Spinal Kinematics in Elite Oarswomen during a Routine Physiological "Step Test"

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ABSTRACT

MCGREGOR, A. H., Z. S. PATANKAR, and A. M. J. BULL. Spinal Kinematics in Elite Oarswomen during a Routine Physiological "Step Test." *Med. Sci. Sports Exerc.*, Vol. 37, No. 6, pp. 1014–1020, 2005. **Introduction:** Biomechanical measures of movement are being used increasingly to understand injury mechanisms and enhance performance. Frequently, rowing injuries are attributed to poor rowing technique. This suggests a need to understand technique and its influencing factors. This study aimed to quantify rowing technique in terms of lumbopelvic motion, force production, and work done at different work intensities. **Methods:** An electromagnetic motion measuring device in conjunction with a load cell was used to determine the ergometer rowing kinematics of 12 elite international oarswomen during a routine step test. This test comprised six steps at a series of different stroke ratings starting at 18 strokes per minute and ending at maximal-output rowing. **Results:** As work intensity increased, force output increased significantly ($P < 0.0001$). Stroke length remained relatively consistent throughout the steps, although there was a nonsignificant shortening from 136.5 cm (±6.4 SD) at 18 strokes per minute to 130.6 cm (±8.1) at maximal testing. Changes in kinematics were also observed, particularly at the catch and finish positions. There was a trend towards less anterior pelvic rotation occurring at the catch with an associated reduction in lumbar rotation and greater extensions occurring in both at the finish at the higher rating. Overall, rowers underutilized pelvic rotation to achieve these positions relying predominately on lumbar rotation. **Conclusion:** This study quantified the spinal kinematics of elite rowers at different incremental work intensities and noted subtle but important changes to lumbopelvic and spinal kinematics at increasing work levels, particularly at maximal intensity. Such changes particularly are thought to be important with respect to the development of low-back pain. **Key Words:** ROWING, TECHNIQUE, LUMBOPELVIC RHYTHM, FORCE PROFILES, STROKE RATINGS

There is an increasing interest in understanding the biomechanical factors affecting rowing from the perspective of both boat mechanics (9,10) and body kinematics (10,14). This information is thought to be of interest with respect to both performance (19) and injury (13,16,20). However, there are several factors that may influence rowing kinematics. These include performance level (16,19), previous injury (13,16), fatigue (10), stroke rating (14), and the test environment, including the ergometer used (3).

When races are being decided by tenths of a second (1), it is important that avenues that may enhance performance are pursued. This is paralleled by a need to understand the mechanics of the body during the stroke in an attempt to prevent injury (13,20). Earlier studies examining lumbopelvic kinematics and their relation to force curve profiles have focused primarily on club-level or recreational rowers (10,14), and have often not been performed in a routine stressful test environment. Differences in kinematics have been noted between club and elite international rowers at low-intensity training rates, and changes in technique have been noted in club-level rowers with increasing training intensity. However, little is known about elite rowers' technique. Research relating to force curve profiles in rowers suggests that elite rowers are more consistent than novices (18,19); however, little is known about their lumbopelvic kinematics.

This study aimed, therefore, to investigate the lumbopelvic kinematics of the rowing stroke in a group of international oarswomen during a routine physiological incremental "step test."

METHODS

Study population. The local research ethics committee approved this study, and informed written consent was obtained from all subjects. Twelve elite oarswomen from the Great Britain National Team were recruited into this study. The mean age of this population was 26.8 yr ± 4.3 (SD), with a mean height 180.0 cm ± 3.9 (SD) and mean weight 75.1 kg ± 4.6 (SD).

Assessment of rowing kinematics. The kinematics of the lumbopelvic region were assessed during the rowing stroke using the Flock of Birds™ (Ascension Technology, Burlington, Vermont) electromagnetic measuring device. This system quantifies the rotation and translation of electromagnetic sensors in an electromagnetic field in terms of

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Submitted for publication June 2004.
Accepted for publication January 2005.

0195-9131/05/3706-1014/0
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DOI: 10.1249/01.mss.0000171618.22263.58

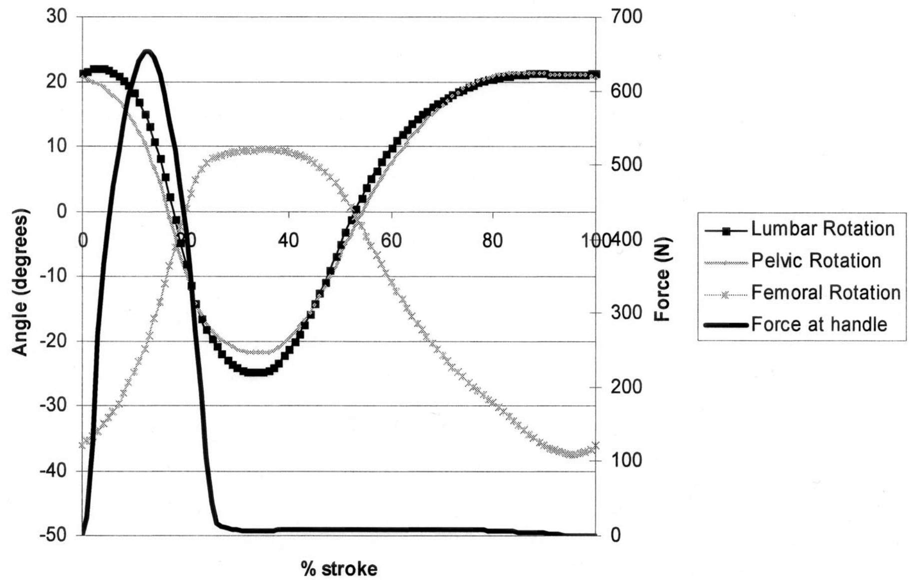

FIGURE 1—Example of average data output from one subject including both kinematic assessment of lumbopelvic motion and tensile force generation while rowing during the second step test.

rotation about and translations along an electromagnetic transmitter axis. The system has been shown to have an accuracy of 0.23% of the step size for translation and 1.8% of the step size for rotations when used within an optimal operational zone of minimal error, which equates to a 1° error for a rotation of 60° (4). The receivers of the system were attached to the skin at the thoracolumbar junction (T12/L1), the lumbosacral junction (L5/S1), and 10 cm proximal to the lateral epicondyle of the right femur. Previous MRI studies have demonstrated the ability of these skin mounted sensors to track vertebral motion (4,6). The electromagnetic sensor transmitter was aligned with the plane of movement of the ergometer, so that sensor movement on the landmarks was recorded as a rotation in the sagittal plane (flexion/extension), and out-of-plane rotations. This system 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 the position of the handle in space (10). This permitted detailed investigation of lumbopelvic rhythm, force production, and work done during the stroke.

Incremental "step" test. Each athlete performed an incremental exercise test comprising five steps on the rowing ergometer, with each step performed at a different stroke rating. The duration of each step was 4 min, and between 950 and 1250 m were rowed depending on the work intensity and ability of each athlete. The first step was conducted at 18 strokes per minute, with subsequent steps at 20, 22, 24, 26, and 28 strokes per minute. There was a 1-min break between each step. This test process is a routine one usually used to establish training levels and to monitor the fitness and health status of the athlete. However, in this instance we used it to test kinematic performance at different training intensities.

Protocol. All testing was performed on a Concept II model C rowing ergometer (Concept Inc., Morrisville, Vermont). The receivers of the electromagnetic motion system were positioned on the subjects to measure femoral, pelvic, and lumbar kinematics as previously described (10). Subjects were asked to perform a brief warm-up. Once they were comfortable and the receivers were checked for any loosening or slippage, the incremental "step" test was then performed. At the end of the "step" test a 2-min maximal rowing test was also performed. For this test, athletes rowed at their maximal capacity for the duration of the test.

Data analysis. The synchronized output from the Flock of Birds and load cell was run through an in-house custom program. This program focused on sagittal plane motion and characterized 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% representing the return to this catch position. The following derived data were recorded for each stroke: peak force, work done through the stroke, power (work done divided by time of the stroke), and stroke length (defined as the maximum horizontal travel of the handle). Work done was defined as the sum of the

TABLE 1. Changes in the force curve profile and stroke profile during the incremental test (mean and standard deviation, $N = 12$).

	Step 1	Step 2	Step 3	Step 4	Step 5	Max
Stroke rate	17.4 ± 0.9	18.4 ± 0.7	19.8 ± 1.2	21.3 ± 1.2	23.6 ± 1.2	31.3 ± 1.2
Peak force (N)	610.5 ± 60.4	660.4 ± 45.2	702.3 ± 67.5	727.9 ± 69.0	741.9 ± 60.8	777.2 ± 64.2
% stroke when peak force occurs	13.7 ± 2.0	13.8 ± 2.0	14.2 ± 1.7	15.4 ± 2.0	16.3 ± 1.9	18.8 ± 1.8
% stroke when end of drive occurs	44.1 ± 6.9	39.7 ± 2.9	42.4 ± 2.6	44.7 ± 3.4	44.4 ± 7.0	54.5 ± 7.2
Stroke length (cm)	136.5 ± 6.4	138.8 ± 7.5	137.6 ± 9.3	138.6 ± 7.9	139.4 ± 8.6	130.6 ± 8.1
Power (W)	147.7 ± 8.8	170.1 ± 6.8	193.6 ± 13.6	216.4 ± 9.9	240.6 ± 10.2	318.9 ± 16.9
Work done (J)	515.2 ± 45.1	557.3 ± 34.2	594.0 ± 54.9	610.6 ± 49.0	614.6 ± 46.3	608.9 ± 43.5

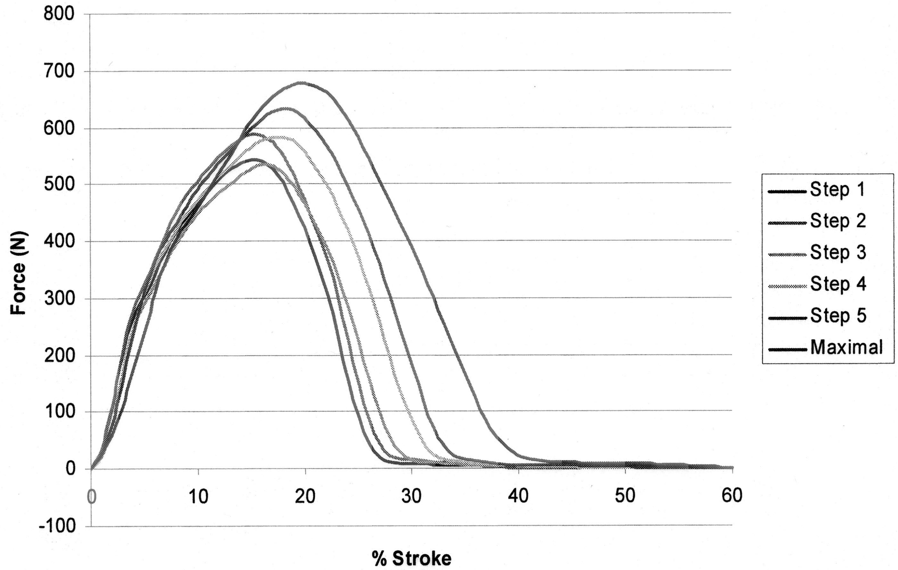

FIGURE 2—An example of changes in the average tensile force curve profiles during the rowing stroke during each of the incremental steps ($N = 1$).

increments of work done at each time point, where force was the tensile force measured at the handle and the handle travel in the sagittal plane was defined as the distance over which the force acted. These kinematic and kinetic data were averaged over each of the steps, with the initial and final strokes eliminated from the analysis, and presented in terms of force, anterior–posterior femoral rotation (thigh flexion-extension), anterior–posterior sacral rotation (anterior/posterior pelvic tilt), and anterior-posterior lumbar rotation (back flexion and extension) (Fig. 1).

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 finish position was defined as the point at which there were was no force application at the handle. In addition, the following kinematics variables were examined: the angle of the femur, lumbosacral, and thoracolumbar sensor at the catch and finish position; and the angle and position in stroke of maximum flexion and extension of the femoral, lumbosacral, and thoracolumbar markers. Finally, the ratio of lumbar to pelvic motion, that is, the ratio of lumbosacral motion to thoracolumbar motion recorded, was determined at the catch and finish positions.

Statistical analysis. Statistical analysis of the data was performed using Analyze-It (Analyze-It Software Ltd., Leeds, U.K) add-in for Excel (Microsoft Corp., Seattle, WA). Differences between the six rowing ratings for each of the variables were examined using a repeated-measures ANOVA with the Tukey's *post hoc* test used to locate where the differences lay. The statistical threshold was set at $P < 0.05$.

RESULTS

All subjects completed the test protocol successfully, with incremental rises at each step as intended, Table 1. As can

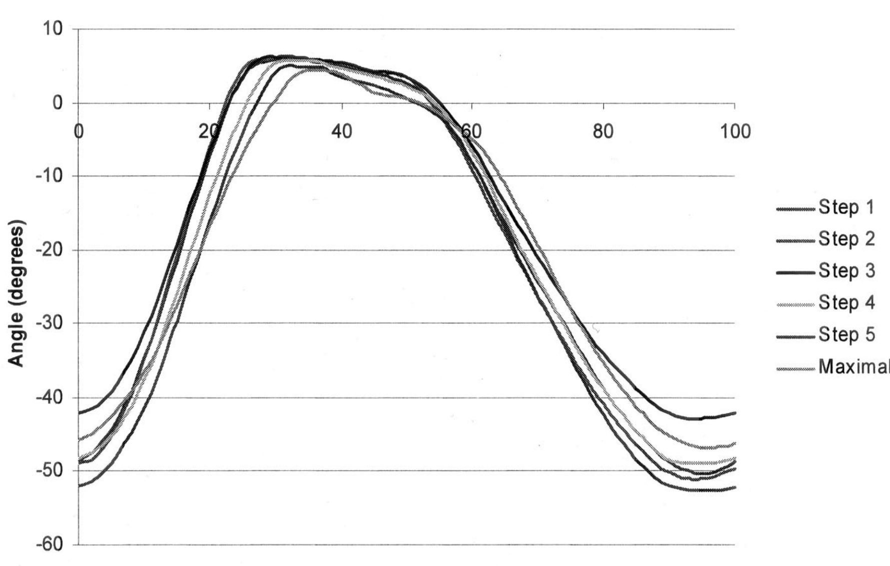

FIGURE 3—An example of changes in the average femoral rotation curve profiles during the rowing stroke during each of the incremental steps ($N = 1$)

TABLE 2. Changes in femoral rotation during the incremental test (mean and standard deviation, $N = 12$), NB movements into flexion negative, movements into extension positive.

	Step 1	Step 2	Step 3	Step 4	Step 5	Max
Femoral flexion at the catch (°)	−42.3 ± 5.4	−42.3 ± 5.6	−41.9 ± 5.2	−42.8 ± 5.6	−43.0 ± 7.6	−43.8 ± 4.8
Maximal femoral flexion (°)	−43.3 ± 6.2	−43.4 ± 6.2	−42.9 ± 5.8	−44.0 ± 5.9	−43.7 ± 8.1	−45.3 ± 5.3
% stroke where maximal femoral flexion occurs	96.5 ± 2.7	96.5 ± 2.7	96.3 ± 2.4	96.3 ± 2.5	95.9 ± 2.9	95.9 ± 2.5
Femoral extension at the finish (°)	2.0 ± 5.4	4.7 ± 5.6	4.3 ± 4.7	2.8 ± 4.1	0.8 ± 4.6	−6.1 ± 7.1
Maximal femoral extension (°)	5.3 ± 4.6	5.7 ± 4.9	6.0 ± 5.1	5.4 ± 5.2	4.4 ± 5.4	3.8 ± 5.4
% stroke where maximal femoral extension occurs	32.8 ± 5.6	30.6 ± 5.3	30.8 ± 5.4	30.2 ± 4.0	30.8 ± 3.0	34.5 ± 2.6

be noted in Table 1, the step rates tended to be just below the set rating for each increment.

Force output. Significant changes were observed in the shape and magnitude of the force output curve at each of the increments (Fig. 2 and Table 1). Significant differences with respect to peak force were observed ($P < 0.0001$) between step 1 and steps 3, 4, and 5 and the 2-min maximal test, and between step 2 and the fifth step and maximal test, with force output rising with increased stroke ratings. Correspondingly, the point at which the peak force occurred during the stroke became later in the stroke at the higher ratings, reaching significance when the first and second steps were compared with the fifth and maximal steps ($P < 0.0001$). The end of the drive phase tended to occur at the same point in the stroke except in the maximal test where it occurred significantly later in the stroke ($P < 0.0001$). Stroke length remained relatively consistent throughout the incremental steps; however, it was noted to shorten during the maximal test, although this did not reach significance (being between 137 cm and 139 cm during the first to fifth steps, shortening to 131 cm on the maximal test.).

Femoral rotation. Small changes were observed in femoral rotation during the stroke (Fig. 3, Table 2). The magnitude of femoral rotation in the sagittal plane at the catch position (0% of the stroke) showed little variation, with maximal rotation occurring just before the catch. The degree of femoral rotation at the finish (which was defined as the point at which there was no force production at the handle), however, showed significantly reduced extension at higher rates ($P < 0.00001$). The statistical analysis also revealed that these differences occurred when each of the incremental steps were compared with the maximal test at a significance level of $P < 0.0001$. This was mirrored by a trend towards maximal femoral extension occurring later in the stroke (occurred between 31% and 33% at steps 1–5, and 35% during the maximal test) and being of lesser magnitude (reducing sagittal plane rotation by 2–3°). In addition, the length of time the legs were held in extension after the finish of the stroke and during the early recovery phase tended to become shorter at the higher ratings with this being most marked during the maximal test (legs held down for between 15.6 and 16.2% of the stroke during steps 1–5, only 13.3% of the stroke for the maximal test).

Lumbopelvic rotation. Minimal changes were seen in pelvic rotation. Anterior rotation of the pelvis is denoted by more positive angles, and posterior rotation is denoted by more negative angles, (Fig. 1). At the catch pelvic rotation was between 8.5 and 13.6º. Less anterior rotation occurred at the higher ratings; this being more marked but still nonsignificant during the maximal test. At the finish, the magnitude of posterior rotation varied between ratings (Table 3). Similarly small and statistically insignificant changes were seen with respect to maximal anterior and posterior rotation. Of interest, however, was the point at which maximal posterior rotation occurred; this occurred later in the stroke with increasing ratings, with differences between the first and second increment and the fifth increment and maximal test, and between the third and fourth increment and the fifth increment ($P < 0.0001$). This would suggest inferior trunk and pelvic control at the finish.

Lumbothoracic rotation. The lumbothoracic rotation patterns followed similar trends to the lumbopelvic rotation. Greater magnitude of lumbar flexion compared with pelvic flexion were observed at the catch. This remained consistent during the different incremental steps although it was noted that the magnitude reduced during the maximal test (26.0° at the catch in step 1 reducing to 22.0° during the maximal test) (Table 4). At the finish, a variable pattern of extension was observed between the increments, with magnitudes of lumbar extension being greater than pelvic rotation. Of interest, maximum lumbar extension occurred after the finish of the stroke, occurring significantly later in terms of the percentage stroke ($P < 0.01$) when the initial three incre-

TABLE 3. Changes in pelvic rotation during the incremental test (mean and standard deviation, $N = 12$), NB anterior rotation of the pelvic denoted by positive angles, posterior by negative.

	Step 1	Step 2	Step 3	Step 4	Step 5	Max
Anterior rotation at the catch (°)	13.3 ± 6.1	13.6 ± 6.4	12.7 ± 6.0	13.1 ± 5.9	12.6 ± 5.9	8.5 ± 4.9
Posterior rotation at the finish (°)	−13.5 ± 8.8	−20.9 ± 7.4	−21.1 ± 5.2	−19.8 ± 7.7	−19.7 ± 8.4	−14.5 ± 9.5
Maximum anterior rotation (°)	85.3 ± 11.4	84.8 ± 10.6	88.3 ± 8.6	88.3 ± 9.0	91.1 ± 7.2	91.3 ± 4.6
% stroke where maximal anterior rotation occurs	15.5 ± 6.1	15.6 ± 6.3	14.5 ± 5.9	15.0 ± 5.9	14.3 ± 6.0	9.6 ± 5.0
Maximum posterior rotation (°)	−23.8 ± 8.2	−25.3 ± 8.2	−27.3 ± 7.8	−27.4 ± 8.1	−28.5 ± 8.7	−30.7 ± 8.0
% stroke where maximal posterior rotation occurs	33.3 ± 2.8	33.3 ± 2.6	34.0 ± 3.1	35.5 ± 3.8	37.3 ± 3.4	40.2 ± 2.7

TABLE 4. Changes in lumbar rotation during the incremental test (mean and standard deviation, $N = 12$), NB lumbar flexion is denoted by positive angles, extension by negative.

	Step 1	Step 2	Step 3	Step 4	Step 5	Max
Flexion at the catch (°)	26.0 ± 5.0	26.2 ± 5.5	25.0 ± 5.6	26.1 ± 5.6	26.2 ± 5.8	22.1 ± 7.4
Extension at the finish (°)	−13.8 ± 10.5	−24.9 ± 5.3	−24.3 ± 4.8	−22.4 ± 7.0	−22.4 ± 7.1	−15.3 ± 14.6
Maximum flexion in stroke (°)	27.1 ± 4.9	27.4 ± 5.5	26.1 ± 5.5	27.1 ± 5.4	27.1 ± 5.7	22.7 ± 7.3
% stroke where maximum flexion occurs	96.2 ± 3.4	96.8 ± 2.8	96.8 ± 2.9	97.2 ± 2.7	97.3 ± 2.8	97.3 ± 2.4
Maximum extension in stroke (°)	−29.3 ± 4.2	−31.2 ± 4.6	−33.1 ± 4.7	−33.7 ± 5.1	−35.0 ± 6.9	−36.8 ± 8.3
% stroke where maximum extension occurs	33.5 ± 2.3	34.0 ± 2.2	34.7 ± 2.7	35.6 ± 3.3	36.4 ± 3.6	38.9 ± 3.5

ments were compared with the maximal test; this may also be related to a change in stroke length at the higher rating.

Ratio of lumbothoracic to lumbopelvic motion. Previous work has indicated the importance of lumbopelvic rhythm to low-back pain in rowers (13,16,21); therefore, the ratio of lumbar to pelvic rotation in the sagittal plane at the catch and finish positions was calculated (Fig. 4). These ratios suggest that the rowers are utilizing more lumbar spine motion than pelvic rotation in reaching the extremes of the rowing stroke position. At the catch, this is marked with a greater percentage of lumbar spine movement to pelvic movement, this observation did not reach statistical significance. At the finish of the stroke, the ratio reduced nonsignificantly, suggesting that the athletes adopted a more "slumped" posture at the finish. However, particularly in the catch ratios great variability is seen between athletes (as observed in the comparatively large standard deviations), suggesting possibly different levels of trunk control and skill.

Movement of the handle. Parameters of handle movement were also investigated. The initiation of movement of the hands towards the body was examined. This was defined as the point at which the handle ceased moving toward the ergometer flywheel and started moving away from the flywheel. This was noted to occur at 97.0–97.3% of the stroke cycle, depending on the stroke rating with little if any difference observed between ratings. However, the initiation of "hands away" or movement of the handle away from the body showed significant variation with these occurring between 31.3 and 33.1% for the low ratings (steps 1–3) and 34.8–36.8% for the higher ratings (steps 4–5), and reaching 42.6% during the maximal test. The differences between low ratings and the maximal test were significant ($P < 0.001$).

Event timings. The following event timings were noted: catch (0% by definition), finish (force zero), legs down, hands away, maximum back rotation, maximum pelvis flexion, legs up, minimum pelvis flexion, minimum back rotation, hands forward, and maximum femoral flexion. The sequence of these events at the catch and finish were assessed. Differences in these events timings were observed between subjects; however, overall each subject was consistent throughout the incremental steps. At the catch, 3 of the 12 rowers replicated the same patterns of events: namely, pelvic rotation followed by thoracolumbar rotation, the hands coming forward maximally and the legs straightening ("legs down"). Another subject closely followed this pattern; however, the legs preceded the hands. The remaining subjects showed a dissynchronization between the pelvis and back movements. Body segments leading the movement varied between the legs, back, and pelvis.

The subjects exhibited consistent patterns at the catch position, as described above. However, they exhibited marked within-subject variability at the finish, particularly at the higher ratings. This resulted in between-subject consistency at these higher ratings: nine of the subjects followed

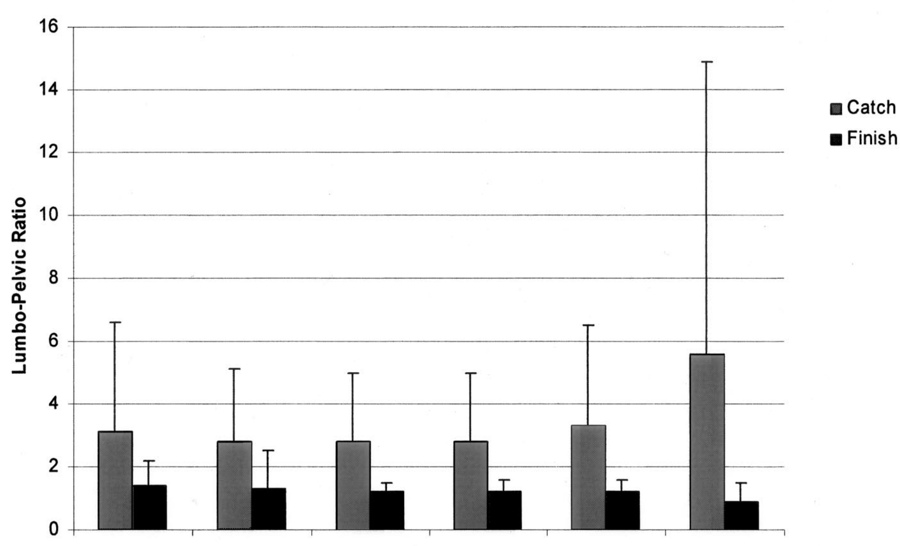

FIGURE 4—Average (error bars standard deviation) ratio for lumbopelvic motion at the catch and finish positions ($N = 12$)

the same sequence of maximal body rotations, namely, femoral extension, followed by hands moving away, pelvis rotating posteriorly, the back extending before finally the leg break to return to the flexed position during the recovery. One subject had the pelvis and back rotating before the hands, and the other two showed again a dissynchronization between the pelvis and back movements.

DISCUSSION

This study examined the kinematics of rowing of an elite group of female rowers during a routine incremental step test. Such step tests are used by coaches and physiologists to establish appropriate training intensities, assess health status, and provide feedback regarding the effectiveness of training. The workload is set according to each individual athlete's capability, and the increments allow a range of normal training intensities to be assessed. During this testing, heart rates and blood lactate responses to incremental work are measured to provide estimates of the athlete's metabolic efficiency. Such a protocol provides an ideal opportunity to assess the effect of incremental work stress on spinal kinematics.

Changes were observed in the force curve profiles during the incremental steps with a rise in peak force and power during testing. The force curves were also noted to shift to the right with peak force production occurring later in the stroke, a feature noted to concur with increased boat velocity (11). This contrasts with the findings from a group of novice rowers (14), where a reduction in peak force was observed at higher intensities due to a possible mistiming of the catch phase in these athletes. It also suggests a more effective technique in elite rowers, which is in line with findings in the literature (18,19). Hartmann et al.'s (8) study examining power strokes noted a reduction in stroke length and peak force in elite rowers, a result not expected by athletes and coaches, and a finding not substantiated by this study, which noted a consistent stroke length throughout steps 1–5.

Although changes in femoral, lumbopelvic, and lumbothoracic rotations were observed with increased ratings, these changes were not as marked as those observed in novice rowers (14). Of note, most changes in kinematics were observed during the 2-min maximal test, suggesting that at race rating technique may be altered and compromised. A major part of athlete coaching focuses on the finer points of technique, suggesting that these finer points are important to performance and that there is an ideal technique that a coach and athlete should strive for. However, it is not clear what constitutes "good technique," or how the kinematic changes observed in this study relate to performance. Of particular note was the shortening of the stroke length, loss of lumbopelvic rotation at the catch, and a tendency toward overextension of the back and pelvic at the finish during the maximal test. This may be a reflection of poor trunk control and muscle endurance, with previous research suggesting trunk imbalance and high fatigue levels in rowers (15). However, further work is required. The changes in lumbopelvic rotation and the overuse of the back may be associated with injury, because they may lead to overloading of the back.

These findings are also reflected in the ratios of lumbar spine motion to pelvic motion or lumbopelvic rhythm. These ratios also suggest that the lumbothoracic spine motion is greater during the forward motion of the trunk than the degree of pelvic anterior rotation, which compromised the lumbopelvic rhythm and influences the resultant stroke length. Also an important finding is that this ratio has a very high standard deviation at the maximal test, suggesting that this control is compromised in different ways by different athletes. This may be of relevance because previous work has associated changes in lumbopelvic rhythm with low-back pain (13). Such changes may be related to patterns of trunk strength in these athletes (15,17) or patterns of motor control; this, however, requires further investigation.

In contrast to the club-level athletes previously investigated, greater individual consistency (i.e., the ability to move using the same segmental motion pattern) was observed in the sequencing of body segments at the catch and finish of the stroke. Consistency among athletes was also noted to be greater at the finish than at the catch position, and much of this consistency at both the catch and finish was linked to the coordination of the lumbar spine and pelvis. Previous research examining forward flexion in a low-back population has suggested that this coordination of movement between the lumbar spine and pelvis is of importance and can be altered in subjects with low-back pain leading to a redistribution of load and stress on the posterior elements of the lumbar spine (7,12), which may contribute to spinal injury and wear related problems. Thus, from an injury perspective, this may be an important finding. Additionally, Baudouin and Hawkin (2) suggested that coordination and synchrony between rowers in the same boat was of importance in optimizing the overall system velocity, thus implicating this finding in performance, a finding previously stressed by Wing and Woodburn (22).

To summarize, this study has identified the spinal kinematics of elite rowers at different incremental work intensities, and noted subtle but important changes to these kinematics at increasing work levels. Such changes, particularly those related to lumbopelvic and thoracolumbar motion, may have importance with respect to overloading the spine and the development of low-back pain.

The authors would like to thank British International Rowing and the Henley Stewards Charitable Trust for their support of this work and would like to extend particular thanks to the athletes involved, their coach Mr. Paul Thompson, and their physiologist Mr. Al Smith.

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