Kinematic Asymmetries of the Lower Limbs during Ergometer Rowing

ERICA BUCKERIDGE[1,2], SIMON HISLOP[1], ANTHONY BULL[2], and ALISON MCGREGOR[1]

[1]*Department of Surgery and Cancer, Imperial College London, UNITED KINGDOM; and* [2]*Department of Bioengineering, Imperial College London, UNITED KINGDOM*

ABSTRACT

BUCKERIDGE, E., S. HISLOP, A. BULL, and A. MCGREGOR. Kinematic Asymmetries of the Lower Limbs during Ergometer Rowing. *Med. Sci. Sports Exerc.*, Vol. 44, No. 11, pp. 2147–2153, 2012. **Purpose**: Rowing injuries, particularly of the lumbar spine, are often attributed to poor technique. Rowing technique comprises a series of coordinated movements between the back, upper limbs, and lower limbs, and abnormalities in these may lead to injury. The aim of this study was to test the hypothesis that ergometer rowing is symmetrical with respect to lower limb motion and that deviations from symmetry result from rowing experience, work rate, or stroke position. **Methods**: Twenty-two rowers in three levels of ability participated in this study. A motion analysis system was used with an instrumented rowing ergometer, which incorporated load cells at the handle and seat. Kinematic measurements of the knees, hips, lumbar–pelvic joints, and pelvic twist, in addition to measures of handle force, seat force, stroke length, mediolateral seat drift, and mean external power, were made during an incremental step test. **Results**: Elite rowers exhibited the largest handle force and mean external power ($P < 0.01$) and least mediolateral seat drift ($P < 0.01$). All groups demonstrated lower limb asymmetries, with hip asymmetries significantly greater than knee asymmetries ($P < 0.01$). Regression analysis indicated that both hip and knee range of motion (ROM) asymmetry was significant ($P < 0.05$) in predicting lumbar–pelvic flexion at the catch and maximum handle force of the stroke. However, hip ROM asymmetry showed a better relation with lumbar–pelvic flexion compared with knee ROM asymmetry, explaining a greater proportion of the variance. **Conclusion**: Bilateral asymmetries during the rowing stroke, particularly at the hips, can contribute to suboptimal kinematics of the lumbar–pelvic region. Quantification of hip ROM asymmetries may therefore be a useful tool in predicting the development of low back pain in rowers. **Key Words:** SPINAL KINEMATICS, BILATERAL, MOTION ANALYSIS, LOAD CELL, ELECTRO-MAGNETIC

Rowing is a cyclic activity that requires a precise, fluid technique to maximize the mean velocity of the system (boat, rower(s), and oars) over a competition distance, i.e., 2000 m for Olympic competitions. During rowing, contact forces between the rower and equipment act on the feet, seat, and handle/oar. These forces result from acceleration of the rower; thus, accurate sequencing of rowers' segments is important in maximizing the power-producing capacity of the rower (7). First, the legs initiate the drive through rapid extension of the knees, followed by a posterior lean of the torso to maintain power through the trunk, finally drawing the hands toward the body to finish the stroke. Inability to execute the rowing stroke correctly or with poor technique affects efficiency of power transmission and consequent rowing performance (12). In addition, poor technique is thought to be a major cause of chronic rowing injuries, particularly affecting the lumbar spine region (5).

Sculling and sweep oar rowing require different trunk and upper limb kinematics because of the asymmetrical nature of sweep oar rowing, which requires the rower to rotate their trunk, causing the upper limbs to follow an asymmetrical arced trajectory. In addition, there are some differences in lower limb kinematics where scullers' legs move in parallel, whereas a sweep rowers' outside leg (leg opposite the oar) is positioned more laterally than the inside leg (11). Many studies have investigated kinematics of the rowing stroke (13,22,24,30). However, few have examined kinematics with respect to bilateral asymmetry of the lower limbs, with measurements often being made on one side of the body (5), with Caplan and Gardner (8) combining joint angles for the left and right side

Address for correspondence: Erica Buckeridge, Charing Cross Hospital, Imperial College London, 7L16 East Wing, London W6 8RF, United Kingdom; E-mail: e.buckeridge09@imperial.ac.uk.
Submitted for publication November 2011.
Accepted for publication May 2012.

0195-9131/12/4411-2147/0
MEDICINE & SCIENCE IN SPORTS & EXERCISE®

DOI: 10.1249/MSS.0b013e3182625231

of the body to give a mean angle for each joint. Janshen et al. (14) found similar ranges of motion between left and right; hip, knee, and ankle angles in the sagittal plane in a small group of seven national rowers. However, it may be incorrect to assume that the left and right sides of the body perform symmetrically, particularly in novice and club level rowers with lesser technical experience than elite rowers. The rowing stroke is similar to a lifting task where it is advocated to lift with symmetrical coordinated movements to minimize torsional loading and thus lower back disorders (15). Despite rowing being performed in a seated position with body weight supported, there is evidence to suggest that pelvic asymmetry can affect the dynamics of trunk motion while sitting, thus putting the lumbar spine under greater stress (1). Consequently, executing the rowing stroke with asymmetrical lower limb motion may result in compensatory pelvic motions and cocontractions of muscles such as the transverses abdominis and erector spinae to keep the trunk stabilized, thus influencing the action of the spine. Past work has shown that rowing technique deteriorates at progressively higher work rates by demonstrating an increase in lumbar–pelvic flexion (17), which in itself has been shown to be an important risk factor for rowing injury (19). Therefore, the aims of this study were to examine lower limb kinematic asymmetries and their consequent impact on lumbar–pelvic kinematics during varying intensities of ergometer rowing and between rowers of varying standards. It was hypothesized that ergometer rowing would be symmetrical with respect to motion of the legs and that deviations from this symmetry would result from rowing experience (i.e., novice, club, and elite), work rate, or stroke position (i.e., catch, maximum handle force (MHF), finish, and recovery).

METHODS

Participants. This study received local ethical approval, and written informed consent was obtained from all subjects. Twenty-two male rowers were recruited into this study from local rowing clubs in London. Of these, six were novice rowers, eight were club level rowers, and eight were elite rowers. Group classification criteria are outlined in Table 1. The sample size was deemed large enough for a moderate effect size of 0.5 and statistical power of 95% with an α significance level of 0.05. Subjects with a leg difference of more than 1 cm, current episode of low back pain, or any other serious illness or injury were excluded from participation in this study.

Instrumented ergometer and motion capture. All rowers performed their trials on a modified Concept II model D ergometer (Concept2, Morrisville, VT) (21). The ergometer was instrumented at the handle with a uniaxial load cell (ELHS model; Entran, Lexington, KY) to measure pulling force on the handle (2.5 kN range, 0.5% combined nonlinearity and hysteresis). The flywheel was instrumented with a linear encoder with 5000 increments per revolution (ERN120; Heidenhain Ltd., Traunreut, Germany) to enable measurements of stroke length. The seat was instrumented with four uniaxial load cells (ELPM model, Entran) to measure center of pressure (COP) and vertical forces on the seat (21) (1.25 kN range, ± 0.15% hysteresis, and 0.15% nonlinearity). Signals from the instrumented rowing machine were hardware synchronized and connected to a personal computer through a multichannel signal conditioning unit (SC-2345; National Instruments, Austin, TX).

Rower kinematics were recorded using the Flock of Birds (FOB) motion capture system (Ascension Technology, Burlington, VT). The system consists of an extended range electromagnetic transmitter, situated at a location that would optimize measurement accuracy (20), and four receivers (S1–S4) whose translations (x, y, z) and rotations (α, β, γ) could be quantified within the electromagnetic field. Previous work has validated this system's suitability for measuring spinal and lower limb motion (2–3,5).

Subject preparation and digitization. The lumbar FOB sensor (S3) was placed at the thoracolumbar junction (T12/L1), the pelvic sensor (S2) was attached at the lumbar–sacral junction (L5/S1), and the remaining two sensors were attached to the anterior tibial spine at a point midway between the knee and ankle on the right (S4) and left (S1) legs. Adhesive pads (PALstickies™; PAL Technologies Ltd., Glasgow, Scotland) were used to secure the sensors to skin.

Before recording, some bony landmarks were digitized by attaching S3 to a digitization stylus. The tip of the digitization stylus was placed on the landmark of interest and rotated about that point to create a cloud of 3-D position data. A sphere fitting procedure was then used to work out the 3-D position of that point relative to the sensors already attached to the body segments, so that the trajectories of the landmarks could be tracked at all points during the rowing stroke.

The following landmarks were bilaterally digitized while the rower was seated: fifth metatarsals (MET5) (expressed in the global frame), lateral and medial malleoli, lateral and medial femoral epicondyles (expressed in S1 or S4 frame), anterior superior iliac spines (ASIS), and posterior superior iliac spines (expressed in S2 frame). The rower then stood to perform a functional test to find each hip joint center (6). This involved strapping the digitizing stylus to the subject's thigh and the subject rotating their thigh to capture all ranges of motion about their hip to enable a sphere fitting procedure to find the center of rotation (expressed in S2 frame).

TABLE 1. Study population details.

Group	N	Mean Age ± SD (yr)	Mean Mass ± SD (kg)	Mean Height ± SD (cm)	Experience	2-km Personal Best ± SD (Minutes:Seconds)
Elite	8	24.6 ± 4.5	87.9 ± 10.5	189.9 ± 8.5	>3 yr (participated in a World Championship)	6:05 ± 0.11
Club	8	21.3 ± 1.5	80.8 ± 8.6	184.4 ± 6.8	>1 yr	6:28 ± 0.08
Novice	6	20.8 ± 3.1	84.4 ± 6.4	186.0 ± 7.6	≤0.5 yr	6:38 ± 0.14

Testing protocol. Each subject performed a 10-min warm-up on the ergometer before testing. They then performed the following step test with at least a 5-min rest period between steps:

Step 1: 4 min of rowing rating 18 strokes per minute—this is a pace consistent with the athletes standard UT2 (utilization training 2 where athletes aim to keep their heart rate between 130 and 150 bpm) pace.
Step 2: 4 min at 20 strokes per minute at a pace consistent with the athlete's personal best score for 30 min at rate 20.
Step 3: 500 m at a pace consistent with the athlete's personal best 2000-m pace.
Step 4: 30 strokes at maximal rate and power output.

Data collection and analysis. Custom software was written in LabVIEW (version 7.1, National Instruments) to initialize and synchronize the signals from the instrumented rowing machine and FOB, to acquire measurement data from all sensors at a rate of 50 Hz, and write the data to an ASCII file.

All recorded strokes cycles were normalized to 101 data points with 0% representing the catch of the stroke and 100% representing the completion of the stroke before the subsequent catch point. In this study, the catch was considered to be a point that corresponded to the start of propulsion and was defined as the onset of tensile force at the handle where the force first exceeds 75 N. This has been found to be a highly robust and repeatable measure of the catch (13,18). The finish was defined as the point at which tensile force production was less than 50 N. Of all the normalized strokes recorded within a trial, 10 strokes in the middle of each trial were extracted for statistical analysis.

3-D kinematic data of bony landmark trajectories was derived using a custom written program in MATLAB (MathWorks Inc., Natick, MA). 3-D landmarks and sensor positions were transformed from the global coordinate frame to the local coordinate frame with the origin defined as the midpoint of the left and right MET5 landmarks. Bilateral hip joint angles were calculated using the joint coordinate system (10) where the hip joint coordinate frame was derived from the pelvis and thigh coordinate frames (19). Because of problems digitizing the lateral malleoli, bilateral knee joint angles were defined as the angle between a line joining the hip joint center and the proximal origin of the shank (defined as midway between the two femoral epicondyles at the time of digitization) and the line of the respective shank sensors. Lumbar–pelvic angles were determined by subtracting the value of the pelvic sensor from the lumbar sensor. Pelvic twist was calculated based on the positions of the left and right ASIS landmarks. It was defined as the angle that the vector between the ASIS landmarks made with the vector between the MET5 landmarks. A positive angle was defined as clockwise pelvic twist, and a negative angle was defined as anticlockwise pelvic twist.

Performance parameters were calculated as follows. Stroke length was quantified on the basis of maximum and minimum handle displacement values, whereas mean external power per stroke was defined as the integral of the handle displacement–handle force curve divided by stroke time. Seat COP was quantified based on the values of the seat's load cells. Deviations in COP from the seat's midline resulted in mediolateral drift, with cumulative drift values calculated per stroke. The absolute of the symmetry index (ASI) proposed by Robinson et al. (27) was used to assess the degree of asymmetry in hip range of motion (ROM) and knee ROM and was calculated using the following equation:

$$\mathrm{ASI}(\%) = \frac{2|\chi_{\mathrm{right}} - \chi_{\mathrm{left}}|}{(\chi_{\mathrm{right}} + \chi_{\mathrm{left}})}\ 100 \qquad [1]$$

X_{right} is the value of the right limb and X_{left} is the value of the left limb. An ASI value of zero indicates perfect symmetry, and increasingly positive values indicate increasing magnitudes of bilateral asymmetry.

All measured parameters were sampled at four points in each stroke: the catch, the point of MHF during the drive phase, the finish position, and at 10% of the recovery. Good organization of the recovery phase sequence (arms straightening, anterior rotation of the trunk and pelvis, and knees flexing to bring the weight of the rower onto the feet) prepares the rower for the change of direction at the catch and progression of the drive phase. Thus, measuring 10% of the recovery can help assess the recovery sequence.

Statistical analysis. All statistical analyses were performed using SPSS (version 19; IBM Corporation, Armonk, NY). Group means and SDs from 10 strokes of each trial were computed, and normality of the data set was tested using the Shapiro–Wilk test. A two-way mixed model ANOVA was run to determine whether bilateral differences in hip and knee joint angles were statistically significant and to look for differences in parameters such as MHF, mean external power, stroke length, mediolateral seat drift, and knee and hip ROM, with respect to rowing experience, stroke positions, and work rates. A two-way mixed model ANOVA was also used to examine differences in ASI of the hip and knee joints with respect to rowing experience and work rate. Where an overall significance was seen, Bonferroni *post hoc* tests were conducted for further analysis. A multiple linear regression model was used to evaluate whether asymmetries in hip ROM and knee ROM could predict lumbar–pelvic flexion at the catch and MHF. Significance level for all tests was set at $P < 0.05$.

RESULTS

Performance-related parameters. The means and SDs for all performance-related parameters are presented in Table 2. MHF and mean external power were the two performance parameters found to be significantly greater in elite rowers compared with both club and novice rowers ($P < 0.01$). There were also significant increases in these parameters at each of the four progressive work rates ($P < 0.01$). However, only mean external power demonstrated a significant interaction effect for work rate and experience ($P < 0.05$). In

TABLE 2. External performance measures at steps 1–4 for all rowing groups (mean ± SD).

		Step 1	Step 2	Step 3	Step 4
MHF (N)	Elite	921.9 ± 86.7	1031.5 ± 93.0*	1016.1 ± 64.8*	1066.3 ± 79.4*
	Club	871.8 ± 68.4$	921.5 ± 66.5*,$	888.6 ± 79.8*,$	920.4 ± 73.1*,$
	Novice	823.1 ± 100.3$	885.2 ± 106.8*,$	872.6 ± 84.3*,$	954.8 ± 79.8*,$
Mean external power (W)	Elite	253.8 ± 24.1	311.5 ± 30.1*	437.2 ± 36.8*,£	581.0 ± 73.1*,£
	Club	238.8 ± 27.5$	278.0 ± 25.8*,$	383.4 ± 36.0*,£,$	474.0 ± 52.9*,£,$
	Novice	211.1 ± 20.7$	246.9 ± 19.8$	378.8 ± 33.6$	477.6 ± 61.6$
ML seat drift (mm)	Elite	115.6 ± 76.0&	125.8 ± 51.7&	135.3 ± 48.7&	208.4 ± 94.8&
	Club	118.7 ± 74.1&	131.5 ± 70.5&	169.6 ± 55.4&	188.9 ± 69.0&
	Novice	211.1 ± 20.7	246.9 ± 19.8	378.8 ± 33.6	477.6 ± 61.6
Stroke length (mm)	Elite	1506.3 ± 70.0	1537.5 ± 60.3	1512.5 ± 70.0	1545.0 ± 70.0
	Club	1552.5 ± 104.3	1576.3 ± 100.9	1530.0 ± 117.4	1516.3 ± 113.0
	Novice	1486.3 ± 81.3	1491.7 ± 78.7	1485.0 ± 77.7	1525.0 ± 57.1

* Statistically significant difference from step 1 ($P < 0.05$).
£ Statistically significant difference from step 2 ($P < 0.05$).
$ Statistically significant difference from elite ($P < 0.05$).
& Statistically significant difference from novice ($P < 0.05$).
ML, mediolateral.

addition, there was a progressive increase in mediolateral drift at each of the four progressive work rates ($P < 0.01$), with novice rowers exhibiting significantly greater mediolateral drift on the seat compared with elite and club rowers ($P < 0.05$). However, stroke length did not differ between groups ($P = 0.64$).

Lower limb kinematics. With regard to ROM of the lower extremities, there was a trend for hip ROM to decrease from elite to novice rowers (Table 3). Elite rowers also appeared to exhibit greater knee extension at the finish position, with seven of eight elite rowers hyperextending one or both of their knees, whereas this was only evident in 2 of 6 novice rowers. Knee ROM demonstrated no statistical differences between novice, club, and elite rowers ($P = 0.21$); however, hip ROM may have the potential to distinguish between groups ($P = 0.08$). In terms of the effect of work rate on kinematics, knee and hip angles demonstrated a reduction in ROM as work rate increased ($P < 0.01$).

Bilateral differences in sagittal plane kinematics were observed at the hip ($P < 0.01$) and knee joints ($P < 0.01$); however, there were no subsequent interactions between asymmetry and rowing experience (hip, $P = 0.76$; knee, $P = 0.37$) or work rates (hip, $P = 0.09$; knee, $P = 0.27$). Hip asymmetries were evident at all four points in the rowing stroke ($P < 0.01$), whereas knee angles only exhibited asymmetries at MHF and 10% recovery ($P < 0.01$). ASI values for hip ROM and knee ROM were not sensitive to work rate or rowing experience; however, hip ROM was more asymmetrical than knee ROM ($P < 0.05$). This is demonstrated in the bilateral hip and knee angle trajectories seen in Figure 1.

TABLE 3. Hip and knee ROM and ASI and pelvic twist in the three groups of rowers (mean ± SD).

	Elite	Club	Novice
Right knee ROM (°)	134.5 ± 14.1	135.1 ± 14.1	140.4 ± 9.0
Left knee ROM (°)	135.3 ± 14.9	138.3 ± 14.9	139.6 ± 13.8
Knee ROM ASI (%)	3.0 ± 2.1	5.4 ± 5.3	5.0 ± 5.7
Right hip ROM (°)	97.2 ± 10.6	94.9 ± 10.7	90.6 ± 8.4
Left hip ROM (°)	92.7 ± 9.0	93.2 ± 8.2	87.2 ± 8.1
Hip ROM ASI (%)	6.4 ± 3.4*	6.3 ± 5.9*	9.0 ± 10.3*
Absolute pelvic twist (°)	14.5 ± 6.2	10.9 ± 5.8	12.3 ± 6.4

* Statistically significant difference from knee ROM ASI ($P < 0.05$).

Lumbar–pelvic kinematics. Lumbar–pelvic kinematics in the sagittal plane was sensitive to stroke position, with the lumbar–pelvic angle differing at all stroke positions ($P < 0.01$) except between catch and MHF (Fig. 2). There was a significant interaction effect between work rate and stroke position ($P < 0.01$) where an increase in work rate saw corresponding increases in lumbar–pelvic flexion at the catch and a reduction in lumbar–pelvic flexion at the finish (Fig. 2). Lumbar–pelvic kinematics of the frontal plane significantly differed between MHF and 10% recovery ($P < 0.01$). However, rowing experience, stroke position, and work rate had no effect on lumbar–pelvic kinematics in the transverse plane ($P > 0.05$).

In addition, there were no changes in pelvic twist as a result of rowing experience, work rate, or stroke position, nor did the direction of pelvic twist correlate with the direction of knee and/or hip asymmetry. Hip and knee ROM asymmetries were significantly correlated with lumbar–pelvic angle at the catch and MHF (Table 4). Regression analysis indicated that both hip and knee ROM asymmetries were significant ($P < 0.05$) in predicting lumbar–pelvic flexion. However, hip ROM asymmetry showed a better relation with lumbar–pelvic flexion compared with knee ROM asymmetry, explaining a greater proportion of the variance in the dependent variable (Table 4).

DISCUSSION

This study investigated kinematic asymmetries of the lower limbs during ergometer rowing. Using an adaptation of the system described by Bull and McGregor (5), it was found that ergometer rowing is not symmetrical with respect to lower limb kinematics, and this carries implications for both rowing performance and injuries.

In terms of rowing performance, there was an upward trend of handle force, stroke length, and mean external power for all groups of rowers as work rate increased. Conversely, work rate had the opposite effect on hip and knee ROM, with a consistent reduction in ROM. This was because rowers became progressively less effective at flexing their hips and knees at the catch and were not extending their knees as fully

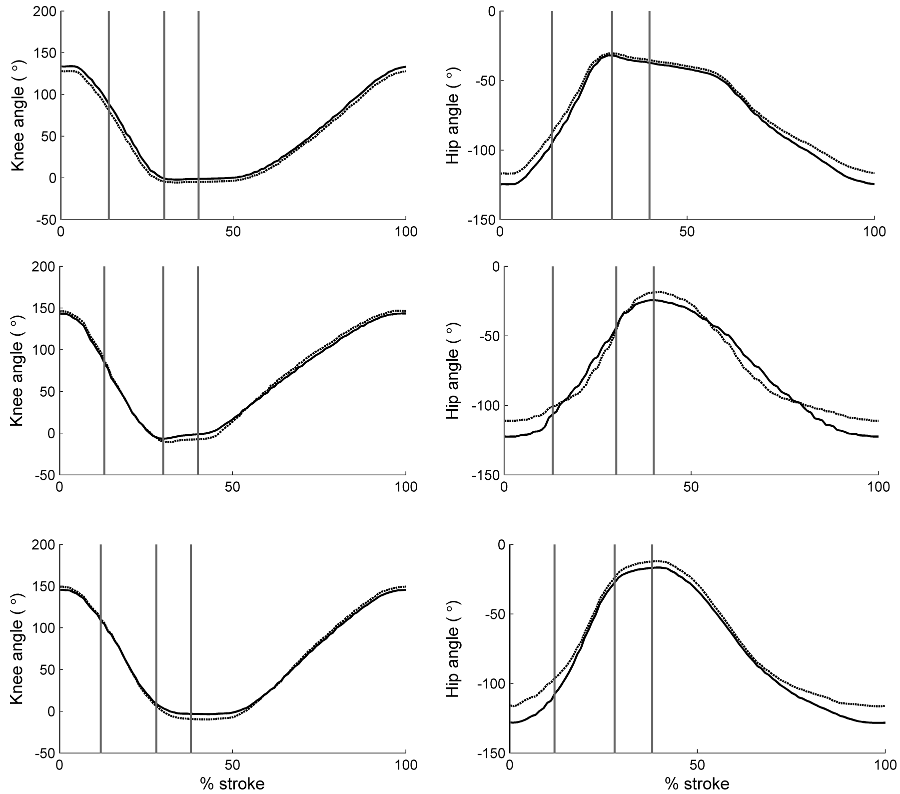

FIGURE 1—Bilateral joint angles over a normalized rowing stroke (*top row*, elite rower; *middle row*, club rower; *bottom row*, novice rower). *Solid line* represents right side, *dotted line* represents left side. 0° is full joint extension; hip flexions are negative, knee flexions are positive. *Vertical lines* represent MHF, finish, and 10% recovery positions from left to right.

at the finish of the stroke. In general, elite rowers had the largest hip ROM throughout the stroke and extended their knees the most at the finish. These observations correspond with suggestions from Murphy (19) that effective knee extension at the finish makes it easier to anteriorly rotate the pelvis during the recovery phase. Therefore, the greater performance parameters achieved by elite rowers (i.e., MHF and mean external power) may be due to more effective knee and hip kinematics, thus putting the pelvis in a stronger position at the catch. However, none of the kinematic parameters measured in this study were found to be significantly different between rowers of different standards. It has previously been noted that mediolateral drift on the seat is a predictor of performance on the rowing machine (19), and at all rates, it was found that elite and club rowers have significantly less mediolateral drift on their seat than novice rowers. However, the mechanisms that resulted in these groups' lower mediolateral drift scores cannot be accounted for by the results of their lower limb kinematic measures or associations with pelvic twist, because these did not significantly differ between groups. Therefore, additional nonkinematic factors such as asymmetries in knee extensor strength and hamstring flexibility may also contribute to the superior performance measured in elite and club rowers; these were not assessed in this study.

Bilateral differences between lower limb joint angles were observed in elite, club, and novice rowers at all work rates (Table 3). Rowers were tested at incremental work rates based on the findings of McGregor et al. (17), who found that with increased ratings, technique of rowers progressively deteriorated, which can be characterized by a reduction in pelvic anterior rotation at the catch (19). However, the current study indicates that such a decline in technique is not coupled with an increase in lower limb asymmetry, as

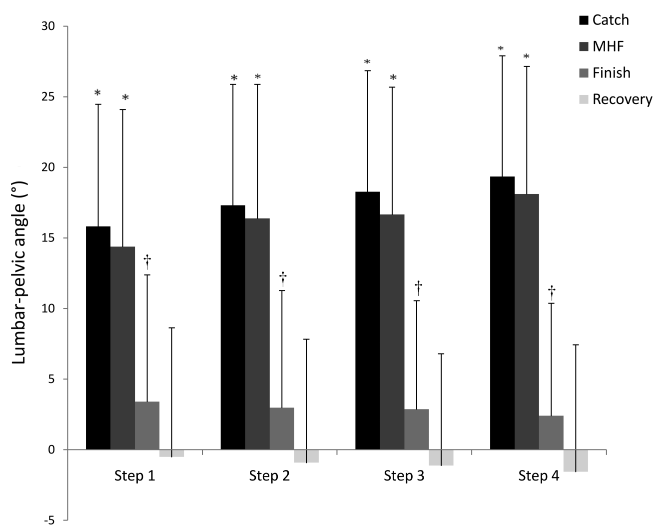

FIGURE 2—Average (*error bars* indicate SD) lumbar–pelvic flexion–extension angles at the catch, MHF, finish, and 10% recovery positions during four incremental steps. Lumbar–pelvic flexion is positive and lumbar–pelvic extension is negative. * Statistically significant difference from finish and recovery ($P < 0.05$). † Statistically significant difference from recovery ($P < 0.05$).

TABLE 4. Proportion of lumbar–pelvic flexion explained by kinematic asymmetries.

		R	R^2
Catch	Hip ROM ASI	0.59*	0.35*
	Knee ROM ASI	0.28*	0.08*
MHF	Hip ROM ASI	0.60*	0.36*
	Knee ROM ASI	0.33*	0.11*

* $P < 0.05$.

consistent levels of asymmetry were observed throughout the step test. Asymmetrical hip joint angles were evident at all four points in the stroke, whereas knee joint asymmetry occurred at just MHF and 10% recovery. In addition, ASI values of hip ROM were significantly greater than knee ROM, further emphasizing that the hips are at greater risk of asymmetrical motion compared with the knees (Fig. 2).

Prior research has been carried out looking into the effects of the asymmetrical rowing motion. It was hypothesized that muscle asymmetries and imbalances may be a cause of the high incidence of lower back pain seen in rowers (23). However, they found no significant difference in quadriceps force production or EMG muscle activity between the dominant and nondominant legs in sweep oar rowers and controls. Rowers have been identified to have poor hamstring strength relative to their quadriceps, and this hamstring weakness is believed to contribute to lower back injuries by impacting the lumbar–pelvic rhythm, thus increasing stresses placed on the spine (16). Consequently, the degree to which the hips are able to flex at the catch, in addition to the symmetry of this movement, could have a direct impact on the flexion and rotational developments of the lumbar–pelvic joint throughout the rowing stroke. Therefore, if lower limb asymmetries contribute to suboptimal lumbar–pelvic kinematics at the start of the drive phase, this could influence the likelihood of attaining a back injury. Stallard (29) stated that lumbar flexion and rotations at the start of the drive phase results in stretched spinal ligaments and tight apposition of the spinal joint facets, and any imbalances at this time will strain the lumbar spine causing ligament and joint capsule injury. This study demonstrated that the lumbar–pelvic joint is flexed between 15° and 21° at the start of the drive phase, and significant changes to these kinematics occurred as the stroke progressed. This indicates that rowers were not able to hold a strong stable trunk position from catch to finish, which is known to be deleterious to performance (19).

Despite Parkin et al. (23) observing no kinetic or muscle activation asymmetries, it was expected that asymmetrical lower limb kinematics would impact on the action of the pelvis and lumbar spine. This is because lower limb asymmetries would induce pelvic asymmetries at the base of the spine, which may transfer to a distortion of the spine itself, thus leading to theories that rowing asymmetry is related to spinal injury (25). The results here demonstrate that knee ROM asymmetry had poor predictive relations with lumbar–pelvic flexion at the catch and MHF, explaining just 8% and 11% of variance in lumbar–pelvic flexion, respectively. A moderately predictive correlation was found between hip ROM asymmetry and lumbar–pelvic joint flexion at both the catch position and MHF, accounting for 35% and 36% of variance in lumbar–pelvic flexion, respectively. It is not surprising that hip asymmetries explain a greater proportion of variance in lumbar–pelvic kinematics due to the origin and insertion of the iliopsoas muscle group, a hip flexor that crosses both hips and lumbar spine. Consequently, tight or overactive hip flexors will directly result in anterior pelvic tilt (28). Biarticular muscles such as the biceps femoris, semitendinosus, and rectus femoris all work on both the knee and hip joints. Therefore, the knees can only affect lumbar–pelvic motion via the hips and cannot directly impact the action of the pelvis, resulting in very low predictive power in the regression model.

Hip asymmetries were found to influence lumbar–pelvic flexion in this study despite a lack of correlation with pelvic twist. Distal segments of the lower and upper extremities are fixed in rowing; thus, asymmetries at the lower limbs must be compensated for through flexions and rotations at the lumbar–pelvic joint to maintain symmetrical handle motion in the sagittal plane. The direction of pelvic twist did not correlate with lower limb asymmetry, suggesting rotations about the transverse plane were not sensitive enough to mediate the effect of hip asymmetry on lumbar–pelvic kinematics, and that other means of compensation took place. Although it cannot be established as a cause and effect relation, there was clearly an association between hip ROM asymmetries and lumbar–pelvic kinematics in the sagittal plane, as demonstrated by the regression analysis. Consequently, the moderate correlation of the hips' effect on lumbar–pelvic kinematics at the catch and MHF indicates a need to carry out bilateral measurements of sagittal plane hip ROM in rowers of all standards. Goniometers are commonly used for the measurement of segment and joint angles, such as asymmetry of hip ROM (9), knee flexion (26), and pelvic tilt (31). Therefore, simple measurements of hip ROM asymmetry could be an effective way of preempting lower back problems in rowers and facilitates coaches and physical trainers in implementing interventions to improve hip symmetry and potentially lumbar–pelvic kinematics.

It must be noted that there was a limitation in the number of FOB sensors; therefore, the medial and lateral femoral epicondyles were tracked with respect to the tibial sensors rather than sensors attached to the femur. This method can result in maltracking of the epicondyles, partially because of anterior–posterior translation of the tibia during flexion–extension motions (4), resulting in fluctuations of femur length of up to 20 mm in this study. However, this would cause knee angles at the catch and MHF to be affected by less than 2°. Furthermore, femur length changes were bilaterally similar, with a root mean square error of 3.5 ± 1.3 mm (calculated for 10 strokes for all 22 rowers). Therefore, digitizing the femoral epicondyles relative to the tibial sensor had little impact on asymmetry values obtained at the knees and hips. As such, asymmetries observed in this study were due to kinematic differences rather than measurement errors.

This study has shown the rowing stroke on an ergometer to be asymmetrical, with significant bilateral differences between the knees and hips at specific positions in the stroke, with asymmetries also observed in joint ROM. A symmetrical stroke, in terms of force production at the lower limbs, would result in more equal loading of the spine, thus reducing the likelihood of injury (29). Consequently, more work should be done to discern the link between asymmetry of the rowing stroke and back injury. Instrumented foot stretchers that measure vertical and horizontal foot forces would be invaluable in quantifying the bilateral forces transferred during the rowing stroke and also provide other means of assessing technique and performance through the relation between symmetry of applied forces, joint moments, and power output. Nevertheless, the results of this study indicate a link between asymmetrical hip ROM and lumbar–pelvic kinematics. If asymmetrical kinematics can be identified in rowers through simple measurements of hip ROM, then techniques that predispose an athlete to injury can be identified and altered accordingly via biofeedback to the athlete and coach, thus going some way to prevent future injury.

This project was funded by the EPSRC and GB Rowing.
The authors would like to extend particular thanks to Mr. Paul Thompson for his expertise and insights into rowing technique.
No conflict of interest was reported for the authors.
The results of the present study do not constitute endorsement by the American College of Sports Medicine.

REFERENCES

1. Al-Eisa E, Egan D, Deluzio K, Wassersug R. Effects of pelvic asymmetry and low back pain on trunk kinematics during sitting: a comparison with standing. *Spine*. 2006;31(5):E135–43.
2. Bull AMJ, Berkshire FH, Amis AA. Accuracy of an electromagnetic measurement device and application to the measurement and description of knee joint motion. *Proc Inst Mech Eng H*. 1998;212(5):347–55.
3. Bull AMJ, Holt B, Wragg P, McGregor AH. Validation of the use of a skin-mounted device to measure out-of-plane rotations of the spine for a rowing activity. *J Musculoskelet Res*. 2004;8:129–32.
4. Bull AMJ, Kessler O, Alam M, Amis AA. Changes in knee kinematics reflect the articular geometry after arthroplasty. *Clin Orthop Relat Res*. 2008;466(10):2491–9.
5. Bull AMJ, McGregor AH. Measuring spinal motion in rowers: theuse of an electromagnetic device. *Clin Biomech*. 2000;15(10):772–6.
6. Camomilla V, Cereatti A, Vannozzi G, Cappozzo A. An optimized protocol for hip joint centre determination using the functional method. *J Biomech*. 2006;39(6):1096–106.
7. Caplan N, Coppel A, Gardner T. A review of propulsive mechanisms in rowing. *P I Mech Eng P-J Spo*. 2010;224(Pt 1):1–8.
8. Caplan N, Gardner T. The influence of stretcher height on posture in ergometer rowing. *Eur J Sport Sci*. 2010;10(4):263–8.
9. Ellison JB, Rose SJ, Sahrmann SA. Patterns of hip rotation range of motion: a comparison between healthy subjects and patients with low-back-pain. *Phys Ther*. 1990;70(9):537–41.
10. Grood ES, Suntay WJ. A joint coordinate system for the clinical description of three-dimensional motions: application to the knee. *J Biomech Eng*. 1983;105:136–44.
11. Herberger E. *Rowing/Rudern: The GDR Text of Oarsmanship*. Toronto: Sports Book Publisher; 1987. p. 235.
12. Hofmijster MJ, Soest AJ, van Koning JJd. Rowing skill affects power loss on a modified rowing ergometer. *Med Sci Sports Exerc*. 2008;40(6):1101–10.
13. Holt PJ, Bull AM, Cashman PM, McGregor AH. Kinematics of spinal motion during prolonged rowing. *Int J Sports Med*. 2003;24(8):597–602.
14. Janshen L, Mattes K, Tidow G. Muscular coordination of the lower extremities of oarsmen during ergometer rowing. *J Appl Biomech*. 2009;25(2):156–64.
15. Kingma I, van Dieen JH, de Looze M, Toussaint HM, Dolan P, Baten CTM. Asymmetric low back loading in asymmetric lifting movements is not prevented by pelvic twist. *J Biomech*. 1998;31(6):527–34.
16. Koutedakis Y, Frischknecht R, Murthy M. Knee flexion to extension peak torque ratios and low-back injuries in highly active individuals. *Int J Sports Med*. 1997;18(4):290–5.
17. McGregor AH, Bull AMJ, Byng-Maddick R. A comparison of rowing technique at different stroke rates: a description of sequencing, force production and kinematics. *Int J Sports Med*. 2004;25(6):465–70.
18. McGregor AH, Patankar ZS, Bull AMJ. Spinal kinematics in elite oarswomen during a routine physiological "step test." *Med Sci Sports Exerc*. 2005;37(6):1014–20.
19. Murphy AJ. *Elite Rowing: Technique and Performance [dissertation]*. London: Imperial College; 2009. p. 296.
20. Murphy AJ, Bull AMJ, McGregor AH. Optimising and validating an electromagnetic tracker in a human performance laboratory. *Proc Inst Mech Eng H*. 2011;225(4):343–51.
21. Murphy AJ, Chee STH, Bull AMJ, McGregor AH. The calibration and application of a force-measuring apparatus on the seat of a rowing ergometer. *P I Mech Eng P-J Spo*. 2010;224(Pt 1):109–16.
22. Page P, Hawkins D. A real-time biomechanical feedback system for training rowers. *Sports Eng*. 2003;6:67.
23. Parkin S, Nowicky AV, Rutherford OM,McGregor AH. Do oarsmen have asymmetries in the strength of their back and leg muscles? *J Sports Sci*. 2001;19(7):521–6.
24. Pollock CL, Jenkyn TR, Jones IC, Ivanova TD, Garland SJ. Electromyography and kinematics of the trunk during rowing in elite female rowers. *Med Sci Sports Exerc*. 2009;41(3):628–36.
25. Reid DA, McNair PJ. Factors contributing to low back pain in rowers. *Br J Sports Med*. 2000;34(5):321–2.
26. Rheault W, Miller M, Nothnagel P, Straessle J, Urban D. Intertester reliability and concurrent validity of fluid-based and universal goniometers for active knee flexion. *Phys Ther*. 1988;68(11):1676–8.
27. Robinson RO, Herzog W, Nigg BM. Use of force platform variables to quantify the effects of chiropractic manipulation on gait symmetry. *J Manipulative PhysiolTther*. 1987;10(4):172–6.
28. Schache AG, Blanch PD, Murphy AT. Relation of anterior pelvic tilt during running to clinical and kinematic measures of hip extension. *Br J Sports Med*. 2000;34:279–83.
29. Stallard MC. Backache in oarsmen. *Br J Sports Med*. 1980;14(2–3):105–8.
30. Torres-Moreno R, Tanaka C, Penney KL. Joint excursion, handle velocity, and applied force: a biomechanical analysis of ergonometric rowing. *Int J Sports Med*. 2000;21:41–4.
31. Walker ML, Rothstein JM, Finucane SD, Lamb RL. Relationships between lumbar lordosis, pelvic tilt, and abdominal muscle performance. *Phys Ther*. 1987;67(4):512–6.