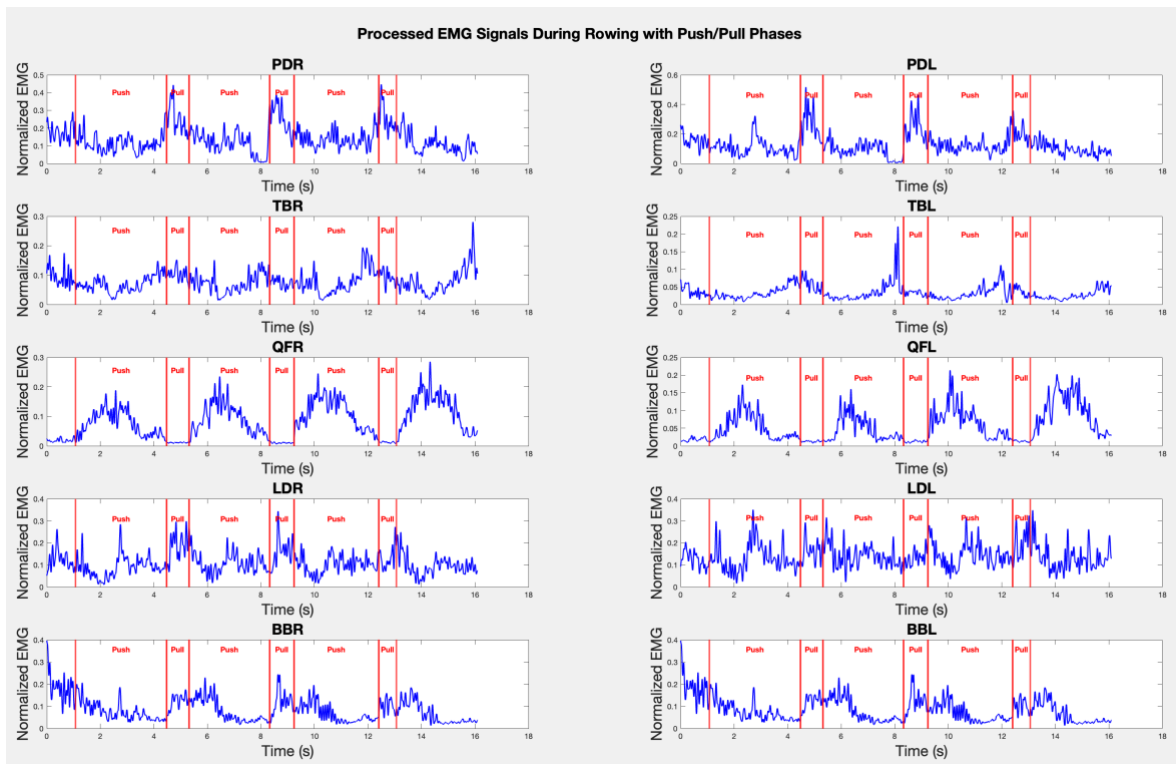


Figure 8 EMG Data from Trial 15 collected during rowing motion

For Trial 15, the computed Trunk Stability Score (TSS) was 0.7544, indicating moderate stability. The mediolateral (ML) trunk sway was measured at 0.0103 m, while the handle ML force usage was 6.4088 N.

Notably, the rower spent 0.0% of the time outside the stability zone, suggesting a well-maintained balance throughout the trial. The measurement, however, was done on an able-bodied subject, therefore, further tests are required on SCI patients. The study confirmed that the proposed methodology effectively quantifies trunk stability. Load cell limitations impacted ML force readings, particularly on the left handlebar, which may have contributed to discrepancies in computed stability metrics. The selected α and β values effectively balanced positional deviations and compensatory stabilisation forces, aligning with biomechanical principles. However, future research should refine these parameters through regression-based

optimisation. Moreover, the EMG analysis demonstrated clear differentiation between muscle groups, confirming the expected activation patterns across the rowing stroke phases.

Figure 10 illustrates the ZMP trajectory across the rowing cycle, highlighting fluctuations in trunk positioning. Stability was maintained throughout the movement, with no excessive deviations beyond the support zone. The ZMP analysis supports the use of TSS as an objective metric for evaluating postural stability strategies during rowing. By integrating force, motion capture, and EMG data, the study demonstrates the effectiveness of the dual-lever ergometer in promoting active trunk control.

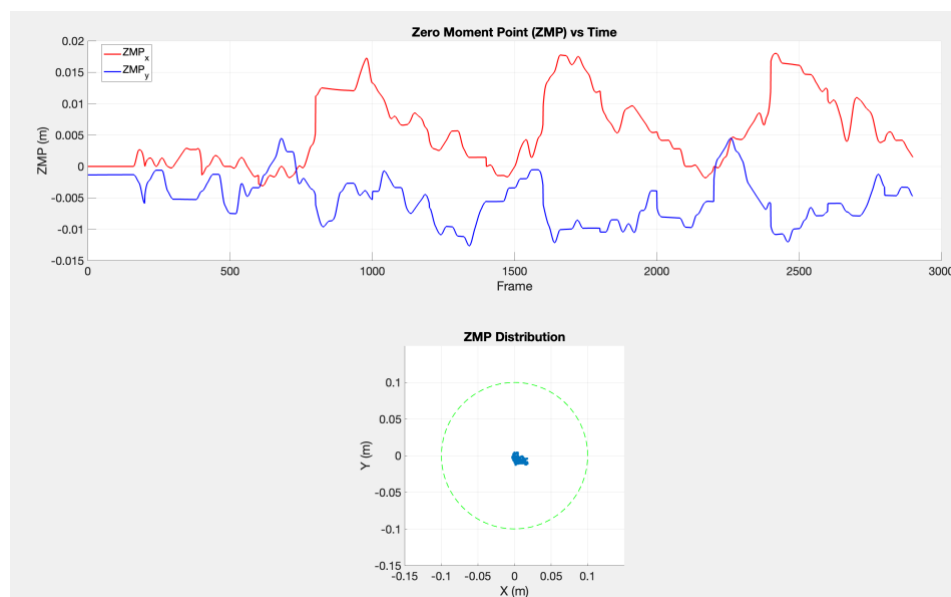


Figure 9 Trial 15 example data of Zero Moment Point in x and y plane

7 Conclusions

This project developed and tested a dual-lever rowing ergometer incorporating a Chebyshev “Lambda” linkage, aimed at improving and possibly accelerating the rehabilitation of trunk stability and coordinated muscle control in SCI. The novel ergometer design enabled near-linear horizontal handle motion. This contrasts to a simple lever rower with abnormal arc rowing motion and more closely follows the motion of the oar handles on-water. The system also facilitates full sagittal plane trunk motion, which may improve the biomechanical efficiency of current FES rowing styles. Presently, these are characterised by short stroke length and high stroke rate rowing that is regarded as biomechanically inefficient.

Experimental trials using motion capture, load cells, and EMG analysis demonstrated that the Trunk Stability Score (TSS) effectively quantifies postural control, with Trial 15 results showing a TSS of 0.7544 and zero time spent outside the stability zone. EMG analysis confirmed distinct muscle activation patterns, aligning with expected rowing biomechanics, further suggesting that the ergometer may be effective in upper-body and postural training in SCI.

Despite these results, several limitations were identified. The TSS weighting coefficients (α and β) were determined empirically and require further refinement using regression-based optimisation. Force sensor accuracy impacted ML force readings, suggesting the need for higher-precision load cells. The study was conducted on an able-bodied participant, and further trials with SCI patients are necessary to assess clinical relevance.

These findings support the potential of the dual-lever ergometer for SCI rehabilitation, offering a quantifiable and structured approach to postural stability training.

Future work should focus on expanding participant trials, refining sensor accuracy, and integrating real-time feedback mechanisms to enhance usability in rehabilitation and performance training settings. In the development of the ergometer system, we anticipate the integration of FES to further enhance the training, particularly in tetraplegics undergoing muscle and nerve transfer reconstructive surgery. Later development includes also gamifying the interface and conducting tests on SCI patients.

8 References

- [1] R. L. Lambach et al., "Bone changes in the lower limbs from participation in an FES rowing exercise program," *J Spinal Cord Med*, 2018.
- [2] Concept2, "Concept2 RowErg." [Online]. Available: concept2.com
- [3] R. S. Gibbons et al., "FES-rowing in tetraplegia: a preliminary report," *Spinal Cord*, vol. 52, 2014, doi: 10.1038/sc.2014.159.
- [4] A. E. Draghici et al., "Assessing kinematics and kinetics of FES rowing," *J Biomech*, vol. 53, 2017, doi: 10.1016/j.jbiomech.2017.01.007.
- [5] K. Schwartzkopf-Phifer et al., "Comparison of intervention programs to improve trunk stability," *Int J Sports Phys Ther*, vol. 18, 2023, doi: 10.26603/001c.89667.
- [6] G. van Oort and S. Stramigioli, "Geometric interpretation of the Zero-Moment Point," *ICRA*, 2011, doi: 10.1109/icra.2011.5980133.
- [7] I. Danilov et al., "ZMP trajectory from human body locomotion dynamics," *Proc. Joint Conf. on Computer Vision, Imaging, and Graphics*, 2016, doi: 10.5220/0005726001600166.
- [8] H. A. M. Seelen et al., "Development of new muscle synergies in postural control," *J Electromyogr Kinesiol*, vol. 8, 1998, doi: 10.1016/s1050-6411(97)00002-3.
- [9] N. van Zyl et al., "Expanding tendon-based techniques with nerve transfers for upper limb function," *The Lancet*, 2019, doi: 10.1016/s0140-6736(19)31143-2.
- [10] S. Koch-Borner et al., "Rehabilitation after posterior deltoid to triceps transfer," *Arch Phys Med Rehabil*, vol. 97, 2016, doi: 10.1016/j.apmr.2016.01.037.
- [11] J. H. Jeong et al., "Posterior deltoid-to-triceps tendon transfer: A case report," *Ann Rehabil Med*, vol. 40, 2016, doi: 10.5535/arm.2016.40.2.351.
- [12] T. Clark et al., "A novel lever-actuated design proposal for FES rowing ergometers," 2024.
- [13] B. Tessedorf et al., "An IMU-based sensor network for rowing technique," *Proc. ISSNIP*, 2011, pp. 253–258.
- [14] Wikipedia contributors, "Chebyshev lambda linkage." [Online]. Available: [Wikipedia](https://en.wikipedia.org/wiki/Chebyshev_lambda_linkage)
- [15] H. J. Hermens and B. Freriks, "SENIAM." [Online]. Available: seniam.org
- [16] J. M. Maciukiewicz et al., "Influence of posture variation on EMG signals," *J Electromyogr Kinesiol*, vol. 62, 2022, doi: 10.1016/j.jelekin.2019.05.020.