ORIGINAL ARTICLE

An ergonomic comparison of rowing machine designs: possible implications for safety

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Objectives: Ergometer training is a common cause of injuries in rowers. A randomised crossover study comparing two power head designs was carried out to examine ergonomic risk factors.
Methods: Six elite male rowers undertook 20 minute fatiguing rowing pieces with both fixed and floating power heads. A CODA MPX infrared telemetric motion analysis detector and the ergometer's interface were used to measure displacement, force, work performed, and power output.
Results: There was no significant difference in the total work performed, power per stroke, or metabolic load between the two ergometer designs. Fatigue was shown by a mean (SEM) fall of 9.7 (0.79) W/stroke (95% confidence interval (CI) 8.0 to 11.5) between minutes 8–10 and minutes 16–18 ($p<0.001$). The stroke length was 53 (13) mm (95% CI 18 to 89) longer with the fixed power head ($p<0.02$). With fatigue, the stroke with the fixed power head lengthened at the "catch" (beginning of the stroke) by 19.5 mm ($p<0.01$) and shortened at the finish of the stroke by 7.2 mm ($p<0.05$). No significant changes in stroke length were seen with the floating power head. The mean force per stroke was 12.1% (95% CI 3.0 to 21.2) (27.3 (8.0) N) higher with the power head fixed versus floating ($p<0.02$).
Conclusions: It is postulated that longer stroke lengths and greater forces are risk factors for soft tissue injuries. Further research into whether floating power head rowing ergometers are associated with lower injury rates than fixed power head designs is now needed.

Ergometer training on rowing machines has been thought by elite rowers to be a common cause of land training injuries, particularly back injuries.[1] It is still not known whether low back pain occurs more often in rowers than the general population. In elite rowers, more than 50% of injuries occurred off the water during land based training.[1 2] Injuries in rowing are rare events (1 per 1000 hours) compared with other sports.[2] However, when they do occur, they cause elite rowers to lose an average of 24 days of training a year[1] often preventing selection for the national teams.[2] At the elite level, training sessions on most days of the week involve continuous rowing on the water for 60–90 minutes at intensities just below the anaerobic threshold.[3] Ergometers are often used for training and assessing rowers. In these rowers, land based training carries a 10-fold higher risk of injury per hour than water based training,[2] the leading causes suggested being weights and ergometer training.[1]

Stationary rowing ergometers (fixed power head designs) are the most commonly used type in this country. Other designs are based on mounting the whole ergometer on wheels (wheeled ergometer) or mounting the power head on rollers so that it can move independently of the seat on the slide track (floating power head design). The mechanical characteristics of these designs have been compared.[4 5] Floating power head and wheeled ergometer designs more closely simulate the mechanics and kinetic energy characteristics of rowing on the water than do stationary ergometers.[4 5] However, these studies did not examine risk factors for injuries.

In repetitive lifting, an action similar to rowing, muscle fatigue rather than primary failure of passive structures was the most important factor leading to instability of the spine.[6] A substantial part of the bending moment in the flexed spine was resisted by passive structures as muscles fatigued with repetitive lifting.[7] Gradual disc prolapse is an injury reported in rowers.[8] Perhaps this is a result of repetitive lumbar flexion under load because this was shown to lead to gradual disc prolapse in a cadaveric study.[9] Fatigue has been shown to lead to loss of coordination in rowers on the water.[10] However, there has been no published work on the relation between fatigue, coordination, and injury on rowing ergometers.

We therefore conducted a randomised crossover study to examine the ergonomic differences between two commonly used rowing ergometer power head designs. The trial design allowed us to study the effects of fatigue as well as account for the large variation between subjects.

METHODS

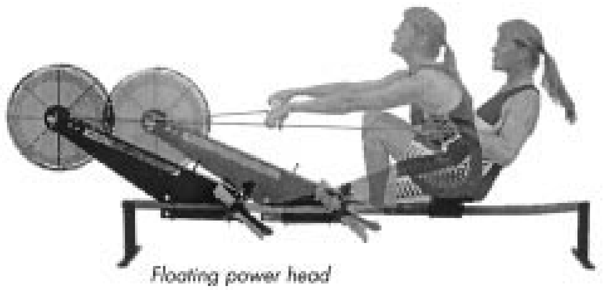
Study population

Six elite male oarsmen as classified by the Amateur Rowing Association[11] (mean age 30 (range 22–40); mean (SD) height 1.87 (0.07) m; mean (SD) mass 80 (11) kg) volunteered for the study. Exclusion factors were: a history of serious injury, recent illness, and inexperience on the rowing ergometers used. Prior ethical approval was granted from the Royal National Orthopaedic Hospital Trust ethics committee. Signed consent was obtained from each subject.

Equipment and methods

The subjects each performed two 20 minute rows on a RowPerfect rowing ergometer (Care RowPerfect BV, JV Hardenberg, The Netherlands) in the laboratory. This ergometer has a "floating" power head—that is, the footplate with the power head unit and the seat are both mounted on the slide track and are thus free to move independently (fig 1). The mass of the power head (about 17 kg) is similar to that of a section of a boat containing one oarsman. To simulate a fixed power head ergometer, the floating head was clamped at one end. The chain was placed on the larger of two cogwheels, and a 39 cm disc was used to set the resistance on the fly wheel for all pieces. The display settings were set to simulate a coxless four boat type. A Polar surface chest monitor and telemetric sensor was connected to the ergometer interface. The ergometer interface provides force data, sampled every 20th stroke,

Fixed power head



Floating power head

Figure 1 Photographs showing rowing movements with the power head fixed and floating. Courtesy of C. Pekkers.

Table 1 Characteristics of subjects in each group

Characteristic	Group 1	Group 2
No of subjects	3	3
Age (years)	28.7 (5.9)	32.7 (6.4)
Height (m)	1.8 (0.03)	1.9 (0.1)
Weight (kg)	77.8 (4.2)	81.9 (16.1)
Target pulse (beats/min)	172.0 (2.7)	170.7 (3.1)

Values are mean (SD) of the group. The significance of the differences between the groups was tested with Student's *t* test. No significant differences were found.

derived from measurement of the speed of the flywheel. The accuracy and repeatability obtained from comparison with a calibrated force plate was ± 0.1%.

The subjects were randomised (without replacement) into a crossover study design so that half started with a fixed power head and the other half with a floating power head. The subjects stretched and warmed up on the ergometer for at least 10 minutes before each row. A break of at least 45 minutes between the two pieces was given for rest and rehydration while the power head was changed. The subjects were given a minimum pulse rate to maintain during the pieces, to ensure that they were exercising above their anaerobic thresholds and developed fatigue. This was determined by previous physiological testing at the British Olympic Medical Centre, including measurement of capillary blood lactate levels. The subjects were asked to use the first several minutes to achieve the target pulse rate and then to keep the pulse rate steady.

Displacements were measured by a CODA MPX motion analysis system (Charwood Dynamics Ltd, Rothley, Leicestershire, UK) using infrared active markers fixed to the subjects' skin or to the ergometer by adhesive tape. Twenty one markers were in fact used, but only data from markers on the handle and footplate are reported in this paper. Three dimensional coordinates were obtained for each marker at 100 Hz. The standard deviation of repeated measurements was less than 0.2 mm, and the accuracy obtained from a calibration grid was ± 0.3 mm. Forty second samples of rowing were taken every two minutes. Each acquisition period was divided into stroke cycles. Each cycle was defined by the maximum horizontal displacement of the handle with respect to the footplate. This defined the beginning of the stroke ("the catch"). Incomplete cycles at the beginning and end of the data acquisition period were discarded. The data were averaged across all of the complete cycles. It was not possible to synchronise data from the CODA and the ergometer interface, which were therefore analysed separately.

Fatigue was examined by comparing a time period after the anaerobic threshold was reached and a period towards the end of the piece which was not affected by the subjects "sprinting" to the line. Some data were not obtained successfully. Therefore the periods for comparison of the ergometer data were from 8 to 10 minutes and from 16 to 18 minutes, amounting to two minute samples. The periods for the CODA data were from 7 to 12 minutes and from 13 to 18 minutes, each period encompassing three 40 second data acquisitions, amounting to a total of a two minute sample. The length of the periods was chosen to include sufficient data for the repeated measures analysis.

Main outcome measures

The outcome measures recorded from the ergometer interface were: power output; work performed; force displacement curves; pulse rate; stroke rate; time elapsed; stroke number. Stroke length was recorded by the CODA system.

Missing data

The first ten minutes of ergometer data for one subject was lost as the result of computer failure. The remaining data for that row was used for the analysis, the sampling periods being 11–13 minutes and 17–19 minutes.

Statistical analysis

Significance tests were based on the paired *t* test for the effects of fatigue on the means of the ergometer derived variables. Normalised peak force data were examined using an unpaired *t* test. The CODA derived stroke length data were examined using two way analysis of variance with replication. A grid of *t* tests, as applied to the special case of crossover trials,[12] examined the differences between the power head design, the order of the trials, and the interaction between power head design and trial order. A repeated measures calculation was used where appropriate. The normality of the data was examined with a Kolmogorov-Smirnov test.

Statistical power

Statistical significance was defined at the two tailed $p = 0.05$ level. Confidence limits at the 95% level are presented where appropriate. The final data set generated more than 85% power to detect the observed changes in stroke length and differences in normalised force displacement curves between the fixed and floating power heads.

RESULTS

Table 1 compares the key characteristics of the subjects in each group. Table 2A classifies the main ergometer and pulse rate data by power head design. The same work was performed with both power heads. Pulse rates were above the target rates for the second half of each piece. Table 2B classifies the same data by first versus second pieces. There were no significant differences in the time to reach target pulse rates or mean pulse rates during the period from 14 to 19 minutes comparing floating versus fixed power heads or first versus second pieces.

Subjects showed a mean (SEM) fall of 9.7 (0.79) W/stroke (95% confidence interval (CI) 8.0 to 11.5) between minutes 8–10 and minutes 16–18 ($p<0.001$). There was no significant difference in this fall between the fixed and floating power heads. Further effects of fatigue were indicated by a fall in total work and mean power per stroke between the first and second pieces (table 2B).

Table 2 Measurements made during rowing pieces from the ergometer interface

Variable	Fixed	Floating	Difference (95% CI)	Standard error	p Value
(A) Comparison between fixed and floating power heads					
Work performed (kJ)	368	365	2 (−8 to 13)	4	NS
No of strokes	464	506	−42 (−15 to −69)	10	<0.02
Power per stroke (W)	314	308	6 (−11 to 23)	6	NS
Work performed per stroke (J)	813	728	84 (55 to 113)	10	<0.001
Pulse rate: minutes 14–19 (beats/min)	180	183	−3 (−7 to 1)	1	NS
Time to target pulse (s)	449	392	57 (−174 to 287)	83	NS
Variable	**1st Piece**	**2nd Piece**	**Difference (95% CI)**	**Standard error**	**p Value**
(B) Comparison between first and second pieces					
Work performed (kJ)	371	361	10 (−0.3 to 20)	4	<0.06
No of strokes	477	492	−15 (−42 to 12)	10	NS
Power per stroke (W)	320	301	19 (2 to 36)	6	<0.05
Work performed per stroke (J)	797	744	52 (23 to 81)	10	<0.01
Pulse rate: minutes 14–19 (beats/min)	180	183	−3 (−6 to 1)	1	NS
Time to target pulse (s)	457	385	72 (−158 to 303)	83	NS

Significance is given by two way *t* test analysis. Values are means, differences and standard errors of the differences (95% confidence intervals).

Table 3 Change during the piece in length at each end of the stroke measured by the CODA system

	Fixed power head		Floating power head	
	Length change (mm)	p Value	Length change (mm)	p Value
(A) Comparison between fixed and floating power heads				
Catch	19.5 (32.6)	<0.01	−3.5 (36.3)	NS
Finish	7.6 (27.2)	<0.05	−4.9 (30.8)	NS
	First piece Length change (mm)	p Value	Second piece Length change (mm)	p Value
(B) Comparison between first and second pieces				
Catch	7.6 (50.0)	NS	8.4 (12.4)	<0.001
Finish	2.3 (41.4)	NS	0.4 (7.8)	NS

Values are the mean differences (SD) between the average displacements during minutes 7–12 compared with minutes 13–18. Positive numbers indicate movement towards the power head. Significance is given by two way analysis of variance with replication.

Stroke length

Analysis of the CODA data showed that the stroke length, after target pulse rates were achieved, was 53 (13) mm (95% CI 18 to 89) longer with the fixed than with the floating power head (p<0.02). In addition to this observation, there were further changes in the horizontal handle displacement (stroke length) as the pieces progressed with the fixed power head only. Specifically, in the horizontal plane, the handle went further beyond the footplate at the beginning of the stroke (stroke lengthening at the catch) and also finished nearer the footplate at the end of the stroke (stroke shortening at the finish) (table 3A). Comparison of the stroke length with first versus second piece showed no increase during the first piece but a small increase during the second piece (table 3B).

Force data

The force versus handle displacement data from the ergometer interface was sampled every 20th stroke. Figure 2 shows typical curves for the mean data for one rower. The mean force per stroke across all the subjects was 12.1% (95% CI 3.0 to 21.2) (27.3 (8.0) N) higher with the power head fixed versus floating (p<0.02).

To examine the differences in shapes between fixed and floating heads, the curves were normalised to give them the same area. This was achieved by dividing each point on the curve by the mean value for the whole curve. Figure 3 shows the normalised curves for the same rower as shown in fig 2. The mean work performed to half of the handle displacement (the area under the curves to the left of the vertical line in fig 3) was 64.1% of the total work performed with the fixed power head and 67.8% with the floating power head. The difference

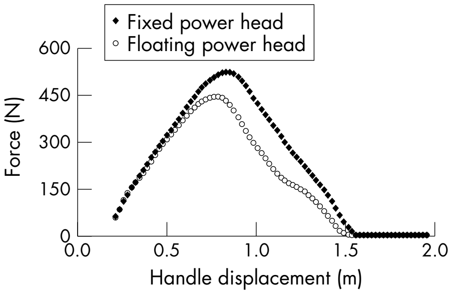


Figure 2 Example of the mean force versus handle displacement plots with the power head fixed and floating for one rower. Data are averaged over one piece.

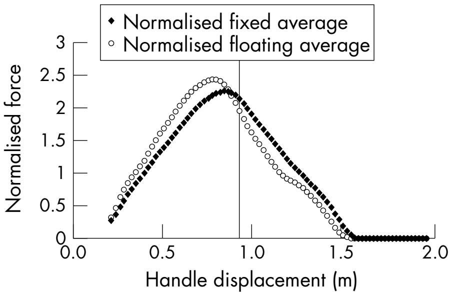


Figure 3 Example of the normalised mean force versus handle displacement plots with the power head fixed and floating for the same rower as in fig 2. Data averaged over the whole of one piece. The area under each curve to the left of the vertical line represents percentage of total work performed to half of the total handle displacement.

was 3.7 (1.2)% (95% CI 0.67% to 6.80%) ($p<0.05$). In contrast with the raw data, the peak force was higher in all subjects with the floating power head ($p<0.05$). In five out of six subjects, the peak force occurred earlier in the stroke with the floating power head compared with the fixed power head.

DISCUSSION

Differences between the force displacement profiles on fixed compared with floating power head rowing ergometers have been found. The stroke length was longer on the fixed power head ergometer than the floating power head. The stroke length increased further, particularly at the catch, with fatigue on the fixed power head but not the floating power head. The fixed power head ergometer led to higher mean forces being developed for the same metabolic load and total work performed. These differences may increase the risk of injury when training at submaximal loads on fixed power head ergometers compared with floating power head ergometers.

Discussion of method

The randomised crossover design reduced the effect of fatigue being carried over from the first to the second piece. However, this could be reduced further by performing the pieces on separate days.

Critical to the design of the study was the need to reproduce fatigue. Urhausen and colleagues[13] have validated the use of pulse rates for determining exercise intensity in relation to blood lactate measurements in rowers, on both the water and a rowing ergometer. As pulse rate is approximately linearly related to $\mathrm{V}\mathrm{O}_2$, we concluded that we had produced adequate fatigue, above the subjects' anaerobic threshold, with this protocol. The subjects invoked a variety of adaptations to maintain power output in the face of fatigue. In spite of these adaptations, we still observed a small fall in the power output per stroke within the pieces.

Work performed

The total work performed over the whole piece was the same with both power heads, consistent with setting the same target pulse rates for each piece. The stroke rate was lower and the work performed per stroke was higher with the power head fixed (table 2A). This would explain the observed difference in the areas under the force displacement curves in fig 2, which represent the mean work performed per stroke. The power per stroke was defined as the work performed per stroke divided by the time for each stroke. The difference in stroke rate accounted for the observation that the power per stroke was similar with both power heads.

Stroke length and biomechanics

The stroke length was 53 mm longer with the power head fixed. Following the principle of the conservation of momentum, the kinetic energy of the body in the static case can be shown to be much higher than the kinetic energy of the body plus power head in the floating case.[14] The kinetic energy of the moving masses (given by $0.5mv^2$) has to reduce to zero at each end of the stroke and is higher by a factor of about 6 (or about 60 J per stroke) for the fixed power head. The kinetic energy is likely to be absorbed by muscles working eccentrically to decelerate the moving masses. The work-energy theorem predicts that the distance taken to reduce the kinetic energy to zero will be further when the kinetic energy is higher. This is consistent with our observations of longer stroke lengths with the power head fixed.

The longer stroke lengths with the power head fixed presents a possible risk factor for injury to the musculotendinous junction.[15] This would be exacerbated by our observation that fatigue caused further lengthening at the beginning of the stroke. Lengthening of the back extensor muscles in rowers may cause the transference of loads to the posterior viscoelastic structures of the vertebral units. This has been observed with fatigue in repetitive lifting studies.[7] If studies of activation of these muscles confirm their role in decelerating the body at each end of the stroke (as seen with repetitive bending[15]), this would provide a plausible link to the production of back injuries.

Mair and colleagues[15] showed that fatigue in muscles working eccentrically resulted in a reduction in their ability to absorb kinetic energy and an increase in their length before being irreversibly damaged. This may explain the increase in stroke length with fatigue that was observed with the fixed power head. When muscles are working eccentrically, a smaller proportion of the fibres are active than when the same force is developed concentrically.[16] Therefore the force is distributed across fewer fibres leading to a greater stress (force per unit area), which is potentially damaging.

Take home message

The stroke length is longer and the mean forces are higher on fixed compared with floating power head ergometers. This could increase the risk of injury. Therefore direct research into injury rates with the different ergometers would be very desirable.

Force displacement curves

Our normalised force displacement curves (fig 3) concord with the findings of Hänyes and Lippens.[17] They show that the force on the handle rose later with a fixed power head ergometer compared with the forces in a boat, similar to our comparison between fixed and floating power heads. Rekers[4] showed directly that the force displacement curves were very similar in size and shape when a floating power head was compared with a boat.[4]

In fig 2, the mean forces developed during the power phase were significantly higher with the power head fixed. As fatigue developed, some of these forces could be transferred to passive viscoelastic structures (tendons, ligaments, cartilage, and intervertebral discs) leading to permanent deformation.[7] Theoretical calculations have shown that the forces within the body may vary by much greater amounts than those observed on the handle in changing the power heads.[4] Therefore there may be a higher chance of injury with the power head fixed.

The earlier increase in force development during the stroke with the power head floating (fig 3) was predicted from theoretical considerations.[4 14] With the power head fixed compared with floating, much of the initial force developed on the footplate would be dissipated in accelerating the whole body mass before that force could appear on the handle.

Further study

Further analysis of our data will allow us to calculate the kinetic energy of the system to test the theoretical arguments above. Future work using this experimental setup could yield information about changes in coordination and accessory movements with fatigue to identify further risk factors for injury.

Conclusion

The reduction in injury risk obtained by using floating power head ergometers instead of fixed power head ergometers cannot be quantified here. However, given the trend towards low intensity long distance training, we would expect further research to find that changing to floating power head ergometers would reduce injuries attributable to ergometer training.

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Conflicts of interest: The ergometer was donated to the laboratory by the manufacturer who was approached only after the design of the project and the testing protocol had been established.

REFERENCES

1 **Bernstein IA**. Injury reporting system in rowing. *Proceedings of the Senior Coaches Conference*. London: British Amateur Rowing Association, 1994.
2 **Budgett RGMcB**, Fuller GN. Illness and injury in international oarsmen. *Clin Sports Med* 1989;**1**:57–61.
3 **Hartmann U**, Faulmann L, Altenburg D, *et al*. *Proceedings of the Senior Coaches Conference*. London: British Amateur Rowing Association, 1992.
4 **Rekers C**. Verification of the RowPerfect rowing ergometer. *Proceedings of the Senior Coaches Conference*. London: British Amateur Rowing Association, 1993.
5 **Martindale WO**, Robertson DGE. Mechanical energy in sculling and in rowing an ergometer. *Can J Appl Sport Sci* 1984;**9**:153–63.
6 **Gardner-Morse M**, Stokes IAF, Laible JP. Role of muscles in lumbar spine stability in maximum extension efforts. *J Orthop Res* 1995;**13**:802–8.
7 **Sparto PJ**, Parnianpour M, Reinsel TE, *et al*. The effect of multijoint kinematics and load sharing during a repetitive lifting test. *Spine* 1997;**22**:2647–54.
8 **Stallard M**. Back injuries in rowing: the surgeon's contribution. *Proceedings of the Senior Coaches Conference*. London: British Amateur Rowing Association, 1994.
9 **Adams MA**, Hutton WC. Gradual disc prolapse. *Spine* 1985;**10**:524–31.
10 **Wing AM**, Woodburn C. The coordination and consistency of rowers in a racing eight. *J Sports Sci* 1995;**13**:187–97.
11 **British Amateur Rowing Association**. Rules of racing. *The Almanac*. London: British Amateur Rowing Association, 1999.
12 **Armitage P**, Berry G. *Statistical methods in medical research*. 3rd ed. Oxford UK: Blackwell Sciences, 1994:245–9.
13 **Urhausen A**, Weiler B, Kindermann W. Heart rate, blood lactate and catecholamines during ergometer and on water rowing. *Int J Sports Med* 1993;**14**:20–3.
14 **Dudhia A**. FAQ: the physics of ergometers. http://www.atm.ox.ac.uk/rowing/physics.html. Updated 15/2/99.
15 **Mair SD**, Seaber AV, Glisson RR, *et al*. The role of fatigue in susceptibility to acute muscle strain injury. *Am J Sport Med* 1996;**24**:137–43.
16 **de Looze MP**, Toussaint JH, van Dieën JH, *et al*. Joint movements and muscle activity in the lower extremities and lower back in lifting and lowering tasks. *J Biomech* 1993;**26**:1067–76.
17 **Hänyes VB**, Lippens V. Vom Messen im Boot und auf dem Ruderergometer. *Rudersport* 1988;**30**:10–14.

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