FATIGUE LEADS TO ALTERED SPINAL KINEMATICS DURING HIGH PERFORMANCE ERGOMETER ROWING

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Low back injuries in rowing are attributed to intense, repetitive, loading through the spine. Good technique and postural control are essential to maximize performance and minimize injury risk. This motion capture study recorded 3D spinal kinematics of 14 athletes during rowing at varying speeds on an instrumented ergometer and correlated motion with power metrics and athlete demographics. Sagittal plane rotation decreases in the lumbar spine and increases in the thoracic spine as speed increases. Transverse and frontal planes have little influence on force output. Declining postural control can be seen within each trial and worsened with higher rate. Assessments of form differences across athletes using relative motion between spine segments at critical stroke points show greater lumbar flexion (compared to thoracic) at the catch and neutral alignment at max handle force.

KEYWORDS: Rowing, ergometer, spine, lower-back, lumbar, thoracic, fatigue, kinematics

INTRODUCTION: Low back pain is the most commonly reported injury amongst rowers (Smoljanovic et al., 2009; Wilson, Gissane, Gormley, & Simms, 2010); this has been attributed to high training volumes on the ergometer, technique, and compressive forces on the spine. The four spinal curves - cervical, thoracic, lumbar and sacral – are optimized for high flexibility and compressive strength. However, when loaded inappropriately, as in rowing where the back acts as a brace to transmit large load from the legs to the handle, the back is more susceptible to injury (Reid & McNair, 2000). It has been suggested that the spine should be flexed as much as 45° to maximize force generation (Nilsen, Daigneault, & Smith, 2002), however, this creates large bending moments in the vertebrae, which with high repetition, muscle fatigue, and deterioration in posture, increases back injury risk. Spine kinematics during rowing have been quantified by simple metrics including lumbo-pelvic and lumbo-thoracic rotation in the sagittal plane (McGregor, Patankar, & Bull, 2007) and inverse dynamics estimates compressive forces are 4.6 times body mass (Morris, Smith, Payne, Galloway, & Wark, 2000). Prior research has largely been limited to sagittal plane mechanics as the most prominent affecter, but out of plane asymmetries can contribute to decreased efficiency and spinal injury. The goal of this study was to measure three-dimensional spinal kinematics through the rowing stroke, observe effects of a fatiguing task on biomechanics, examine intersegmental differences at critical stroke points, and correlate motion with power metrics and athlete demographics.

METHODS: Fourteen healthy volunteers participated (6 female/8 male; height: 182.6±11.7 cm; mass: 79.8±13.6 kg; age: 26.7±5.5 years). All subjects were active rowers at the time of the study. Imperial College research ethics committee granted approval and written informed consent was obtained from each participant.
Twenty-two 14mm reflective marker clusters located at C7/T1, T6/T7, T12/L1, L5/S1, and 6 pelvis markers, created four spinal segments: upper thoracic, lower thoracic, lumbar, and sacrum. A 10-camera optical motion capture system (Vicon, UK) recorded athlete kinematics at 100Hz during a fatiguing task comprising four, 3-minute rowing trials at increasing rate (18/24/28/32 strokes per minute, spm; 2-3min rest intervals) on an instrumented ergometer (Concept 2, VT, USA). Load cells at the handle, seat, and footplates, and a rotary encoder on the flywheel captured kinetics at 1000Hz. Synchronized motion data and external force data were processed with a 4th order Butterworth low-pass filter in MATLAB (MathWorks, MA, USA). Each rowing trial was divided into individual strokes where the *catch* was the minimum sagittal handle position and the *finish* was defined as maximum handle displacement. Each stroke was time normalized from 0-100% of completion using a cubic spline interpolation, such that *drive* time was from *catch* (0%) to *finish*, and *recovery* time was from *finish* to a subsequent *catch* (100%). Time normalization allowed for comparison across rates and between athletes. Spinal segment angles were calculated using a Z-Y-Z Euler sequence. $\boldsymbol{\alpha}$ is the angle of flexion/extension in the sagittal plane. $\boldsymbol{\beta}$ is the angle of lateral bending in the frontal plane and $\boldsymbol{\gamma}$ is the angle of rotation in the transverse plane. Sagittal plane lumbar-pelvic and lumbar-

thoracic ratios were calculated at each frame by dividing the ***α*** angle of the upper segment by the ***α*** angle of the lower segment (McGregor et al., 2007). To examine the effect of the fatiguing protocol on postural control, flexion/extension at the *catch* was correlated with stroke number within each trial and between rates. Statistics included repeated measures ANOVA and Pearson correlation (*ccoeff*).

RESULTS: Mean *α* angles for the lumbar, thoracic, and sacrum follow similar patterns through the stroke with maximum flexion at the *catch* and maximum extension at the *finish*, with slight increases in both as rate increased (Figure 1). When *max handle force* (*MHF*) is achieved, pelvic and lumbar angles are near zero, indicating that the lower spine is nearly vertically aligned when loading is at its highest. Patterns in lateral bending (β) and spinal torsion (ϒ) show small angular variation through the stroke and no statistically significant changes with rate. Large standard deviations suggest that bending and torsion are dependent more upon the individual athlete, particularly when close to the *finish* position.

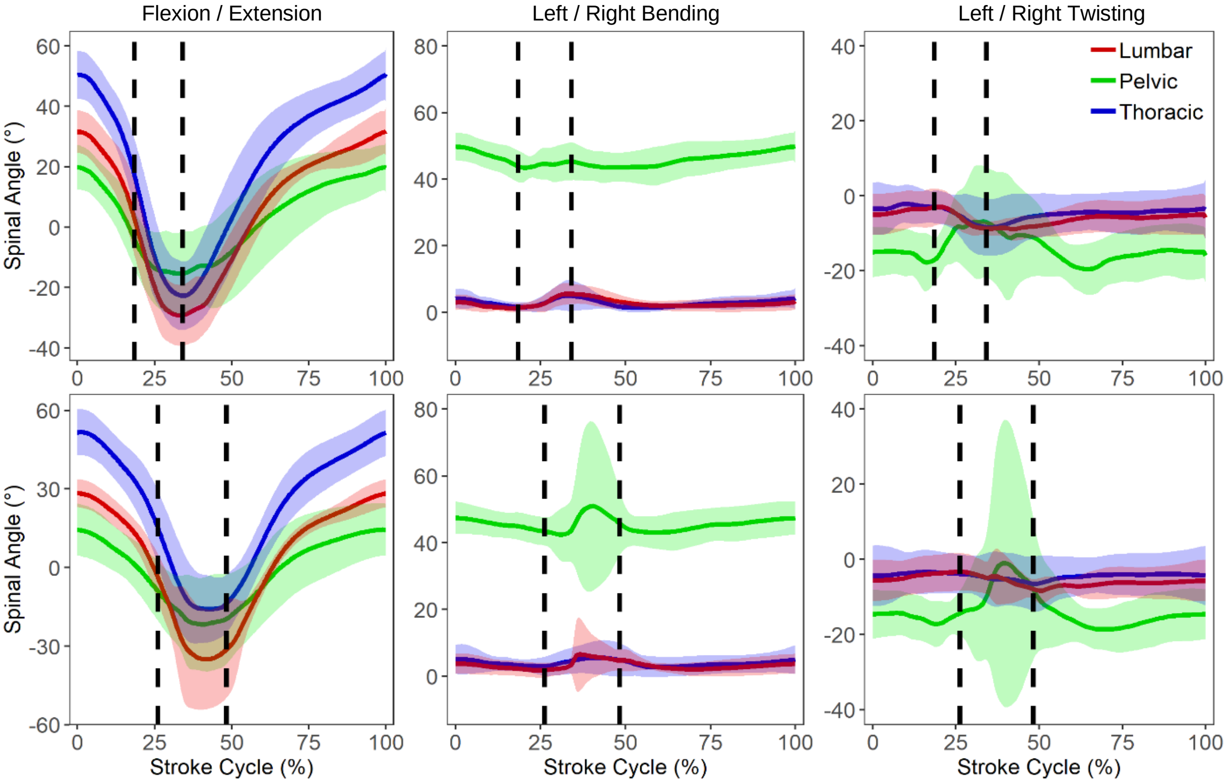

Figure 1: Spinal segment angles (mean ± std) through the stroke at lowest rate, 18spm (top row) and highest rate, 32spm (bottom row). Vertical dashed lines indicate timing of *MHF* and *finish*.

Ratios of angle change provide a concise way of quantifying relative movement between spinal segments. Overall, the lumbo-thoracic ratio is lower than the lumbo-pelvic ratio, potentially because the thorax remains straighter compared to the lumbar spine (Figure 2). At the *catch*, as intensity increases lumbo-pelvic ratio increases and lumbo-thoracic ratio decreases ($p<0.01$). At the *finish*, both lumbo-pelvic and lumbo-thoracic ratios are lower than at the *catch* ($p<0.001$), indicating that lumbar rotation is increased compared to pelvic rotation and thoracic rotation is increased compared to lumbar rotation (Figure 2). Large standard deviations at *MHF* and *finish* may be attributed to variation in athlete demographics, particularly '*sidedness*'. There were no statistically significant patterns seen in lateral bending or in spinal torsion for either change in rowing intensity or position during the rowing stroke.

Mean flexion/extension angle at the *catch*, which may be a surrogate for postural control, changed for all segments between low and high rate ($p<0.01$) and was correlated with stroke number within trial. Subjects were more capable of maintaining the same *catch* angle at low rate, compared to high rate (Figure 3). At 18spm, thoracic, lumbar, and pelvic segment *catch* angles increased slightly (0.031°, 0.014°, 0.008° per stroke, respectively [*ccoeff* = 0.89, 0.66, 0.41]) while at 32spm lumbar and pelvic *catch* angles decreased substantially (-0.073°, -0.093°

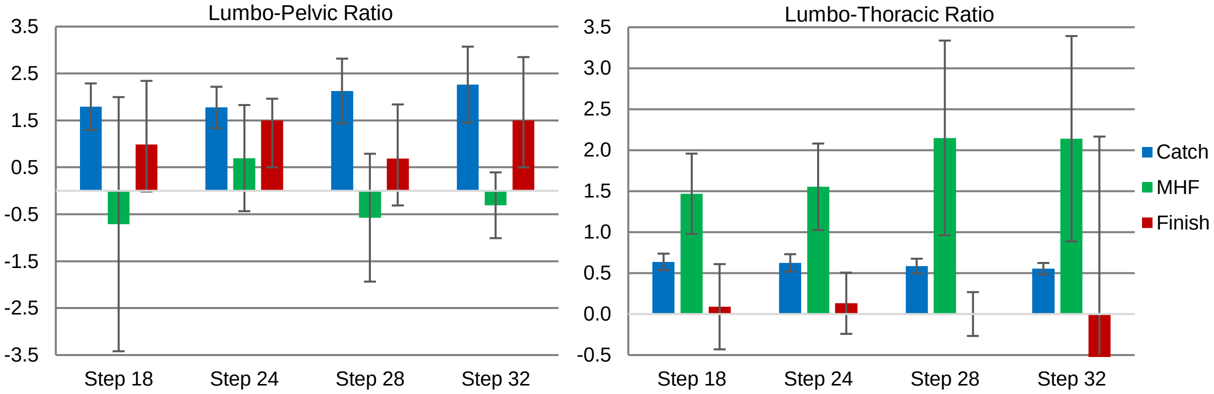

Figure 2: Lumbo-pelvic (left) and lumbo-thoracic (right) ratios at *catch, MFH* and *finish* positions (mean ± std). Step rates are in strokes per minute (spm).

per stroke [*ccoeff* = -0.95, -0.94]). Thoracic angle showed little change at 32spm, decreasing only -0.024° per stroke (*ccoeff* = -0.61).

Athlete '*sided-ness'* - where subjects were grouped by preferred rowing type (scull, starboard sweep, or port sweep) - showed a trend for the sculling group to display less lateral bending or transverse twisting kinematics than either sweeping cohort, particularly at the level of the thoracic spine (Figure 4). However, due to small sample size per cohort (*n=4-5*), no statistical differences were found. Including additional athletes in the future should improve study power to help delineate bilateral asymmetries arising from *'sided-ness'*.

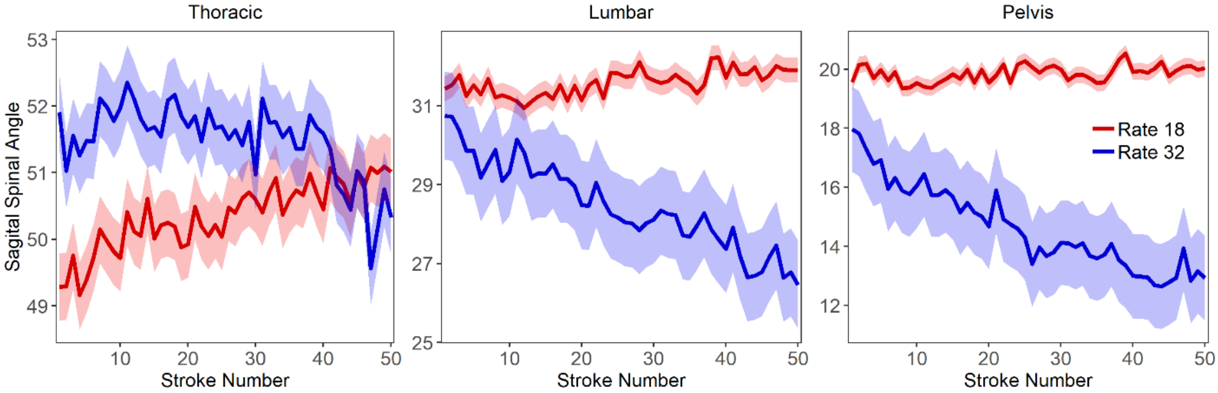

Figure 3: Fatigue effects sagittal plane postural control at the *catch,* even over relatively short pieces. Rate of postural change accelerated at high rate compared to low rate.

DISCUSSION: The *catch*, *finish*, and *MHF* each represent vulnerable positions in the stroke. Similar to literature, our study found anterior pelvic tilt decreased at the *catch* at higher rate and will impact lumbar-pelvic flexion (McGregor, Bull, & Byng-Maddick, 2004). Our study showed little change in lateral bending and torsion either within or between rate, in contrast to Wilson (2010) who found frontal plane lumbar angulation increased 4.1±1.9° with rate during a similar step test protocol.

Rowers achieve '*stroke length'* through a combination of lumbar, thoracic, and pelvic rotation and whole spine kinematics change with prolonged effort. Increasing thoracic angle with rate suggest declining postural control and adoption of a slumped position of the upper spine during this fatiguing task. Lorbergs et al. (2017) suggested that kyphosis of the thoracic spine can negatively impact lung function and rib cage mobility. Results suggest that straight or neutral alignment it is important during *MHF*, the point at which spinal load is highest, for efficient load transfer and stability.

Reid & McNair, (2000) note that lumbar muscular fatigue can affect proprioception, so visualizing sagittal plane postural decline allows athletes to gauge how they are effected by perceived fatigue and its implications on performance over time. As negative changes in lumbar-pelvic kinematics and reductions in range of motion have been connected to low back pain, this has important implications in spinal health. Rowing injury epidemiology studies do

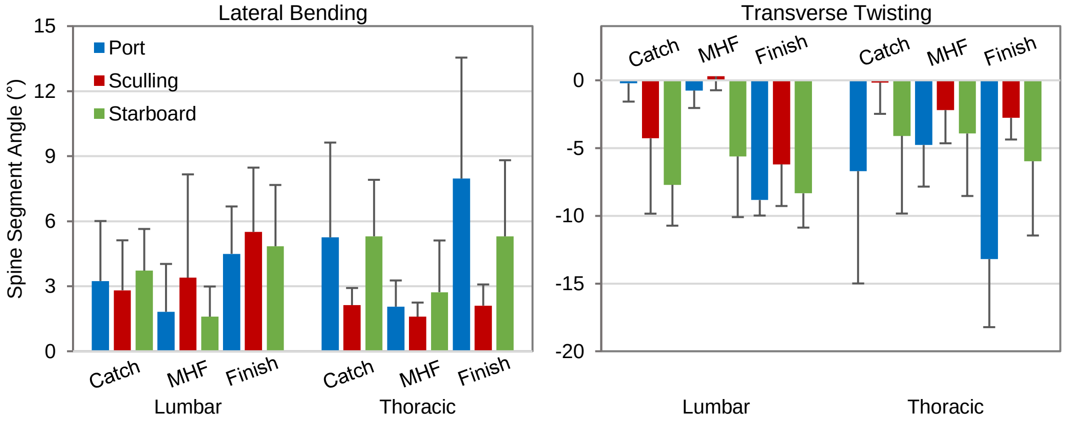

Figure 4: Differences in lumbar and thoracic segment angles (mean ± std) in lateral bending (left) and spinal torsion (right) for each style / class of rowing category.

not concur if spine injuries are more common in sweep rowers but our study suggests that scullers are less prone to postural changes in frontal and transverse planes.

Effects of asymmetries and athlete demographics should be investigated further and to elicit a full fatigue response a longer test is recommended, as previous research has shown the reaching of a plateau in postural decline (Mackenzie, Bull, & McGregor, 2008).

CONCLUSION: Results from this study highlight the spatiotemporal relationship between key stroke metrics and spinal kinematics. Providing an accurate representation of spinal movement in all planes is important for understanding what an optimized rowing technique looks like. Such bio-feedback allows athletes and coaches to visualize how the entire spine is moving through every stroke and enables rowing form to be analyzed during standard physiological adaptation tests. Incorporating kinematics into training may help athletes engrain beneficial posture control and achieve specific performance outputs, so that athletes can row more effectively and using a technique that minimizes the risk of potential spinal injury.

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