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Research article

A COMPARISON OF KINEMATICS AND PERFORMANCE MEASURES OF TWO ROWING ERGOMETERS

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ABSTRACT

Rowing injuries have been attributed to poor technique, suggesting a need to understand the mechanics of rowing and the influence on technique of different training regimes and ergometers. The aims of this study were to investigate the repeatability of the kinematics of the lumbopelvic region during rowing and to compare these kinematics between rowing on two different ergometers. An electromagnetic motion measuring device in conjunction with a load cell was used to determine the ergometer rowing kinematics of 12 rowers. Subjects were tested on three occasions at two different stroke rates, with an interval of one week between testing. Two datasets were obtained for the Concept II, to establish the repeatability of the kinematics, and one for the WaterRower. Bland and Altman's mean difference technique was used to test for consistency of technique, and the difference between ergometers was assessed using Students' paired T-tests. The kinematic measures of the lumbo pelvic region during rowing demonstrated high repeatability. The two ergometers showed a similarity in force profiles but some significant differences in rowing kinematics. There was greater rotation of the thigh segment in the sagittal plane throughout the stroke on the WaterRower ($p < 0.01$). There were also trends indicating that rotation of the pelvis in the sagittal plane was different between the two ergometers, for example on the Concept the mean angle of the pelvis at the catch was 5.4° and on the WaterRower it was 2.4° ($p < 0.05$). Measurement of lumbopelvic kinematics during rowing on a Concept II ergometer is repeatable. However, rowing kinematics varies between ergometers. Because a full analysis comparing rowing kinematics on water with rowing ergometers has not been made in this study, no conclusions regarding which ergometer simulates rowing on water can be made. The implications of the effect of these differences in technique requires further investigation.

KEY WORDS: Lumbo-pelvic rhythm, spinal biomechanics.

INTRODUCTION

Rowing is a skillful sport with distinct phases to each stroke, which have to be combined in an effective manner to ensure maximum power output and acceleration of the boat through the water. These phases can be summarised as the catch, drive, finish and recovery (Redgrave, 1995). An understanding of the mechanics of the rower in achieving these stages of the stroke is slowly evolving (Bull and McGregor, 2000; Holt et al., 2003), however, it is not yet clear how this is related to both performance and injury. Rowing injury rates are low, indeed much lower than in contact sports (Budgett and Fuller, 1989). However, injuries still occur and lead to elite rowers missing an average of 24 training days per year (Bernstein et al., 2002), and can relate to the success or failure of a crew.

A common and widely studied problem in rowing is that of low back pain and related lumbar spine injuries (Bull and McGregor, 2000; Caldwell et al, 2003; O'Kane et al., 2003; O'Sullivan et al.,

2003; Reid and McNair, 2000; McGregor et al., 2004; Roy et al., 1990; Teitz et al., 2002;). The spine and trunk extensor muscles play a vital role in the rowing stroke by providing a stable base for transfer of the power generated by the arms and the legs to the blade (Holt et al., 2003; Lamb, 1989; Roy et al., 1990). Consequently, during the stroke cycle great forces are placed on the flexed lumbar spine.

It has been postulated that the repetitive action of the stroke with loading and unloading of the spine predisposes the rower to low back injury. This however, requires further research (Bernstein et al., 2002; Caldwell et al., 2003; McGregor et al., 2002; Reid and McNair, 2000). Other studies incriminate land training and in particular the use of the rowing ergometer (Bernstein et al., 2002; Teitz et al., 2002). Rowing ergometers are designed to simulate the movements performed during rowing on water. They are used in training and routine testing of oarsmen and women, and have been noted to do this with a high level of success (Lamb, 1989). However, there are no data to compare the rowing kinematics of the body on water with that on ergometers. Most notable is the discrepancy between sweep rowing that includes an out-of-plane rotation, and ergometer rowing that is essentially a planar activity. Whilst the ergometer has been indicated to have high reliability in performance measures (MacFarlane et al., 1997; Schabort et al., 1999), less is known regarding the technique the rowers used to achieve these performance measures.

Traditionally, rowing machines have provided simple data on time taken to row a set distance. More recently many machines have been adapted to allow further parameters to be measured such as stroke length and force data. Such information has been used as a feedback to rowers to refine and correct faults and weaknesses in their stroke (Bernstein et al., 2002; Bull and McGregor, 2000; Lamb, 1989). One study went on to measure spinal kinematics of the rowing during the rowing stroke (Bull and McGregor, 2000) and through a series of subsequent studies identified key factors which influence the rowing stroke (Holt et al., 2003; McGregor et al., 2004, O'Sullivan et al., 2003). Through this type of work, information pertaining to injury mechanisms and injury prevention can be gathered. However, at present the repeatability of these kinematics measurements of ergometer rowing are not known.

Additionally it is not known how the design of the ergometer impacts body kinematics. Two basic designs of ergometer exist, the fixed head or stationary (for example, Concept II ergometer - Concept II, Morrisville, Vt, U.S.A.) and floating or moving head (for example, RowPerfect ergometer - Care Rowperfect BV, Hardenberg, The Netherlands). Bernstein et al. (2002) postulated that the moving head design leads to a more realistic rowing stroke and noted differences in parameters of the stroke profile when compared to the fixed head design. However, the relevance of these differences is unclear. In an attempt to more closely replicate the rowing action a new fixed flywheel ergometer, the WaterRower (WaterRower UK Ltd, London, United Kingdom), was designed, the flywheel of which moves a mass of water rather than air. This system, unlike the others is claimed by the manufacturers to be able to maintain a constant resistance through the stroke in order to more realistically represent the on-water scenario. However, the mechanics and kinematics of this ergometer have not been examined.

Therefore, the aims of this study were firstly to determine the repeatability of kinematic measurements of rowing performance that relate to the lower back and pelvis and secondly to examine how these parameters of performance vary between two different fixed head rowing ergometers.

METHODS

Subjects

Twelve novice male rowers were recruited from the Imperial College School of Medicine Boat Club and written informed consent obtained. All rowers had rowed a minimum of one year and a maximum of five years. The subjects had an average age of 21.7 ± 1.8 years (SD), an average height of 1.79 ± 0.05 m and an average mass of 74.4 ± 7.0kg. All were sweep rowers with 7 also being scullers. Subjects with a current episode of low back pain or any other serious illness or injury were excluded from participation in this study. All subjects regularly trained on a Concept II ergometer; their experience of the WaterRower system was limited to a familiarisation session in the laboratory that consisted of rowing on the WaterRower for a short period until the rowers were confident of rowing according to normal training protocols.

Assessment of rowing kinematics

The kinematics of the lumbo-pelvic region was assessed during the rowing stroke using the Flock of Birds™ (Ascension Technology, Vermont, USA) electromagnetic measuring device as previously described (Bull and McGregor, 2000). This was further integrated with a load cell (Oarsum, NSW, Australia) positioned on the handle of the ergometer that permitted measurement of tensile force at the handle during the stroke and a further motion sensor to determine stroke length (Holt et al., 2003). Data

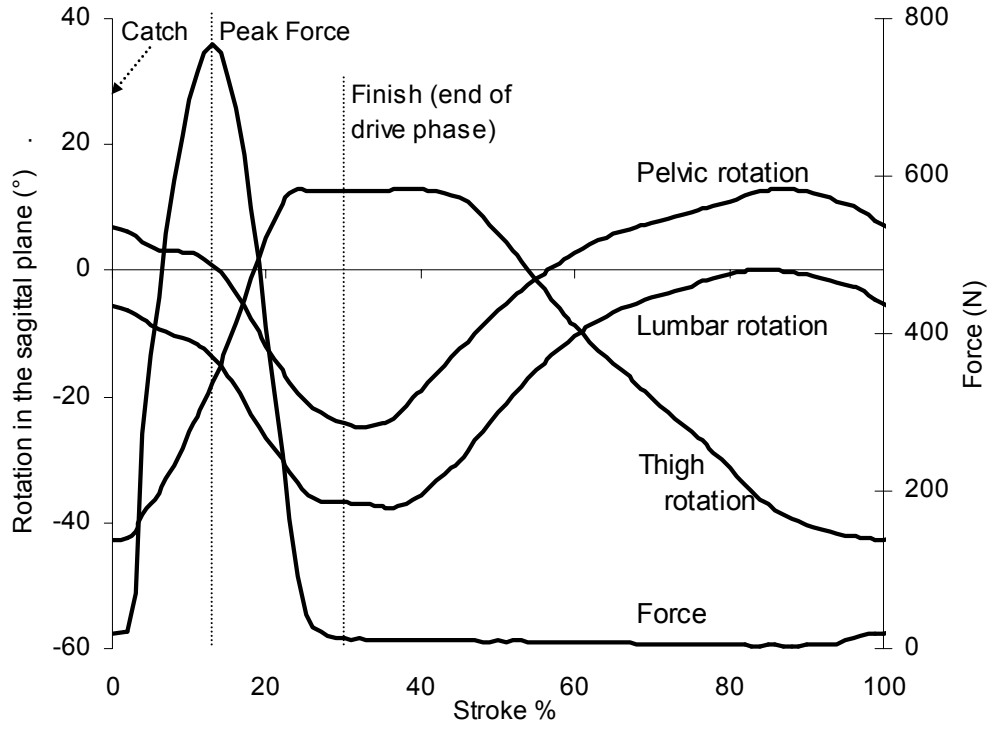

Figure 1 Example of the average stroke profile of one subject .Rotation of the lumbar segment, rotation of the pelvis and the rotation of the thigh in the sagittal plane in relation to the force the rower is applying to the ergometer handle throughout the stroke. The stages of the stroke used in the analysis are identified: the catch; the point of peak force; and the finish.

were captured at 35 Hz. From these measurements a detailed investigation of lumbo-pelvic rhythm and force production during the stroke was obtained.

Study protocol

Subjects were asked to perform a brief warm-up on the rowing ergometer to accustom themselves to the equipment. After this, they performed a 300 metre training session at a rate of between 18-20 strokes per minute. This also consisted of maintaining a heart rate of between 130-150 beats per minute. Once the rate was maintained, data were recorded from approximately 50 m into the piece until 10 m from the end of the piece. All strokes recorded during the 240 m were used in the subsequent analysis. This exercise was then repeated at a rate of 28-30 strokes per minute. The procedure was repeated on two further occasions each with an interval of one week between recordings. At each session either a Concept II ergometer or a WaterRower ergometer was used in a random order such that by the end of the experiment two recordings were made on the Concept II and one on the WaterRower. The two sets of measurements on the Concept II were used to assess the repeatibility of the measurement technique. The first one of these was used to compare with the WaterRower measurements. The study did not compare the individual repeatibility of each ergometer.

Data analysis

The synchronised output from the Flock of Birds and load cell was run through an in-house custom programme (Holt et al., 2003). This programme focused on sagittal plane motion and characterised the stroke into percentage points with 0% representing the catch position of the stroke that was determined from the onset of tensile force production, and 100% being the return to this catch position. Kinematic and tensile force data were averaged over each rowing session and presented in terms of force, anterior-posterior roation of the thigh in the sagittal plane, anterior-posterior rotation of the pelvis in the sagittal plane, and anterior-posterior rotation of the lumbar region in the sagittal plane (Figure 1).

The following data points were determined from the averaged data; peak force, power, work done through the stroke, and stroke length (determined by the travel of the handle). The point at which different phases of the stroke occurred were examined including where peak force was achieved and when the drive phase ended. The following kinematics variables were examined: thigh, pelvic and lumbar rotation at the catch and finish position,

Table 1 Repeatability of force profiles and kinematics measures of performance (n=12). Data are means (±SD).

	Rate 18-20	Rate 28-30
Stroke length (cm)	.2 (9.8)	-.2 (8.3)
Peak force (N)	-2.0 (135.8)	7.5 (90.4)
% point peak force occurs	-.1 (1.7)	.0 (1.6)
Stroke rate (SPM)	.01 (2.7)	.2 (1. 7)
Stroke power (Watts)	-3.2 (37.2)	4.0 (33.0)
Lumbar rotation at catch (deg)	-1.4 (6.8)	-.8 (8.2)
Pelvic rotation at catch (deg)	1.1 (16.3)	1.6 (15.6)
Lumbo-Pelvic Ratio at catch	19.5 (153. 9)	-7.5 (37.7)
Femoral rotation at catch (deg)	3.2 (16.2)	2.0 (12.3)
Lumbar rotation at finish (deg)	-0.8 (9.4)	-.4 (5.3)
Pelvic rotation at finish (deg)	-1.3 (12.7)	1.1 (15.9)
Lumbo-Pelvic Ratio at finish	-.01 (.4)	-.0 (.4)
Femoral rotation at finish (deg)	3.5 (12.8)	1.8 (6.8)
Lumbar rotation at peak force (deg)	-1.4 (8.9)	-1.0 (7.4)
Pelvic rotation at peak force (deg)	-2.0 (11.9)	-.8 (11.6)
Lumbo-Pelvic Ratio at peak force	-6.2 (26.1)	-.1 (7.8)
Femoral rotation at peak force (deg)	3.2 (16.8)	2.2 (11.6)

and the angle and stage in the rowing stroke where maximal and minimum rotation of these segments occurred. Finally the ratio of lumbar to pelvic rotation was determined at the catch and finish positions.

Statistics

The mean and standard deviation of each of the variables generated for each data set was calculated using Microsoft Excel™. The two sets of data generated on the Concept II rowing ergometer were compared at both rowing rates to look at the consistency of the rowers' technique using Bland and Altman's (1986) mean difference technique. A good level of repeatability was set at a calculated difference of less than 1.85 N for force and 1.85° for rotations. The first Concept II readings were then compared with the WaterRower data using Students' paired T-tests, with the statistical threshold being set at $p = 0.05$, again this was done at both rowing rates recorded.

RESULTS

Data repeatability

Considering the force curve data (Table 1), the mean difference values were all near zero (within ±1.85) indicating good repeatability for these variables. The mean difference values for the stroke power and peak force were, however, higher, suggesting lower levels of repeatability. For the kinematic data, the majority of variables had low mean difference values at both stroke rates, indicating that the data were repeatable. However, the repeatibility of the lumbo-pelvic ratio at the catch had very high standard deviations. On closer inspection of the data, it was noted that at the low rate there were two subjects with very much higher ratios than the other subjects, with one rower's ratio being -243° and the other 41°, while the majority remain between ±20°. If these outliers are removed, the mean difference would become 1.33 ± 25.57 with the range -24.24 to 26.89. A similar finding was observed at the high stroke rating for this variable.

Ergometer comparison

Table 2 summarises the findings in terms of force curve profiles. There were no significant differences in between the two ergometers for all variables.

Differences were, however, noted when the kinematic variables were compared (Table 3). When body segment angles at the finish were considered, no significant differences were observed between the ergometers in terms of pelvic or lumbar rotation,

Table 2. Force curve profile summaries of the two ergometers (n=12). Data are means (±SD).

	Concept II		WaterRower	
Stroke Rate	18-20	28-30	18-20	28-30
Stroke length (cm)	139 (8)	139 (7)	139 (10)	140 (1)
Peak force (N)	828 (111)	897 (94)	825 (92)	911 (101)
% point peak force occurs	11.5 (1.3)	14.6 (1.5)	11.6 (.9)	14.9 (1.0)
Power (Watts)	217 (41)	344 (50)	226 (40)	345 (51)

Table 3. Kinematic variables generated on the 2 ergometers (n=12). Data are means (±SD).

	Concept II		WaterRower	
Stroke Rating	18-20	28-30	18-20	28-30
Lumbar rotation at finish (deg)	-26.1 (8.6)	-30.8 (7.1)	-28.9 (9.4)	-31.8 (10.1)
Pelvic rotation at finish (deg)	-33.2 (9.1)	-38.1 (8.8)	-34.1 (9.8)	-36.7 (11.3)
Lumbo-Pelvic Ratio at finish (deg)	.8 (.2)	.8 (.2)	.9 (.2)	.9 (.2)
Lumbar rotation at peak force (deg)	13.2 (9.4)	11.1 (9.9)	13.2 (5.9)	12.6 (5.5)
Pelvic rotation at peak force (deg)	-6.2 (9.0)	-8.3 (8.2)	-6.9 (9.1)	-3.7 (11.9)
Lumbo-Pelvic Ratio at peak force (deg)	-1.9 (6.3)	-1.8 (4.1)	-3.1 (10.0)	-1.6 (2.7)
Thigh rotation at peak force (deg)	-13.7 (4.6)	-15.7 (4.2)	-21.9 (4.2)	-20.6 (5.4)

apart from at the low stroke rate where lumbar rotation posteriorly (corresponding to back extension) was noted to be greater on the WaterRower ($p < 0.05$). Significant differences were observed in thigh rotation (rate 18-20 $p=0.005$ and rate 28-30 $p=0.04$) at the finish of the stroke (Figure 2). The reduced thigh rotation suggests the rowers were not fully straightening their legs on the WaterRower.

The lumbar rotation recorded at the point of peak force did not alter significantly between the Concept II and the WaterRower ergometers. The thigh rotation was different (rate 18-20 $p = 0.001$ and rate 28-30 $p = 0.01$) with the thigh demonstrating more rotation when rowing on the WaterRower ergometer.

WaterRower ergometer

Lumbar rotation at the catch position for the low stroke rate did not change significantly between the ergometers; there was a significant difference ($p = 0.03$) in the pelvic rotation (Figure 3). At the catch the pelvis had less anterior rotation on the WaterRower than on the Concept II. Interestingly, the data indicate that the lumbar spine rotation was greater on the WaterRower than the Concept, although there is not a significant difference ($p = 0.39$). The higher stroke rate demonstrates a similar trend but it does not reach significance ($p = 0.06$). This would indicate that the rower is utilising flexion of the back rather than hip flexion to achieve the catch position on the WaterRower. The other significant difference noted was an increase in thigh rotation at the catch on the WaterRower (Figure 4), this occurred at both stroke rates (rate 18-20 $p = 0.004$ and rate 28-30 $p = 0.024$).

DISCUSSION

This study examined the repeatability of rowers' technique in terms of spinal kinematics and force curve output on a Concept II rowing ergometer. Overall technique was found to be highly repeatable for kinematic variables, however, some loading differences were observed, such as in peak force and stroke power. These parameters are, however, more susceptible to variation as a consequence of the rowers' training schedule and subsequent fatigue, a factor previously noted by Holt et al. (2003). This

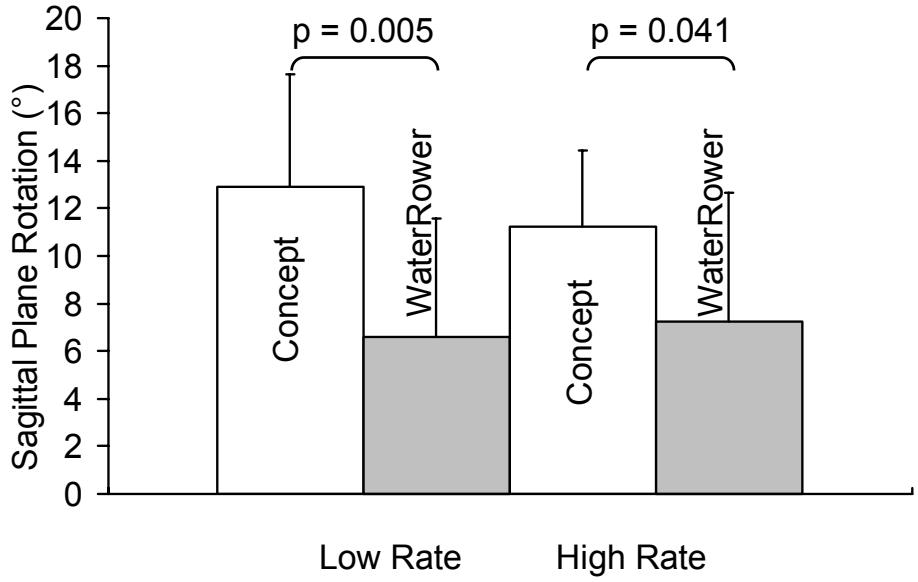

Figure 2. Comparison between the Concept II and WaterRower ergometers: the degree of thigh sagittal rotation at the finish during the low and high stroke rate sessions.

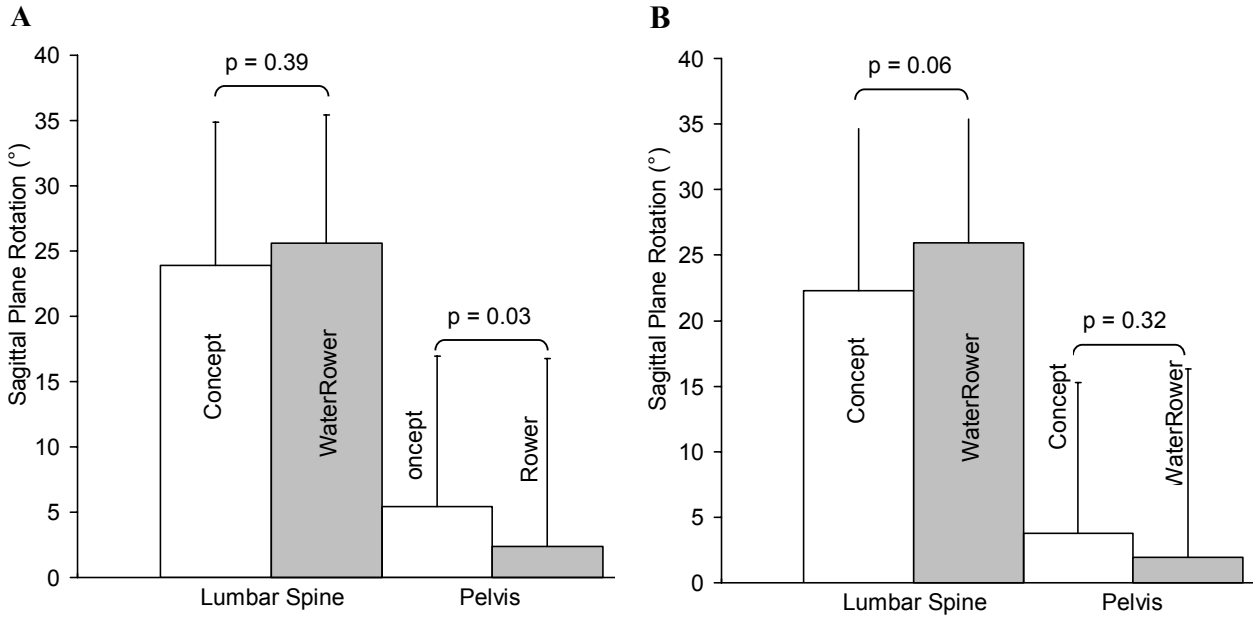

Figure 3. Comparison between the Concept II and WaterRower ergometers: lumbar sagittal rotation and pelvic sagittal rotation at the catch. A) At low stroke rate, B) At high stroke rate.

would appear to correlate with the findings of Schabort et al. (1999) who found a high level of repeatibility of physiological performance by rowers when they were repeatedly tested on the Concept II ergometer. Greater consistency in these measures would be anticipated in more senior rowers.

The second aspect of this study was to compare rowing technique, again in terms of kinematics movement of the spine and force curve output, of two fixed head designs rowing ergometer, the Concept II and the WaterRower. Previous studies have compared technique between a fixed head and a floating head ergometer, and noted that the oarsmen take a longer stroke on the fixed head ergometer, and generated a longer stroke length as they fatigued (Bernstein et al., 2002). The comparison of the two fixed head ergometers demonstrated many similarities in the force curve data and stroke length. The kinematic data, however, were not so comparable, with the most striking differences observed in thigh rotation. Throughout the stroke the thighs were held in posterior rotation on the WaterRower, so that at the finish the athlete's legs did not fully extend, and at the catch the thighs were in greater posterior rotation than on the Concept II ergometer. One of the basic principles all rowers are taught is that at the finish of the stroke the legs should be straight (Redgrave, 1995). The data demonstrates that this was only achieved on the Concept II ergometer. The reasons and full implications for this are unclear.

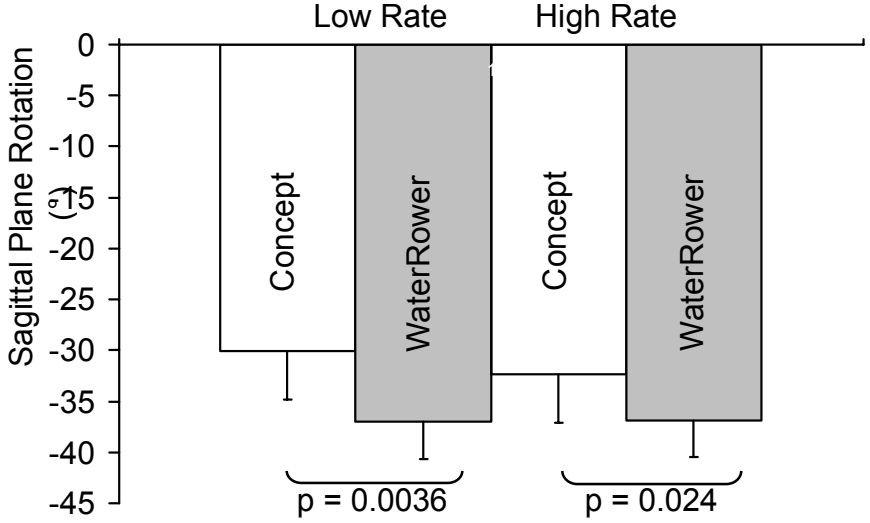

Figure 4. Comparison between the Concept II and WaterRower ergometers: thigh sagittal rotation at the catch during the low and high stroke rate sessions.

While the subjects were given a chance to familiarise themselves with the WaterRower ergometer and were personally confident that they achieved a good rowing technique, there is a possibility that they did not use it for long enough to develop a consistent technique. Schabort et al. (1999) found that familiarisation with the test environment, including the ergometer used, led to enhanced and more consistent performances. They postulated that this could be in part due to decreased anxiety levels. However, the problems observed on the WaterRower related to poor, rather than inconsistent technique.

An alternative explanation for the differences observed relate to the design of the WaterRower. One possibility was that the angle of the footplate and its relation to the seat was different between the two ergometers, and it was this that led to the differences observed. Modification of these design details was not the aim of this current project.

A further interesting trend with respect to body posture was seen at the catch. At the catch, a clinical understanding would be that the rotation of the lumbar segment should be of a similar magnitude to that of pelvic rotation to keep the spine in a strong position. A large difference between these rotations would suggest an increased loading of the soft tissues due to the greater motion of one segment relative to the other. On the WaterRower the lumbar spine was not in line with the pelvis, it was held in greater anterior rotation, while the pelvis tended to be in posterior rotation. The thighs were more anteriorly rotated on the WaterRower (clinically termed 'compression'), which could be related to this poorer posture. This suggests lumbo-pelvic rhythm and control may be altered on the WaterRower, the effects of which require further investigation with respect to loading of spinal structures. Previous studies have suggested that alterations in lumbo-pelvic rhythm are a factor associated with low back trouble in rowers (McGregor et al., 2002; O'Sullivan et al., 2003). Large forces are postulated to act on the spine during rowing (Reid et al., 2000), and an alteration in lumbo-pelvic rhythm may lead to an uneven distribution of this load which may in turn lead to damage, this however, requires further research.

CONCLUSIONS

In conclusion, rowing kinematics on the Concept II ergometer can be quantified in an accurate and repeatable manner. These measures demonstrate that differences in technique exist between ergometer designs, and the findings suggest that the WaterRower can lead to what is thought to be an aberrant technique. The implications of this require further investigation.

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KEY POINTS

- Measurement of lumbopelvic kinematics during rowing on a Concept II ergometer is repeatable.
- Rowing kinematics varies between the WaterRower and Concept II

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