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Sagittal plane motion of the lumbar spine during ergometer and single scull rowing

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Abstract
Lumbar spine injury in rowers is common and ergometer rowing has been cited as a risk factor for this injury. The purpose of this study is to compare lumbar kinematics between ergometer and single scull rowing and to examine the effect of fatigue on kinematics. The sagittal lumbar spine motion of 19 elite male rowers (lumbar spine injury free in the previous six months) was measured with an electrogoniometer during a 'step test' on an ergometer and in a single sculling boat. Maximum range of lumbar flexion was recorded in standing for reference. Power output and heart rate were recorded during the ergometer tests. Heart rate was used as a surrogate for power output in the sculling test. Maximum lumbar flexion increased during the step test and was significantly greater on the ergometer ($4.4° \pm 0.9°$change), compared with the boat ($+1.3° \pm 1.1°$change), ($3.1°$difference, $p = 0.035$). Compared to the voluntary range of motion, there is an increase of 11.3% (ergometer) and 4.1% (boat). Lumbar spine flexion increases significantly during the course of an ergometer trial while changes in a sculling boat were minimal. Such differences may contribute to the recent findings linking ergometer use to lower-back injury.

Keywords: *Injury, fatigue, kinematics, electrogoniometer, power output*

Introduction

Rowers spend a lot of time in training, and international rowers frequently train two to three times daily during the months of winter (Wilson et al., 2010). Rowing is an activity that involves cyclical flexion and loading of the lumbar spine that may occur hundreds of times over a training session either on the water or on an ergometer. The rowing stroke may be divided into two phases: the drive and the recovery. The drive is the main work phase of the stroke and includes the 'catch' when the oar enters the water and the rower applies force. At the catch, the rower's lumbar spine is fully flexed at the point of oar entry to the water (Caldwell et al., 2003). The end of the stroke is called 'the finish', when the rower withdraws the oar from the water at the end of the drive phase, bringing their lumbar spine from a fully flexed position to a relatively extended position (Pollock et al., 2009). Rowing is divided into

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'sweep oar' rowing (one oar each) and 'sculling' (two oars each). Thus, sweep oar rowing requires some asymmetrical movement of the trunk.

Rowers will continue a training session to the point of fatigue on a regular basis. Cyclical lumbar flexion, particularly when combined with fatigue, may alter joint mechanics and loading patterns of the lumbar spine, leading to risk of tissue failure and resulting injury (Dolan & Adams, 1998; Caldwell et al., 2003; Holt et al., 2003; Parkinson et al., 2004; Mackenzie et al., 2008).

Lumbar spine injury has been reported to be the most common injury to rowers (Budgett & Fuller, 1989; Teitz et al., 2002; Teitz et al., 2003; Smoljanovic et al., 2009; Wilson et al., 2010), but the mechanisms that lead to this injury are not well understood. Rowing requires a large amount of lumbar flexion (Caldwell et al., 2003), which is regarded as a major risk factor for injury (Reid & McNair, 2000). Furthermore, it has been hypothesised that the mechanics of the rowing stroke generates forces as large as 2694 N (compressive) and 660 N (shear) in an already flexed lumbar spine (Morris et al., 2000) increasing risk of tissue failure.

In a prospective study of injury, Wilson et al. (2010) noted that increase in time spent in ergometer training was significantly associated with risk of lumbar spine injury and Teitz et al. (2002) showed that ergometer sessions longer than 30 min were a significant predictor of lumbar spine injury. Although other associations have been made between lumbar spine injury and volume of weight training (Budgett & Fuller, 1989; Reid et al., 1989; Coburn & Wajswelner, 1993) as well as between lumbar spine injury and general volume of training (more than seven sessions/week) (Smoljanovic et al., 2009), neither of these factors has been established as significant predictors of lumbar spine injury.

Analysis of lumbar spine motion while rowing on an ergometer has demonstrated that rowers achieve high levels of lumbar flexion during the rowing stroke and that these levels increase during the course of a rowing trial (Caldwell et al., 2003; Holt et al., 2003). However, examination of joint kinematics while the rower is in a boat on the water has been limited to video analysis of multiple body segments (Lamb, 1989), thus on-water comparisons were previously deemed impossible (Steer et al., 2006). As (to date) ergometer training has been identified as the only significant predictor of lumbar spine injury in rowers, it is likely that there are a number of biomechanical, physiological, and psychological factors that differ between boat and ergometer training. As a starting point, it is pertinent to identify if lumbar kinematics differ in these two conditions.

The primary aim of this study is, therefore, to compare sagittal motion of the lumbar spine in rowers on a rowing ergometer and in a single sculling boat, making a comparison with maximum voluntary lumbar flexion as a point of reference. The secondary aim of this study is to examine the effect of fatigue on sagittal plane motion of the mid-lumbar spine. It was hypothesised that the sagittal kinematics of the lumbar spine in rowing would be influenced by rowing mode (ergometer vs. sculling boat) and fatigue.

Methods

Participants

Permission to conduct this study was granted by the Trinity College, Faculty of Health Sciences Research Ethics Committee. All the members of the senior sculling squads of rowing clubs in Dublin were invited to participate in this study. Inclusion criteria were: Over the age of 18 years; rowing at 'Senior' level for at least one year; not presently injured. Rowers who had a lower-back injury in the past six months were excluded. A total of 19 elite male rowers completed this study. The mean age, mass, height, and rowing experience of the participants were 24.2 ± 3.7 years, 82.5 ± 8.4 kg, 1.88 ± 0.05 m, and 6.7 ± 3.5 years, respectively. One subject was a lightweight rower (under 72.5 kg) and the rest were heavyweight rowers (over 72.5 kg).

Instrumentation

Sagittal motion of the lumbar spine was measured using a flexible, twin axis, SG150B electrogoniometer (Biometrics Ltd., Gwent, UK) connected to a data logger system (Biometrics DataLog P3X8). The electrogoniometer was selected as it was the only instrument available that allowed motion analysis both in the field (in a boat, on the water) and in a laboratory setting (ergometer). Previous studies have analysed lumbar spine motion in rowers in a laboratory setting only, with equipment which cannot be used in a boat due to its nature and size (Bull & McGregor, 2000; McGregor et al., 2002; McGregor et al., 2005; Pollock et al., 2009; Strahan et al., 2011).

Reliability and validity of the electrogoniometer

The electrogoniometer used in this study has shown good reliability (Shiratsu & Coury, 2003; Piriyaprasarth et al., 2008) and validity (Shiratsu & Coury, 2003) in previous studies. Prior to the study, the electrogoniometer was verified against a Universal Goniometer (Baseline Diagnostic and Measuring Instruments, EMS, Wantage, UK). The two end blocks of the electrogoniometer were taped to the two arms of the Universal Goniometer that was set at the 0°/180° position and connected to the Biometrics DataLog. The Universal Goniometer was moved from 0° to 90°, stopping for 10 s at each 10° increment until 90° was reached. This procedure was repeated three times. Readings of the Universal Goniometer were compared with the corresponding reading on the electrogoniometer. The results of the three verification trials were analysed with a one-way ANOVA and the residual mean square was used to calculate the variation in score that will occur 95% of the time according to Bland and Altman (1995). The results of this analysis showed that the magnitude of error will be 0.45° throughout all readings. Thus, the verification study showed that the electrogoniometer was suitable for measuring range of motion with an inherent error of 0.45°.

The electrogoniometer when attached to the skin only covered two joints (three vertebrae); thus, the mid-lumbar spine was chosen as this is the area where the greatest degree of sagittal flexion is observed (Bogduk, 2005; Li et al., 2009). The upper electrogoniometer end block was placed over the spinous process of L2 and the lower end block was placed over the spinous process of L4. Prior to applying the electrogoniometer, the skin was sprayed with 'Tuf-Skin' (Cramer Products Inc., Gardner, KS, USA) to reduce slippage of the blocks. The blocks were placed while the participant was standing, and were secured with a double-sided tape. Marks were made with a black permanent pen at the top and bottom of the blocks, to indicate if movement relative to the skin occurred during the test. The DataLog box was placed in a small backpack on the participant's upper back. Figure 1 shows the equipment in situ before testing began. Prior to the test, the participant stood upright, with feet apart at shoulder width. This stance was selected as the zero position of the lumbar spine and the electrogoniometer was set at 0°. All angular displacement recordings were made relative to this zero position.

Experimental protocol

To provide a reference level for the physiological range of motion for the L2–L4 portion of the lumbar spine, the maximum voluntary range of motion of each of the participants was

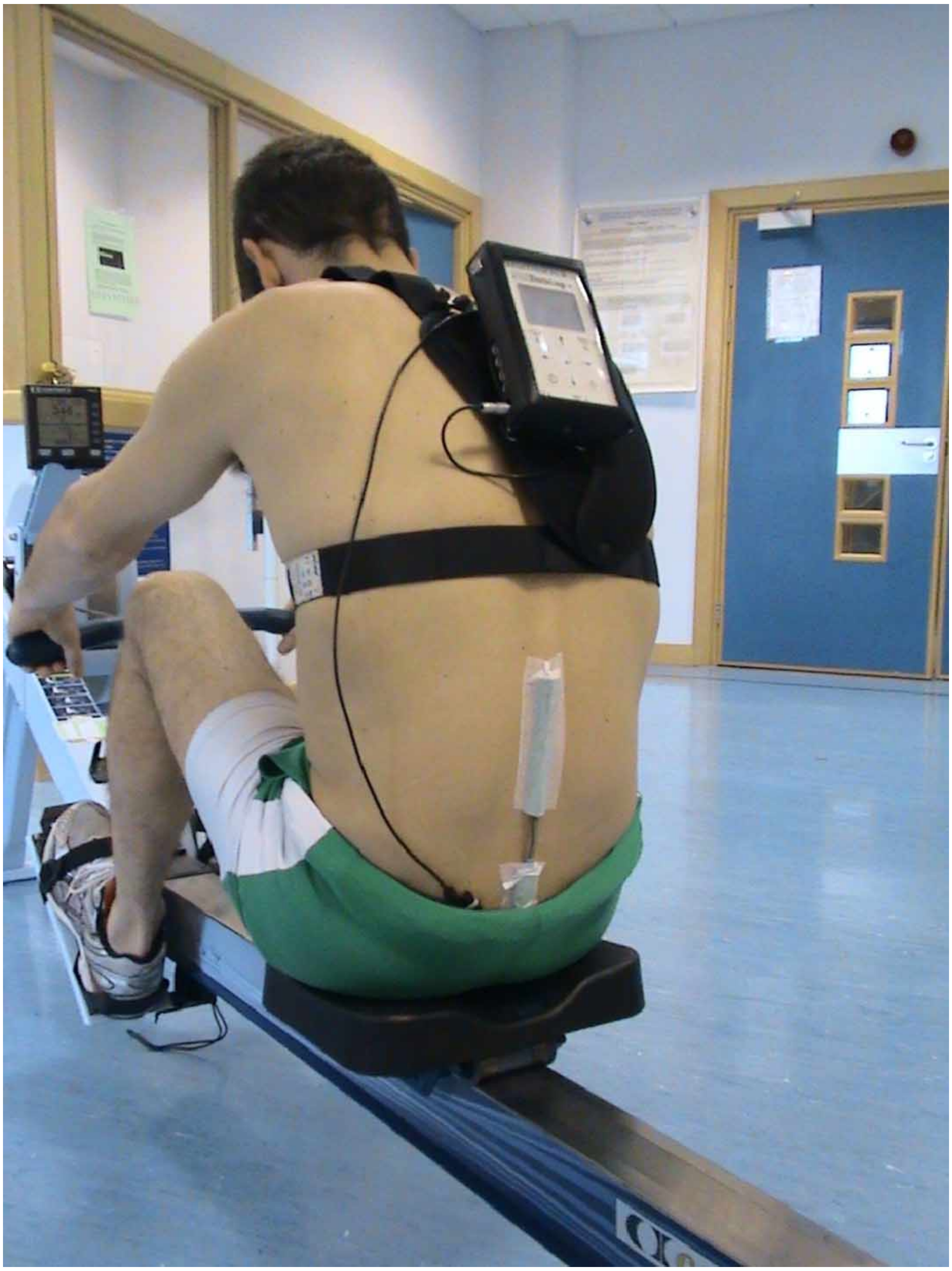

Figure 1. Electrogoniometer and DataLog in situ prior to ergometer testing.

recorded. While in a standing position and prior to warm-up, the participants fully flexed the lumbar spine by bending forwards to touch their toes, while maintaining the knees in an extended position, and the full angular range of lumbar flexion (peak standing flexion) was recorded. This was repeated three times and the mean value was established.

The testing protocol was a physiological multi-stage fitness test or 'step test' as described by Mahony et al. (1999). The test was preceded in each case by a 5 min warm-up period of rowing at 'light pressure'. Each rower started at an initial power output of 160 W and rowed for 3 min at a fixed stroke rate increasing every 3 min in 40-W increments until exhaustion. The damper or resistance setting of the ergometer was set at level 4. A rest period of 1 min was taken between each incremental increase. Exhaustion (as a result of increasing fatigue) was defined as the inability to maintain power output or stroke rate for the whole of the step. If the rower was unable to complete five consecutive strokes at the required stroke rate and/or power output, they were requested to stop. The first step was rowed at a rate of 18 strokes/min with subsequent steps increasing to a maximum of 30 strokes/min with increments of 2 strokes per step taken. Heart rate was measured by short-range telemetry (Polar Electro, Kempele, Finland). Testing was carried out initially on a Concept 2 model C rowing ergometer (Concept Inc., Shelburne, VA, USA). Tests were carried out by all participants in the same stage of an identical training cycle and at the same time of day (late afternoon).

The step test was then repeated for each individual in their own single sculling boat for one week following the ergometer test, and at the same time of day. All sculling boats complied with the racing specifications of the world international rowing body, Federation Internationale des Societes d'Aviron, and had similar rig and setup (the same oar span with foot position adjusted by participants for individual comfort). All tests were carried out on the same stretch of a river in the same direction to reduce effects of a flowing tide. Wind speed was measured using a Kestrel 1000 (Nielsen-Kellerman, Boothway, PA, USA) to ensure that wind speed was less than 10 k/h (2.78 m/s) during all tests. As power output could not be measured in a sculling boat, the test was carried out with the same time intervals and stroke rates as for the ergometer test, but the subjects were asked to increase their power output so that their heart rates reached those levels reached for each step on the ergometer. Heart rate has shown significant correlation with work load between ergometer and boat rowing (Urhausen et al., 1993; Hofmann et al., 2007). The heart rates had been recorded for each step on the ergometer and were placed on a waterproof chart on the front deck of the sculling boat for the athlete to refer to during each step. Heart rate, stroke rate, and interval time were monitored in the boat using a Speedcoach XL1 (Nielsen-Kellerman, Boothway, PA, USA).

The electrogoniometer recorded motion as described above for the ergometer test. Thus, the boat tests used the same stroke rates, time intervals, and exercise intensity as the ergometer tests. Heart rates were used as a surrogate measure for power output in the boat to ensure that the work effort was the same as for the ergometer test.

At the end of each test, the position of the pen marks at the top and bottom of the electrogoniometer end blocks were checked to ensure that no slippage had occurred. Any observable movement of the end blocks of the electrogoniometer during the test was declared as an invalid test and not included in the results (this only occurred once).

Data analysis

The Biometrics DataLog recorded sagittal plane angle changes over the period of the test for each rower. Data was downloaded into Microsoft Excel and subdivided into 3-min increments, reflecting the 3 min time period over which the work effort of the participants was held constant. The maximum flexion values of the lumbar spine were extracted and average values for the whole of each 3-min interval were established. This was repeated for the minimum flexion values. These were defined as the '*maximum flexion angle*' and the '*minimum flexion angle*' for each interval, respectively. The '*lumbar flexion range*' within each 3-min interval was then calculated as the difference between the maximum flexion angle and the minimum flexion angle. For each step, all motion cycles were read and the mean values were calculated. For example, in the first step where the rate was 18 strokes/min, a total of

54 (18 × 3) cycles were read and the mean of 54 values was calculated. Values are reported as the mean for all participants ($N = 19$).

Statistical analysis

Statistical analysis was performed using SPSS v 16. Changes in the maximum flexion angle, minimum flexion angle, and lumbar flexion range between the first and last steps of the protocol were analysed for each rower, using a two-way paired *t*-test for each rowing condition (boat or ergometer) separately in the first instance. To compare findings between the boat and ergometer, the *change* in angles between the first and last step for each rowing condition were calculated for each parameter and a comparison of the mean change scores was performed using a paired *t*-test. Absolute values were not compared between the two rowing conditions, as the starting points may have been different. The mean number of incremental steps completed by each rower was 6.7 ± 0.7 (range = 5–8 steps) steps. The last step that the rower completed fully was analysed as the 'last step'. The first and last steps were compared to represent the pre-fatigued and fatigued states, respectively. The statistical threshold was set at $p < 0.05$.

The maximum flexion angles measured during the last step of the ergometer and the boat test were compared to the peak standing flexion (measured before each test) of each participant. Results were analysed separately for each condition using a paired *t*-test.

Results

Rowers reached larger ranges of sagittal lumbar flexion than the full standing flexion by the final step of the test in both ergometer and boat rowing (Table I). Ergometer rowing resulted in larger sagittal flexion increase from the full standing flexion than the boat rowing ($p = 0.014$) (Table I).

There were significant increases in both lumbar flexion range ($p = 0.003$) and maximum flexion angle ($p = 0.001$) from the first to the last step (Table II) in ergometer rowing. The change in the minimum flexion angle in ergometer rowing was not significant ($p > 0.05$). No significant change from the first to the last step in lumbar flexion range, maximum flexion angle, or minimum flexion angle was observed in the boat test (Table II).

The ergometer rowing condition was characterised by significantly larger increases in lumbar flexion range ($p = 0.029$) and maximum lumbar flexion angle ($p = 0.035$) when compared to the boat rowing condition (Table II). The decrease in minimum lumbar flexion angle was not significantly different between the rowing conditions.

Table I. Maximum lumbar flexion before (pre-test) and following ergometer and boat test.

	Ergometer	Boat	Ergometer vs. boat
Peak standing flexion angle	49.0° ± 7.2° (39.0°–65.0°)	50.1° ± 7.2° (38.9°–62.0°)	
Mean max flexion angle (last step)	54.3° ± 9.4° (35.8°–75.9°)	52.1° ± 8.5° (36.4°–67.1°)	
Change*	5.3° ± 7.1° (11.3% ± 5.2%) 95% CI = 10.5%–18.2% $p = 0.004$	2.0° ± 4.8° (4.1% ± 0.2%) 95% CI = 0.9%–1.1% $p = 0.081$	3.3° ± 5.3° 95% CI = 0.7°–5.9° $t = 2.71$ ($p = 0.014$)

Note: Data are in $M \pm SD$ (range).
*Difference between peak standing flexion angle (pre-test) and mean maximum flexion angle during last step.

Table II. Comparison of kinematic data between ergometer and boat rowing for the first and last steps of the test.

	Ergometer			Boat			
	First step	Last step	Change	First step	Last step	Change	Ergometer vs. Boat
Flexion range	18.9° ± 6.1° (11.3°–33.3°)	23.6° ± 5.3° (13.1°–35.3°)	4.7° ± 5.9° 95% CI = 1.8°–7.6° $t = 3.45$ ($p = 0.003$)	17.6° ± 3.9° (9.8°–241.0°)	18.9° ± 4.3° (9.0°–25.7°)	1.3° ± 3.1° 95% CI = -0.1°–2.8° $t = 1.93$ ($p = 0.069$)	4.7° vs. 1.3 95% CI = 0.4°–6.4° $t = 2.38$ ($p = 0.029$)
Max flexion angle	49.9° ± 8.2° (28.4°–63.9°)	54.3° ± 9.4° (35.8–75.9°)	4.4° ± 3.7 95% CI = 2.6°–6.2° $t = 5.20$ ($p = 0.001$)	50.8° ± 6.8° (36.2°–65.4°)	52.1° ± 8.5° (36.4°–67.1°)	1.3° ± 4.5 95% CI = -0.9°–3.5° $t = -1.26$ ($p = 0.223$)	4.4° vs. 1.3 95% CI = 0.3°–5.9° $t = 2.28$ ($p = 0.035$)
Min flexion angle	31.0° ± 8.9° (13.7°–47.9°)	30.7° ± 9.0° (12.9°–48.3°)	-0.3° ± 6.6 95% CI = -2.9°–3.4° $t = 0.20$ ($p = 0.860$)	33.2° ± 6.9° (15.8°–42.4°)	33.1° ± 7.4° (18.3°–43.3°)	(0.1° ± 3.1 95% CI = -1.4°–1.6° $t = 0.10$ ($p = 0.925$)	-0.3° vs. -0.1 95% CI = -3.5°–3.1° $t = -1.8$ ($p = 0.860$)

Note: Data are in $M \pm SD$ (range).

Discussion and implications

This study showed that the peak standing flexion of the lumbar spine was higher in both ergometer and boat rowing at the end of the test compared to pre-test when it was measured in standing. However, it was significantly greater after the ergometer tests compared to the boat tests. Of note is that in both cases, most individuals reached peak lumbar flexion values that were higher than those seen in full standing flexion (68% of participants in the ergometer test and 63% in the boat test). The high levels of lumbar flexion recorded are in agreement with previous studies (Caldwell et al., 2003; Holt et al., 2003), although values of only 89% of peak standing flexion were reported by Caldwell et al. In the current study, mean values were in excess of 100% of pre-test standing flexion (their maximum voluntary flexion). These findings were not due to slippage of the end blocks. It should be noted that standing flexion required participants to maintain extended knees, while maximum flexion during rowing would have knees fully flexed reducing hamstring length limitations. Also, it is likely the fact that the equipment was examining multiple segments using skin placement means that the range of movement is likely to have been over estimated due to skin distraction (Burnett et al., 2008), which may also explain why the findings appear higher than previous studies that examined kinematics using traditional laboratory-based motion analysis equipment (Caldwell et al., 2003; Holt et al., 2003). Peak standing flexion is a static activity and it is likely that the momentum of the rowing stroke may have also contributed to the range of motion during activity being greater than that statically. Reid (2002) found when using the sit and reach test as baseline, rowers reached lumbar flexion values of 102% which, Reid argued, may have been influenced by the momentum of the rower moving into the catch position. Despite this, the results indicate that rowers achieve very high values of lumbar spine flexion.

When motion of the lumbar spine was measured during the ergometer test, there were two statistically significant findings. Both the maximum flexion angle and the lumbar flexion range increased during the test. The increase in range is explained by the fact that there was an increase in lumbar flexion over time, but the spine returned to the same point of minimum flexion at the start of each stroke cycle. Thus, as the rowers fatigued, their lumbar spines became more flexed in the sagittal plane. This is similar to previous studies that examined sagittal kinematics of the lumbar spine during a fatiguing rowing protocol, and demonstrated a similar kinematics pattern and magnitude of angle changes (Bull & McGregor, 2000; Caldwell et al., 2003; Holt et al., 2003; McGregor et al., 2005; McGregor et., 2007; Mackenzie et al., 2008). Although the rowers were fatigued, it has not yet been established if the change in kinematics is just a result of fatigue or is due to the increasing stroke rate and workload.

A different pattern of kinematics was observed during the boat tests. Although a small increase was seen in maximum flexion angle and range, neither of these findings was significant. No previous studies have measured lumbar spine kinematics in both an ergometer and a boat, thus comparison is not possible. When the results in the boat and the ergometer were compared, it was found that both maximum flexion angle and lumbar flexion range increased significantly more on the ergometer compared to the boat over the test period. This indicates that as the rowers continue a sustained period of rowing, their lumbar spines flex more during ergometer rowing than during boat rowing. These results may help to contribute to understanding why rowing ergometer training increases risk of lumbar spine injury as observed in a recent prospective injury study (Wilson et al., 2010).

Thus, this study has found that both ergometer and boat rowing require the lumbar spine of rowers to be flexed to high range. However, ergometer rowing requires the lumbar spine to flex significantly more and move through a greater range than boat rowing. It was also found that lumbar flexion steadily increases with continued rowing, peaking at the point of exhaustion. The combination of high sagittal plane flexion and repeated loading and fatigue in rowers correlates with studies that have cited the combination of these factors as risk for lower-back injury (Marras et al., 1993; Sorensen et al., 2011). Individually, these factors increase injury risk, but when combined as in this case, risk is increased further. Previous studies have demonstrated that cyclical, loaded lifting, particularly when combined with fatigue, influences motor control strategies (Van Dieen et al., 1998; Van Dieen et al., 2002; Banks & Aghazadeh, 2009; Sanchez-Zuriaga et al., 2010). This study did not specifically examine motor control strategies but the results suggest that there may be some difference in motor recruitment between ergometer and boat rowing and this should be examined further. As no studies have compared spinal kinematics between the boat and ergometer, reasons for differences can only be speculative. The reason why ergometer rowing results in greater flexion of the lumbar spine may be due to the fact that the leverage of the oar may be greater on the ergometer than the boat; the ergometer has a stationary fulcrum at the 'catch' (the start of the stroke where the oar enters the water), whereas in the boat, there is a non-stationary fulcrum as the oar may slip in the water. Another possible reason may be that a boat (by the fact that it is unstable and on an unstable surface) will provide feedback for poor postural control by becoming unstable or difficult to row, providing postural feedback to the rower, whereas the fixed stable ergometer will be 'more forgiving' and less sensitive to postural change. Further analysis is required in this area.

The primary limitation of this study was that traditional motion analysis equipment was unsuitable as it could not be used in a field setting. However, the electrogoniometer has well-established reliability and validity in measuring the lumbar spine and the degree of error noted in a previous validation study at 0.45° meant that findings were still significant if this was factored in. The equipment was light and allowed the rower to perform normally in both tests without moving its position from the lumbar spine. As it was not possible to measure work rates in the water, heart rates were used to ensure that the same work was carried out in the boat as on the ergometer. Also, stroke rates and time periods of the test were exactly the same in the water as on the ergometer. However, while heart rate is a very good physiological assessment of workload, implementation of a supplementary method may provide greater accuracy. There were likely to be slight differences in placement of the electrogoniometer between tests, even considering that this was carried out by the same experienced individual on each occasion. However, no comparisons of absolute values were made between tests, and a within-subject design was used; analysis was made only for increase in angle between first and last steps so while variability may have been present, this should not bias the results.

The findings of this study have highlighted a number of components that merit further research. All participants in the study had been free of lumbar spine injury for at least six months as the aim of the study was to examine kinematic differences between a boat and an ergometer. However, it was not quantified how many participants had previously sustained such an injury. As the incidence of lumbar spine injury in rowers is high, it is likely that a number of participants had a previous injury and further research would warrant stratification into 'never injured' and 'history of injury' groups. This may help identify biomechanical factors that may predict a lumbar spine injury. The damper setting of the ergometer influences the air resistance of the fly wheel and for the purposes of this study was set at 4 that is common in elite rowing testing. However, it is likely that the decreased air resistance at lower damper settings will result in different lumbar kinematics and this should be investigated with a similar protocol; this may ultimately provide a solution to reduce stresses on the lumbar spine of rowers. Furthermore, the catch forces at a lower damper setting may more closely mimic the 'feel' of the catch in a boat when the oar slips slightly in the water on entry. Finally, verbal or visual feedback may influence the lumbar spine position and reduce the amount of lumbar flexion observed in this study; the addition of such stimulus during testing should be investigated to examine its effect.

Conclusion

Ergometer rowing is associated with a significantly greater degree of lumbar spine sagittal flexion compared to boat rowing over the period of a rowing protocol. Both ergometer and boat rowing were associated with an incrementally increasing range of lumbar sagittal flexion as the rower reached the point of exhaustion due to fatigue over the test period. However, only ergometer rowing showed significant increases in lumbar flexion with boat rowing showing smaller, non-significant changes.

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