P. J. E. Holt[1]
A. M. J. Bull[2]
P. M. M. Cashman[2]
A. H. McGregor[1]

Kinematics of Spinal Motion During Prolonged Rowing

Abstract

Low back pain is a common problem in rowers of all levels. Few studies have looked at the relationship between rowing technique, the forces generated during the rowing stroke and the kinematics of spinal motion. Of particular concern with respect to spinal injury and damage are the effects of fatigue during long rowing sessions. A technique has been developed using an electromagnetic motion system and strain gauge instrumented load cell to measure spinal and pelvic motion and force generated at the handle during rowing on an exercise rowing ergometer. Using this technique 13 elite national and international oarsmen (mean age 22.43 ± 1.5 y) from local top squad rowing teams were investigated. The test protocol consisted of a one hour rowing piece. During this session rowing stroke profiles were quantified in terms of lumbopelvic kinematics and stroke force profiles. These profiles were sampled at the start of the session and at quarterly intervals during the hour piece. From this data we were able to quantify the motion of the lumbar spine and pelvis during rowing and relate this to the stroke force profile. The stroke profiles over the one hour piece were then compared to examine the effects of prolonged rowing. This revealed marked increases in the amount of spinal motion during the hour piece. The relevance of this with regard to low back pain requires further investigation.

Key words
Anteroposterior motion · lumbar spine · force curve profiles · rowing kinematics · low back pain

Introduction

Rowing is considered to be among the most physically demanding of all endurance sports [14]. It involves an interaction between physical strength, endurance, the individual skill of the athlete and the optimal design of the equipment. Compared to many contact sports the level of injury in rowing is comparatively low. However, in recent years concern has been expressed about the number of spinal problems, with an incidence of 15–20% amongst elite and club level rowers [15,25].

In rowing the spine constitutes the central part of the kinetic chain linking the power generating sources (the legs and arms) of the stroke, and transferring this power efficiently to the oar. It has been hypothesised that the biomechanical demands of the rowing stroke produce repeated high magnitude forces to the lumbar spine [13,20,21]. However, the models used to determine these forces are not comprehensive and thus these forces may not be as high as predicted. They also do not account for physiological factors such as strength and endurance that may influence the resultant load on the spine [20], which may be important factors for the development of low back pain [23].

Biomechanics research can play an integral role in reducing the incidence and severity of sports injuries [10]. Biomechanical analysis may be particularly pertinent since the technique of rowing is thought to be a major factor in the generation of injuries, particularly spinal injuries [7,13,30]. However, research

Affiliation
[1] Musculoskeletal Surgery, Faculty of Medicine, Imperial College London, Charing Cross Hospital Campus, Fulham Palace Road, London, United Kingdom
[2] Department of Bioengineering, Imperial College London, Bagrit Centre, Mechanical Engineering Building, South Kensington Campus, London, United Kingdom

Correspondence
Dr. A. H. McGregor · Musculoskeletal Surgery · Faculty of Medicine · Imperial College London · Charing Cross Hospital Campus · Fulham Palace Road · London W6 8RF · United Kingdom · Phone: +44 20 8383 8831 · Fax: +44 20 8383 8835 · E-Mail: a.mcgregor@imperial.ac.uk

Accepted after revision: March 21, 2003

Bibliography
Int J Sports Med 2003; 24: 597–602 © Georg Thieme Verlag Stuttgart · New York · ISSN 0172-4622

into rowing has frequently focused on physiological issues [3,4,8,18] or aspects of boat/ergometer performance [1,6,11,19,24,26,27,32] as opposed to the kinematics of the rower. Additionally those studies that have investigated the kinematics of the rower have looked at whole body mechanics [12,31] and have not focused on specific body regions such as the spine.

A tool frequently used in training is the rowing ergometer. This is believed to provide an accurate reproduction on the land of the rowing motion and loading of different body segments on the water [17]. Instrumentation of the ergometer allows for specific data to be assimilated about the rowing stroke [27], which if combined with kinematic data from the athlete [5] may provide a valuable tool for investigating injury mechanisms in rowers.

The primary aim of this study was to investigate rowing technique using a system that combines spinal kinematics data with force curve profile data in order to develop a system to identify injury mechanisms in rowers. The secondary aim of the study was to investigate how rowing technique changes during a prolonged aerobic session (utilisation training), in this case a one-hour training piece on a rowing ergometer.

Material and Methods

Study population

Ethical approval for this study was obtained from the Riverside Research Ethics Committee and written informed consent gained from all subjects. Thirteen elite national and international oarsmen (age: 22.4 ± 1.5 y, height: 188 ± 3.0 cm, Weight: 86.0 ± 6.8 kg) were recruited from Imperial College Boat Club, London. All athletes were sweep rowers with seven rowing strokeside and six rowing bowside. Of these subjects, six had previously reported LBP, which had required conservative intervention and/or had resulted in time off training. Seven subjects had no history of LBP.

Protocol

Athletes were instrumented with the Flock of Birds™ electromagnetic measuring device (Ascension Technology, Vermont, USA) as described by Bull and McGregor [5]. The protocol was modified in one way: the receivers were attached to the skin using a colloidal glue (SLE Diagnostics, England) at the thoracolumbar (T12/L1) junction, the lumbosacral (L5/S1) junction and 10 cm proximal to the lateral epicondyle of the right femur, as opposed to the previous mounting blocks. This permitted the determination of the position and rotation of each body segment relative to a fixed electromagnetic transmitter. Lumbar spine motion was determined from the thoraco-lumbar and lumbosacral segments as described by Dolan et al. [9]. In addition, the ergometer was instrumented with a load cell in-line with the handle connected to the chain (Oarsum, NSW, Australia) that provided information about the tensile force produced at the handle. The output from both the Flock of Birds and the load cell were synchronised using an in-house computer program.

Prior to recording, athletes performed a three-minute warm up on the ergometer, after which the position and fixation of the receivers were checked for any slipping or loss of adhesion. The athletes were then asked to row continuously for one hour at their normal intensity for a sixty-minute ergometer session. This corresponded to a stroke rating between 18 – 20 strokes per minute, and athletes were instructed to keep their heart rate between 130 – 150 beats per minute. During the hour, four two-minute recordings were made from the data. The timing of these were at the start (0 – 2 min); 19 – 21 min; 39 – 41 min and at the end (58 – 60 min) of the hour session. The athletes were aware that these recordings were being made.

Data presentation and statistical analysis

Sagittal plane motion was analysed using the kinematic data recorded. The rowing stroke was characterised in percentage points starting at the catch position and ending at the next catch position, identified as a change in tensile force from zero to a positive value as recorded by the load cell. This provided normalisation of the data between and within rowers. Segmental angles were zeroed at the catch to allow comparisons to be made between athletes and facilitate data interpretation. Kinematics data over the two-minute sample period was averaged and presented in terms of force, anterior-posterior femoral rotation (flexion-extension), and anterior-posterior lumbar spine rotation (flexion-extension).

Statistical analysis of the data was performed using Stata 6.0 (Stata Corporation, Texas, USA). A 2-way (paired) analysis of variance (ANOVA) was performed on the data to test the hypothesis that the rowing technique varied with time. Where the ANOVA revealed significant differences, orthogonal contrasts were performed to localise the factors responsible for this difference [2]. The statistical threshold was set at an alpha level of 0.05.

Data analysis

Fig. **1** depicts a typical force profile of a rowing stroke, which is approximately described by the positive half of a sinusoid during the drive phase of the stroke (0 – 30%). No significant tensile force is generated during the recovery phase of the stroke (30 – 100%). The drive phase of the stroke was subdivided into three phases; steep initial acceleration (Drive Phase I) being followed by a less severe, maintained acceleration (Drive Phase II) and finally Drive Phase III which was signified by the decline from peak tensile force to the value at the catch (in some instances a

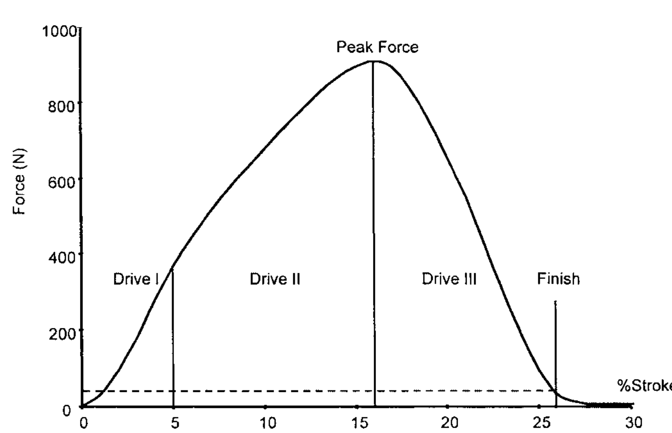

Fig. **1** The force profile of a rower showing the different phases of the stroke up to the Finish.

residual tension was maintained through the handle as the athlete progressed into the recovery stage, therefore baseline tensile force was set at 40 N). The gradient of the tensile force curve, the femoral and spinal rotations curves, for each phase was determined. In addition the peak force generated was noted, as was the finish point (end of Drive Phase III, where no further is work is being produced through the handle) were identified.

Once the different phases of the drive were identified, analyses of the kinematic data were possible and the gradients of the femoral and spinal rotations curves were determined for each phase. Fig. **2** shows typical spinal and femoral rotation. In addition the percentage point and angle values of maximum femoral and spinal rotation were identified.

Results

Description of rowing technique

The starting of the catch position (i.e. 0% and 100% point) was achieved by anterior rotation of the sacrum (pelvis) and the lumbar spine and movement from this position representing a posterior tilting action of the pelvis and extension of the spine. As the rower entered the drive phase there was a rapid acceleration of force evidenced by the high gradient of the tensile force slope (92.4 N/stroke%, SD 22.7). In contrast, the gradient of the femoral rotation was low (0.2°/stroke%, SD 0.4), suggesting that femoral rotation was slight.

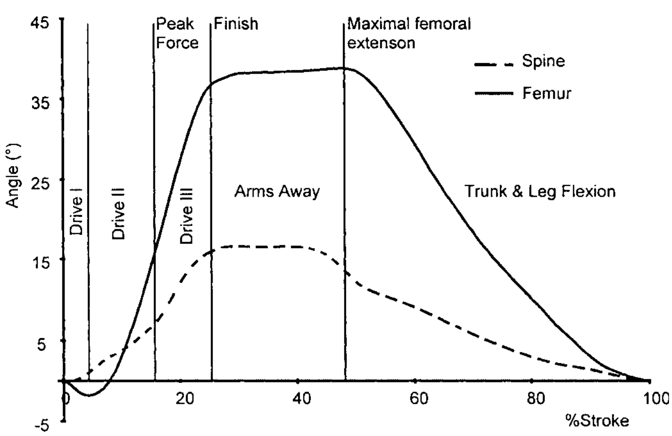

Fig. **2** An example of the kinematic data recorded from the lumbar spine and the femur. Flexion angles in the sagittal plane are shown.

During the second drive phase, there was a subtle deceleration of tensile force production, with the gradient of the curve falling to 60.5 N/stroke% (SD 17.8). The kinematic data demonstrated that during this phase femoral rotation (which resulted in an extension of the knee) increased more rapidly (1.3°/stroke%, SD 0.5). Spinal angular velocity at this stage was minimal (0.3°/stroke%, SD 0.6).

Peak force production of 827.0 N (SD 76.3) occurred at 15.5% (SD 1.6) of the stroke. At the peak, the legs and back continued to move together as in Drive Phase II. The speed of the movement of the back and legs were seen in the gradients of their profiles, 0.5°/stroke% (SD 0.3) and 2.3°/stroke% (SD 0.6), respectively.

In drive phase III, the gradient on the tensile force curve was negative (–90.7 N/stroke%, SD 18.4), and kinematically associated with a fast rotation of the femur (2.2°/stroke%, SD 0.5) and the fastest rotation of the spine (during the whole stroke) into extension (0.9°/stroke, SD 0.4%). The "finish stage" (when tensile force returns to baseline) occurred at 26.8% (SD 1.5) of the stroke, approximately coinciding with an extended position of both the femur and spine (Fig. **3**).

The tensile force trace and kinematic data have been combined in Fig. **3**. From this it can be seen that co-ordination of the femoral and spinal segments of the body was at a high level. In several athletes (7/13), the spine continued to rotate into extension after the finish stage of the stroke was achieved (Fig. **4**). This overextension represents a common fault seen in rowers. The average maximum spinal extension achieved was 16.8° (SD 8.2) and occurred at 37.6% (SD 4.9) of the stroke.

The majority of athletes (8/13) in this study were unable to maintain knee extension at the finish stage of the stroke, demonstrated by an inability to maintain the femoral angular position at a constant value between the 20 and 50% stages of the stroke in

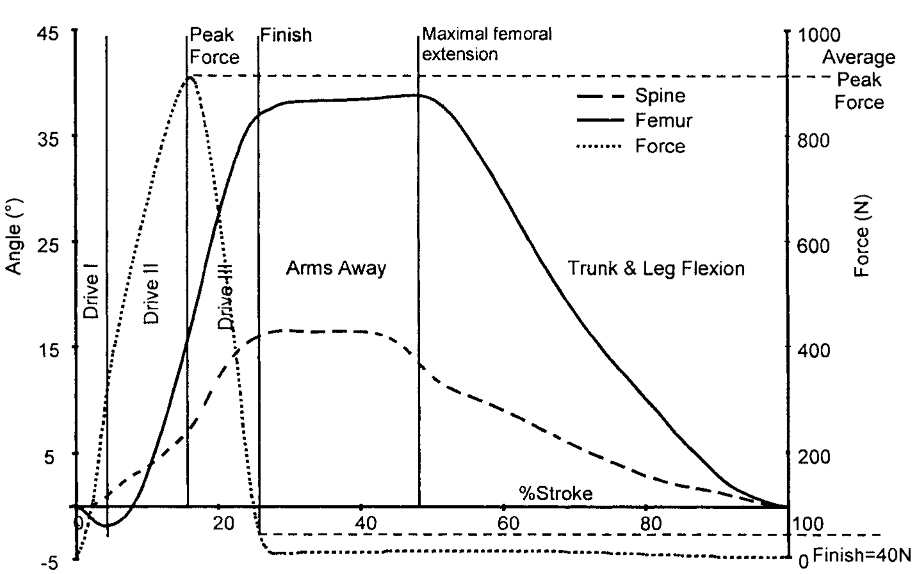

Fig. **3** Graph showing the co-ordination of the legs and back throughout the stroke. Extension of both the legs and back ceases when no more force is being produced. The back flexes prior to the legs flexing. The movement forwards into the catch is very smooth and regular. At the catch, the athlete takes the initial load of the stroke by extending the back slightly, whilst allowing further flexion of the legs. After a few percent of the stroke, the legs begin to accelerate the handle (Example from one athlete).

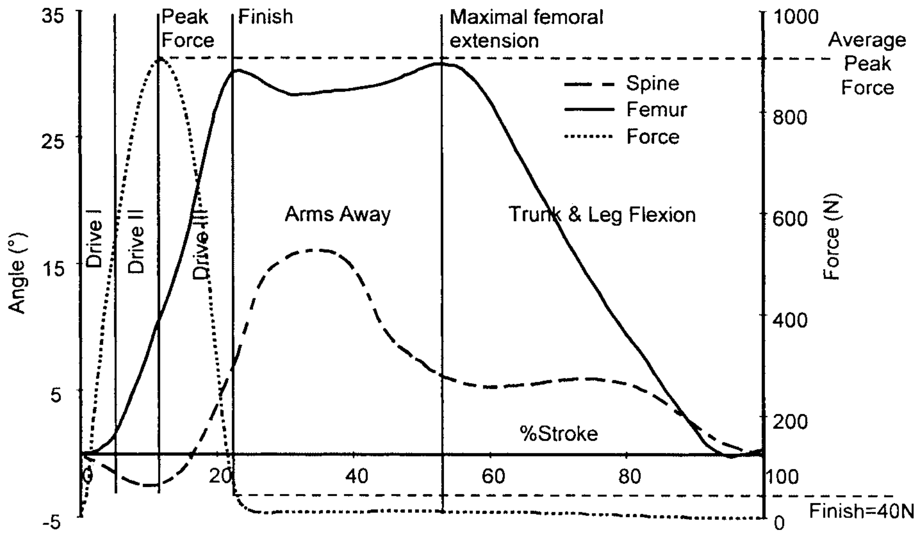

Fig. 4 Demonstration of over-extension of the back and double extension of the legs after the finish of the stroke. The legs are straightened (Finish) and then allowed to flex slightly. They are then straightened again (FemB) before the athlete rolls forwards into the catch (Example from one athlete).

Fig. **4**. Maximal rotation of the femur into extension occurred at, or marginally after, the finish (27.9%, SD 3.1), followed by a rotation into a flexed position during the recovery phase as the spine rotated forwards. This may represent a relative inflexibility in the hamstring muscle group. By the end of the recovery phase, the femur had achieved full extension again (50.3%, SD 4.0). This was followed by femoral rotation into a flexed position to enable the start "catch" position to be achieved. The average maximal range of motion for the femoral component was 37.9° (SD 7.5) of flexion at the catch position.

The effects of prolonged rowing

Significant effects of prolonged rowing ($p < 0.05$) were seen in the following parameters; 1) the gradient of Drive Phase I; 2) the gradient of Drive Phase II; 3) the percentage of the stroke at which the peak force was produced; 4) the percentage of the stroke at which the finish position was reached; 5) the magnitude of maximum flexion of the spine; 6) the percentage of the stroke at which the maximum extension of the spine was reached; 7) the stroke rate. The significance levels are summarised in Table **1** and mean values are shown in Table **2**. Other parameters including percentage point at which peak force occurred were not significant.

Prolonged rowing led to a decreased rate of force production in Drive Phases I and II, consequently leading to a higher percentage of the stroke value for peak force production and finish position. The maximum amount of spinal rotation into flexion attained was greater with prolonged rowing, which consequently led to a later percentage value for maximum spinal extension as the back had to move through a greater range to achieve the same finish position.

Table **1** Continuous ANOVA and orthogonal contrast results. Only parameters that reached significance have been included (n = 13).

	ANOVA P Value	*Orthogonal Contrast – Significant Locations*
Drive I Gradient	0.02	Recording 1 vs. 3 p = 0.01 Recording 1 vs. 4 p = 0.01
Drive II Gradient	0.04	Recording 1 vs. 3 p = 0.01 Recording 1 vs. 4 p = 0.01
Peak Percentage	0.001	Recording 1 vs. 2 p = 0.001 Recording 1 vs. 3 p = 0.01 Recording 1 vs. 4 p = 0.001
Finish Percentage	0.002	Recording 1 vs. 3 p = 0.001 Recording 1 vs. 4 p = 0.001 Recording 2 vs. 4 p = 0.01
Maximum Spinal Flexion	0.003	Recording 1 vs. 4 p = 0.001 Recording 2 vs. 4 p = 0.01 Recording 3 vs. 4 p = 0.05
Maximum Spinal Extension	0.04	Recording 1 vs. 2 p = 0.01 Recording 1 vs. 3 p = 0.02 Recording 1 vs. 4 p = 0.04
Data Points per Stroke	0.002	Recording 1 vs. 4 p = 0.001 Recording 2 vs. 4 p = 0.01 Recording 3 vs. 4 p = 0.01

Table **2** The significant effects of fatigue in a continuous hour ergometer. The mean value for the data in any significant result is shown. (*denotes a non-significant test result. Mean ± S.D. presented, n = 13).

Parameter	*Recording 1*	*Recording 2*	*Recording 3*	*Recording 4*
Drive I Gradient	96.9 ± 29.2	*90.5 ± 23.2	88.2 ± 19.9	86.9 ± 24.1
Drive II Gradient	66.1 ± 19.8	*62.1 ± 20.8	60.9 ± 19.1	59.9 ± 22.3
Peak Percentage	14.8 ± 1.5	15.6 ± 1.9	15.6 ± 1.7	15.9 ± 1.9
Finish Percentage	26.5 ± 1.8	26.8 ± 1.3	27.1 ± 1.6	27.6 ± 2.0
Maximum Spinal Flexion	−0.7 ± 1.4	−1.25 ± 1.8	−1.5 ± 2.0	−2.3 ± 2.3
Maximum Spinal Extension	36.3 ± 4.3	38.1 ± 4.5	37.9 ± 4.6	38.0 ± 8.5
Data Points per Stroke	78.0 ± 4.1	77.5 ± 3.2	76.9 ± 2.6	75.0 ± 3.8

Discussion

This study has combined kinematic profiles of rowing technique with rowing force profiles, the combination of which provides a more complete, and accurate, analysis of the rowing stroke and may yield important information with respect to injury. This signifies an improvement on the work of Bull and McGregor [5] and Smith and Spinks [27]. Further improvements would be the introduction of instrumentation at the handle displaying the height and travel of the handle and hands during the rowing stroke, and the measurement of force at the foot stretcher and the determination of seat position. Work in progress is addressing this limitation. However, the current configurations do permit an analysis of key performance characteristics in conjunction with lower back kinematics. Further analysis has been conducted using principal component statistical analysis and has shown that other descriptions may be able to elucidate changes in technique, or even discriminate between rowers of different levels and those with and without low back pain [22].

Although each athlete's technique was consistent in each of their data samples, differences were noted between athletes. During the initial drive phase some athletes generated a negative femoral gradient. This was shown as a negative femoral rotation at the catch. This suggests that the load of the rowing stroke was being sustained by the spine, which may have injury implications as well as technical performance implications, the discussion of which is beyond the scope of this paper.

Variations in technique were also observed at the finish stage of the stroke particularly with reference to the position of the spine. When athletes are coached they are instructed to stop extending their spines and to "sit up" at the finish of the stroke, when force production has ceased. A significant proportion of athletes in this study were observed to extend the spine beyond the finish position. This may occur for a number of reasons including a weak trunk stabilising mechanism, and possible crossed-pelvic syndrome as described by Jull and Janda [16]. However, further work is needed in this area. The full effects of this continued extension in terms of boat speed require further investigation.

Despite a highly trained rowing population, significant differences were seen in certain parameters of technique over an hour training period. Significant reductions in the gradients of force production for both the Drive Phase I and the Drive Phase II were seen between recordings 1 and 3 and recordings 1 and 4. It is unclear why this should occur during this comparatively low intensity training piece, however, Sparto and Parnianpour [28] noted that lifting velocities and accelerations decreased with repetitive lifting and attributed this finding to muscle fatigue. However, such changes may also be related to other factors such as loss of concentration.

The increase in the maximum angle of flexion of the spine observed during the task may be attributed to trunk fatigue, particularly as previous work has noted a comparative weakness in the trunk musculature in rowers [23]. This may have placed larger loads on the spine and as such this may be an important factor in the generation of LBP in rowers. Previous occupational studies have implicated increases in force generation as a result of increased back motion arising from fatigue [28,29]. Additionally, the percentage value of maximum extension of the spine was found to be significantly less in the recording 1 when compared to recordings 2, 3, and 4. This delay was due to the greater range that the spine had to work through to achieve the finish position. Together these findings provide evidence for an increasing range of spinal movement with prolonged rowing. It is speculated that the athletes increased their spinal motion in order to maintain a constant output on the ergometer, which implies an increased role for the back extensor muscles in force production during the rowing stroke, which may be causative in the generation of LBP. However, further research is required to clarify this.

The percentage at which the peak force of the stroke was produced was significantly different in recording 1 compared to recordings 2, 3 and 4. The stroke rate increased in recording 4 relative to recordings 1, 2 and 3. This change in stroke rate is a common occurrence amongst athletes at the end of long ergometer sessions.

Although prolonged rowing appears to induce changes in rowing technique, it is not possible, at this stage, to quantify the effects of these changes on joint loading at different body segments. It has been assumed that the initial set of readings (recording 1) are representative of an ideal technique; however, this may not be the case as athletes take time to warm-up and achieve their full range of normal motion, as reflected in some of the results gained.

Conclusions

The quantification of rowing technique in elite oarsmen has produced an in depth report of each stage of the rowing stroke. It has also allowed an investigation into the effects of long distance ergometer training on rowing technique in elite oarsmen, the results of which suggest that a deterioration in technique occurs which may have implications with respect to the onset of low back pain.

Acknowledgements

This work has been presented at the annual meeting of the Society for Back Pain Research in Bristol, UK, 2001 and at the World Congress of Biomechanics in Calgary, Canada 2002. This work was funded in part by the Arthritis Research Campaign, IC Trust and the Henley Steward's Charitable Trust.

References

1 Affeld K, Schichl K, Zieman A. Assessment of rowing efficiency. Int J Sports Med 1993; 14: 39 – 41
2 Altman D. Practical Statistics for Medical Research, Chapman and Hall, London 1996: 125
3 Beneke R. Anearobic threshold, individual anaerobic threshold, and maximal lactate steady state in rowing. Med Sci Sports Exerc 1995; 27: 863 – 867
4 Bourgois J, Vrijens J. Metabolic and cardiorespiratory responses in young oarsmen during prolonged exercise tests on rowing ergometer at power outputs corresponding to two concepts of anaerobic threshold. Eur J Appl Physiol 1998; 77: 164 – 169
5 Bull AMJ, McGregor A.H. Measuring spinal motion in rowers: the use of an electromagnetic device. Clin Biomech 2000; 15: 772 – 776
6 Celentano F, Cortili G, di Prampero PE, Cerretelli P. Mechanical aspects of rowing. J Appl Physiol 1974; 36: 642 – 647
7 Christiansen E, Kanstrup IL. Increased risk of stress fractures of the ribs in elite rowers. Scand J Med Sci Sports 1997; 7: 49 – 52
8 Cosgrove MJ, Wilson J, Watt D, Grant SF. The relationship between selected physiological variables of rowers and rowing performance as

determined by a 2000 m ergometer test. J Sports Sci 1999; 17: 845 – 852
9 Dolan P, Mannion AF, Adams MA. Fatigue of the erector spinae muscles. Spine 1995; 20: 149 – 159
10 Elliot B. Biomechanics: an integral part of sport science and sport medicine. J Sci Med Sport 1999; 2: 299 – 310
11 Hartmann U, Mader A, Wasser K, Klauer I. Peak force, velocity, and power during five and ten maximal rowing ergometer strokes by world class female and male rowers. Int J Sports Med ; 1993 : 14: 42 – 45
12 Hawkins D. A new instrumentation system for training rowers. J Biomech 2000; 33: 241 – 245
13 Hagerman FC. Applied physiology of rowing. Sports Med. 1984; 1: 303 – 326
14 Hagerman FC, Hagerman GR, Mickelson TC. Physiological profile of elite rowers. Physician Sportsmed. 1979; 7: 76 – 83
15 Hickey GJ, Fricker PA, McDonald WA. Injuries to elite rowers over a ten year period. Med Sci Sports Exerc 1997; 29: 1567 – 1572
16 Jull GA, Janda V. Muscles and motor control in LBP: Assessment and management. In: Physiotherapy of the Low Back. Twomey LT (Ed), New York, Churchill Livingstone. 1987: 253 – 279
17 Lamb DH. A kinematic comparison of ergometer and on-water rowing. Am J Sports Med 1989; 17: 367 – 373
18 Lormes W, Buckwitz R, Rehbein H, Steinacker JM. Performance and blood lactate on Gjessing and Concept II rowing ergometers. Int J Sports Med 1993; 14: 29 – 31
19 MacFarlane DJ, Edmond IM, Walmsley A. Instrumentation of an ergometer to monitor the reliability of rowing performance. J Sports Med 1997; 15: 167 – 173
20 Mahler DA, Nelson WN, Hagerman FC. Mechanical and physiological evaluation of exercise performance in elite national rowers. JAMA. 1984; 252: 496 – 499
21 Morris FL, Smith RM, Payne WR, Galloway MA, Wark JD. Compressive and shear force generated in the lumbar spine of female rowers. Int J Sports Med 2000; 21: 518 – 523
22 O'Sullivan F, O'Sullivan J, Bull AMJ, McGregor AH. Modelling multivariate biomechanical measurements of the spine during a rowing exercise. Clin Biomech in press
23 Parkin S, Nowicky AV, Rutherford OM, McGregor AH. Do sweep stroke oarsmen have asymmetries in the strength of their back and leg muscles. J Sport Sci 2001; 19: 521 – 526
24 Roth W, Schwanitz P, Pas P, Bauer P. Force-time characteristics of the rowing stroke and corresponding physiological muscle adaptations. Int J Sports Med 1993; 14: 32 – 34
25 Roy SH, de Luca CJ, Snyder-Mackler L, Emley MS, Crenshaw RL, Lyons JP. Fatigue, recovery and LBP in varsity rowers. Med Sci Sports Exerc 1990; 22: 463 – 469
26 Schabort EJ, Hawley JA, Hopkins WG, Blum H. High reliability of performance of well trained rowers on a rowing ergometer. J Sports Sci 1999; 17: 627 – 632
27 Smith RM, Spinks WL. Discriminate analysis of biomechanical differences between novice, good and elite rowers. J Sports Sci 1995; 13: 377 – 385
28 Sparto PJ, Parnianpour M. Estimation of trunk forces and spinal loads during fatiguing repetitive trunk exercises. Spine 1998; 23: 2563 – 2573
29 Sparto PJ, Parnianpour M, Reinsel TE, Simon S. The effect of multijoint kinematics and load sharing during a repetitive lifting test. Spine 1997; 22: 2647 – 2654
30 Stallard MC. Backache in oarsmen. Br J Sports Med 1980; 14: 105 – 108
31 Torres-Moreno R, Tanaka C, Penney KL. Joint excursion, handle velocity, and applied force: a biomechanical analysis of ergometric rowing. Int J Sports Med 2000; 21: 41 – 44
32 Zatsiorsky VM, Yakunin N. Mechanics and biomechanics of rowing: a review. Int J Sports Biomechancis 1991; 7: 229 – 281