Instrumentation of an ergometer to monitor the reliability of rowing performance

D.J. MACFARLANE,* I.M. EDMOND and A. WALMSLEY

School of Physical Education, University of Otago, Dunedin, New Zealand

Accepted 2 July 1996

The aim of this study was to develop a portable data-acquisition system to measure the stroke-by-stroke power output and the force developed at the feet during simulated rowing, and to use the system to investigate the reliability of selected variables used to describe rowing performance. Using a Concept II rowing ergometer, the instantaneous power output was calculated as the product of the force at the handle, measured using a small transducer mounted near the handle, and the velocity of the handle, measured using an infra-red emitter-receiver to detect the passage of each vane of the flywheel. The cumulative force at the feet was measured using an 80386SX computer running Asyst data-acquisition software. Excellent linearity in all transducers was established and a calibration of the system revealed measurement errors of less than 3%. The reliability of the variables used to describe rowing performance was studied using a repeated 90 s maximal test on seven experienced oarsmen. Statistical analysis indicated that, of the 14 variables used, only two failed to meet the set criterion. In conclusion, it was found that a rower's performance during simulated rowing was very reliable and that the selected variables used in this study could be used to objectively describe performance on a rowing ergometer.

Keywords: Instrumentation, reliability of results, rowing ergometry.

Introduction

In recent years, sports science has played an ever increasing role in the development, training and assessment of competitors in many sports. Where possible, the monitoring of the competitor's performance is best done in their natural environment; however, in sports such as rowing, this presents numerous technical difficulties (see Zatsiorsky and Yakunin, 1991), which are more easily overcome by monitoring the competitor in the laboratory.

Optimal physiological assessment in the laboratory requires an ergometer that closely simulates the movement patterns and resistance characteristics of the specific sport as well as having the ability to measure accurately the athlete's power output. The use of friction-loaded ergometers has been very common in the testing of competitors and has been recommended by some for the assessment of rowers (Steinacker *et al.*, 1991). However, friction-loaded ergometers generally do not account for the frictional resistances of the ergometer's transmission, which can result in errors of approximately 10% in the workload (Åstrand, undated; Cumming and Alexander, 1968; Telford *et al.*, 1980). Furthermore, it has been claimed that some frictionloaded rowing ergometers do not provide an adequate simulation of the resistance characteristics encountered when rowing on the water (Koutedakis, 1987), especially when compared with air-braked ergometers such as the Concept II (Hahn *et al.*, 1988).

A number of research groups have collected data on the force developed at the handle during simulated rowing (e.g. Smith, 1983; Wilson *et al.*, 1988), while others have calculated the power produced (e.g. Lakomy, 1984; Mason *et al.*, 1988; Smith and Spinks, 1989, 1995), but none has described in any detail the shape or the reliability of the power-time relationship or included any data on the force generated by the feet. A recent study by Henry *et al.* (1995) showed that instrumented tank rowing can provide useful objective information on rowing performance and that such systems have potential as coaching devices and in

^{*}Address all correspondence to Duncan Macfarlane, Physical Education and Sports Science Unit, University of Hong Kong, 111-113 Pokfulam Road, Pokfulam, Hong Kong.

improving rowing ability. However, since most rowers and researchers do not have access to such facilities, it is perhaps more viable to develop a portable dataacquisition system that can be readily transferred to similar models of a very commonly used rowing ergometer. The aims of this study, therefore, were to develop a portable data-acquisition system that could objectively describe in considerable detail a rower's performance, and to establish the reliability of selected rowing variables.

Methods

Using a Concept II rowing ergometer (Model B, Concept II, Morrisville, VT), the power output of the rower was obtained by calculating the product of the force applied to the ergometer handle and the velocity of the handle. The data-acquisition system was also designed to monitor continuously both the total force at the feet, using locally built force-plates, and the subject's heart rate, using a modified commercial heart rate monitor. The force and velocity at the hands, the force at the feet and the heart rate signals were conditioned in a purpose-built interface and sampled at 30 Hz using a Metrabyte Dash-16 analog-to-digital (A/D) dataacquisition card (Metrabyte Corp., Taunton, MA), in an NEC Portable SX (80386SX, 16 MHz) personal computer running 'Asyst' data-acquisition software (Macmillan Software, New York, NY). A diagram of the instrumentation system is shown in Fig. 1.

Measurements

Force at the handle. The force measuring element was a mild steel ring instrumented with four 120 Ω foil

Figure 1 Schematic diagram of the modified Concept II rowing ergometer and data-acquisition system.

strain-gauges of active length 8 mm, in a full bridge arrangement. Welded couplings allowed the ring to be inserted between the traction chain and handle, together with a protective housing. Residual stresses were relieved by shot-peening. Amplification of the low-level strain-gauge output was accomplished using an Analog Devices 2B31 (Analog Devices, Norwood, MA) high-performance conditioning unit. The unit was designed as a high-accuracy interface for strain-gauge transducers and consisted of a variable bridge supply, a high-performance instrumentation amplifier, a threepole Bessel low-pass filter with a cut-off frequency of 34 Hz and a constant time-delay of 8 ms in the pass band.

Velocity at the handle. The velocity of the handle during the 'drive-phase' was monitored by measuring the velocity of the flywheel using an infra-red emitterreceiver (CNY70, Phillips) to sense the passage of the eight radial vanes on the flywheel. The output pulses from the detector were amplified and passed to a frequency-to-voltage converter (FVC) (LM2917, National Semiconductors, Santa Clara, CA). The FVC output was filtered using a two-pole Butterworth lowpass filter with a cut-off frequency of 10 Hz and a maximum group delay of 28 ms in the pass band.

Force at the feet. Two force-plates were constructed, one for each foot, and their size allowed them to be mounted easily on the existing 'stretcher' of the ergometer. The surface of each foot-plate was made from 12 mm thick aluminium and was supported at each end by a block of high-density foam (Fig. 2). Deflection in a second plate was detected using four foil strain-gauges in a Wheatstone bridge crossover design, such that the output was the sum of the force applied to both plates. Output from the force-plates was amplified by a Kyowa VKR DPM-110A (Kyowa, Japan) strain amplifier and low-pass filtered at a cut-off frequency of 10 Hz.



Figure 2 Cross-sectional schematic diagram of the footplates, showing position of the force transducers.



Heart rate monitoring and conditioning. The subjects' heart rates were monitored using the transmitter belt from a commercially available device (Sport Tester PE3000, Polar Electro, Kempele, Finland) that has been shown to be both accurate and reliable (Leger and Thivierge, 1988; Macfarlane *et al.*, 1989). The PE3000 transmitter was hard-wired to a signal conditioning unit that produced a voltage output proportional to the time between successive R-waves.

Calibration

Calibration of the force transducer. The force transducer was mounted in a JJ Lloyd T5002 tensile tester (Warsash, Southampton) fitted with a 500 N load cell to determine the linearity of the force-voltage relationship ($r^2 = 1.00$). The input resolution of the Dash-16 A/D card was 2.5 mV, which gave a maximum force range of -1320 N with a resolution of 0.66 N at minimum gain.

Calibration of the velocity of the handle. All tests were carried out with the traction chain running over the ergometer's smaller sprocket and with the adjustable fan-aperture fully closed. The length of each chain link was obtained and the constant relating the frequency of pulses from the eight vanes of the flywheel to the handle velocity was determined. Low-level (20 mV peak to peak) sine waves of known frequency (0-200 Hz) were fed into the velocity channel input from a signal generator (Newtronics 200MSTPC, Tel Aviv). The resulting output showed that the FVC was extremely linear ($r^2 = 1.00$) and the resolution of the Dash-16 A/D card gave a maximum velocity resolution of 0.001 m s⁻¹.

Calibration of the force at the feet. Calibration of the foot-plates was performed by repeatedly loading the middle of the plate with four known masses ranged from 20 to 86 kg at a frequency that simulated a stroke rate of 30 min⁻¹. The first 20 s of each 120 s trial was discarded, as there was some initial relaxation effect from the foam in the foot-plates (this would be over-

come during testing because a standardized warm-up immediately preceded each test). A straight-line relationship was found between the voltage output and the four masses ($r^2 = 1.00$) and there was little sign of significant variation in the slopes of all voltage outputs over the last 100 s of each trial. The design of the plates was such that there was some crosstalk from changes in the direction and point of application of the force. However, trials involving the application of a 46 kg mass at a single small point 3 cm apart, simulating the span between the ball of a typically small (size 6) foot and a typically large (size 10) foot, indicated at most a 6% difference in the mean output voltage.

Heart rate transducer calibration. The electrode belt was connected to a Healthdyne ECG Simulator (Model 5000, Marietta, Georgia) and tested at frequencies of 50, 75, 100, 150, 200 and 240 min⁻¹. Since heart rate was inversely proportional to the R-R interval, the calibration curve was hyperbolic and was linearized ($r^2 = 1.00$) by plotting the reciprocal of the transducer output against heart rate. Even at heart rates greater than 200 min⁻¹, the maximal heart rate resolution of the Dash-16 A/D card was approximately 0.2 min⁻¹.

Electronic calibration of the data-acquisition system. To simulate the output generated by a rowing stroke, a square wave (3.23 V amplitude, 0.9 s duration, 1.8 s period) was fed into the force channel and a triangular wave (0.498 V amplitude, 1.8 s period) was fed into the velocity channel. A comparison of the values provided by the computer program and those calculated manually from several representative strokes captured using a digital storage oscilloscope (Meguro MSO-1270, Japan) is given in Table 1.

Software data processing

At a sampling rate of 30 Hz, the program was capable of collecting stroke-by-stroke information from the force and velocity channels and displaying in real time: power output (W), stroke rate (min⁻¹), peak power

Table 1 The percentage error of the computer-generated values when compared with the manually calculated values taken from several representative strokes captured on a digital storage $oscilloscope^{a}$

Variable	Computer-generated	Manually calculated	Percentage error
Stroke rate (min ⁻¹)	30.7	30.6	+0.4
Peak power (W)	1708	1738	-1.7
Mean power per stroke (W)	854	854	-0.03
Mean power per 60 s (W)	444	432	+2.7

^aData are shown for stroke rate, peak power and mean power over a 60 s period for the entire stroke (i.e. 'drive-phase' and 'recovery-phase'). The mean power per stroke was calculated only over the 'drive-phase' of the stroke.

(W), mean power during the 'drive phase' (W), work done during the 'drive phase' (J), the time taken to reach peak force at the hands (TPH, s) and the time taken to reach peak force at the feet (TPF, s). Off-line analysis provided the difference between the times to reach peak force at the hands and feet (the time to peak difference: TPDIFF, s), the duration of each stroke spent above 75% of peak power (power maintenance, s) and information on the shape of the power profiles. Each power profile was normalized by dividing it into five equal bins (quintiles) and the percentage of the total work done in each quintile was calculated by integrating the power profile (P_{20} , P_{40} , P_{60} , P_{80} , P_{100} , %).

Test reliability

Seven very experienced male rowers (mean - s.D. age = 24.3 - 2.1 years) were tested twice under identical conditions with no more than 2 days between the tests. The test consisted of a standardized 3 min warm-up followed by a 90 s maximal effort, during which the subjects received verbal encouragement. The 'distance travelled' (m) by the rower was recorded from the screen of the Concept II work-monitor. The analysis compared the test-retest data for each subject using the data averaged over 0.1-1.5 min. The first 6 s of the test data were not used in data-averaging to avoid contamination of the stroke profiles caused by the initial acceleration of the flywheel.

Reliability was calculated using the intraclass correlation coefficient (ICC) from a two-way ANOVA procedure with subject and trial as the two effects (Bartko, 1966). The reliability correlation coefficient was given by (F-1)/(F+1), where F was the F-ratio of the subject effect: this gives the reliability of a single future trial and derives from (F-1)/(F+k-1), where k is the mean number of trials per subject, here k=2. An equivalent expression for the reliability is $(s^2 - e^2)/s^2$, where s^2 is the sample standard deviation and e is the individual (within-subject) error in the two-way ANOVA. This expression was also used to estimate reliability for the general population, with the assumption that members of the general population would have the same individual error as those in the restricted (testretest) sample. A statistically significant F-ratio for the factor trial (from the two-way ANOVA) meant that the group mean for a particular variable had shifted from one trial to the other. A statistically significant F-ratio for the factor subject meant that when adjusted for a shift in the group mean, the subjects attained significantly different scores for a particular variable; that is, the variable had significant retest reliability.

Results

Table 2 shows the results of the two-way ANOVA for the test-retest trials (n = 7). All variables, except power maintenance (P = 0.055) and the percentage of work done in the last quintile (P = 0.36), were reliable at the P < 0.05 level, with the majority of the test-retest correlation coefficients around 0.9 or higher. There was also no significant shift in the mean of any variable from the first trial to the second trial and, in general, the population reliability was similar to or greater than the sample reliability.

An example of the test-retest mean profiles of an averaged stroke-by-stroke power output and the force at the feet is shown for one experienced rower in Fig. 3, together with some descriptive information on each profile. The consistency in the power and force profiles is clearly evident, as well as some of the variables used to describe the rower's performance.

Discussion

It is most helpful to be able to monitor rowing performance in situ (e.g. Wing and Woodburn, 1995). However, there are numerous technical and environmental difficulties that may limit the viability of obtaining reliable results. Objectively assessing rowing performance in an instrumented rowing tank (e.g. Henry et al., 1995) avoids many of these problems and has been shown to provide very useful data for interpreting various aspects of rowing skill. However, access to such rowing tanks is extremely limited, while most rowers and researchers can gain access to a Concept II ergometer, which has been shown to simulate favourably the rowing action (Hahn et al., 1988). The relevance of information obtained from rowing ergometers to that of 'on-water' performance may be controversial; however, a recent study by Smith and Spinks (1995) showed that the results of testing on a rowing ergometer can at least accurately discriminate between rowers of different abilities. Clearly, any laboratory-based testing of a rower should attempt to simulate the real event as closely as possible, as well as providing a detailed objective assessment of rowing ergometer performance using variables that have been shown to be reliable.

The reliability calculated from the two-way ANOVA is similar, in some respects, to a test-retest Pearson correlation coefficient. It is unaffected by a shift in the mean score on retest and it reflects the extent to which the rank order of the subjects is conserved on retest. The ANOVA also yields a test for a shift in mean score on retest. Only two variables appeared to be unreliable: power maintenance (PM) and the percentage of work done in the last quintile (P_{100}). Since the calculation of

Table 2	Test-retest	reliability	of 1	4 variable	es used	to	describe	rowing	performance	а
---------	-------------	-------------	------	------------	---------	----	----------	--------	-------------	---

Variable	Trial 1	Trial 2	Reliability $(F-1)/(F+1)$	Within-subject error	Sample standard deviation	Estimate of population std. deviation	Estimate of population reliability
PK(W)	2273	2320	0.90**	74	205	575	0.98
AVEP(W)	545	543	0.83**	17	34	123	0.99
WKD(J)	972	977	0.92**	21	68.0	212	0.97
TPF(s)	0.313	0.309	0.95**	0.017	0.069	0.065	0.93
TPH(s)	0.347	0.351	0.96**	0.009	0.047	0.05	0.97
TPDIFF(s)	0.033	0.042	0.96**	0.012	0.056	0.069	0.97
STR (min ⁻¹)	33.0	32.5	0.79**	1.0	2.3	2.3	0.79
PM (s)	0.274	0.264	0.61	0.014	0.024	0.036	0.84
DIST (m)	503	503	0.87**	4	11	50.1	0.99
$P_{20}(\%)$	9.5	9.5	0.95**	0.4	1.6	1.4	0.93
$P_{40}(\%)$	26.8	26.5	0.72*	1.1	2.0	2.1	0.70
$P_{60}(\%)$	33.7	34.0	0.92**	0.6	1.3	1.3	0.81
$P_{80}(\%)$	22.9	22.8	0.87**	1.0	2.7	2.4	0.83
$P_{100}(\%)$	7.1	7.2	0.2	1.0	1.1	1.2	0.32

^aData shown are the mean values (n = 7) for each trial, test reliability, within-subject error, standard deviation of the sample, estimated standard deviation of the population, and the estimated population reliability.

PK = peak power; AVEP = average power; WKD = work done; TPF and TPH = time to peak force at the feet and hands respectively; TPDIFF = TPH -TPF; STR = stroke rate; PM (power maintenance) = duration above 75% of peak power; DIST = distance rowed; $P_{20} \dots P_{100}$ = percentage of work done in each quintile of the stroke.

*P < 0.05; **P < 0.01.

PM involved no interpolation between data points, there was small measurement error (plus or minus one sample interval) in the calculation that may have con-



Figure 3 Averaged test and retest curves of power output (triangles, W) and force at the feet (circles, N) over the 'drivephase' of the rowing stroke for one subject. Also shown for each test is the filename; start and end of the averaging period (min); number of rowing strokes completed; plus the average of work done (J), peak power (W), time to peak force at the hands (TPH, s) and at the feet (TPF, s).

tributed to its unreliability. However, it should be noted that PM barely exceeded the criterion (P < 0.05) for significant reliability (P = 0.055). It is not clear why P_{100} failed to meet the set criterion, but the final part of the drive-phase may allow for greater variations in hand-oar position and trunk extension, leading to small but significant variations in the way power output tapers at the end of the stroke. However, a clear finding is that when characterized by the variables used in this study, individual oarsmen generally use a very consistent technique during simulated rowing. Additional studies that involve electromyographic studies and film or video analysis of the rowing motion (e.g. Wilson *et al.*, 1988; Rodriguez *et al.*, 1990) would be needed to further validate this claim.

The excellent linearity of the force, velocity and heart rate transducer outputs ($r^2 = 1.00$ for all channels), and other sampling errors found in this study, are generally considered very satisfactory for most physiological or biomechanical studies. This was reinforced by the electronic testing of the complete data-acquisition system, which produced a mean error in the four variables measured (Table 1) of 1.21% (range 0.03-2.71%). Theoretically, the computer calculation should have produced a 'mean power per stroke' that was 50% and a 'mean power per 60 s' that was 25% of the 'peak power' respectively; actual calibration testing produced results of 52.0% and 26.0% (see Table 1). The source of these errors was likely to be an unknown combination of (a) sampling errors during data acquisition and processing, (b) a small instability of the signal generator and (c) some imprecision in manually determining the voltages and durations from the storage oscilloscope.

It is interesting to note that the value of instantaneous peak power reported in this study (c.2300 W) is nearly identical to the previously unique value of 2270 W found by Henry *et al.* (1995) in their studies performed in a rowing tank. The results of Henry *et al.* also show average power outputs over 30 s of around 739 W, which are not too dissimilar to the average of 545 W obtained over a longer 90 s period in our study. These results at least tentatively suggest some similarity between the power outputs obtained from simulated and tank rowing, although a more systematic investigation of this claim is warranted.

A meaningful analysis of the power curves can be difficult and although techniques such as Fourier analysis are popular, it is not easy to relate the relative amplitude and phase of the spectral components to specific differences in shapes. A detailed analysis of force-angle data collected from a Repco rowing ergometer is provided by Smith and Spinks (1995); however, their analysis did not attempt to describe the shape or reliability of the power-time curve. The method of analysis using quintiles to try and express differences in stroke-shape was chosen for this study in an attempt to avoid providing excessive quantitative analysis and is similar to that used by Painter et al. (1987) to analyse curves from respiratory flow studies. This was in part done since the rowers felt the maximum number of segments they could modify voluntarily in the drive-phase of their stroke was five, and that a more detailed segmentation (e.g. into tenths) would not allow individual modification of any one segment. Thus, it was felt that this method provided both useful scientific data and information that could be of some applied benefit to the rowing fraternity, such as a possible 'biofeedback' device to help modify a rower's technique (e.g. Gautier, 1985).

A limitation in the plates used to measure the cumulative force at the feet was that they had some initial damping; they were also sensitive to the positioning of the applied force and only measured the force in one direction. Trials established that some damping occurred predominantly over the first 20 s of a test, especially if no force was directed onto the plates in the 30 s prior to the test starting. However, it was found that following the standardized warm-up period, which progressed with only a brief delay to the data-acquisition phase, the damping effect was greatly attenuated. Although there was a 6% variation in the output when a 46 kg mass simulated the ball of a small and large foot (a 3 cm difference in span), during actual physiological testing the forces would be spread over a greater area. As a result, the difference in the 'centres of effort' were unlikely to show any greater variation and the resultant outputs between feet of different sizes were unlikely to vary to any greater extent. A better arrangement would be to mount three-dimensional force-platforms under each foot. However, as this study was only interested in the timing and gross shape of the applied forces, a more precise measurement of the forces and a detailed threedimensional analysis were not justified.

We conclude that the Concept II rowing ergometer can be modified to produce precise and reliable measurements of performance-related variables calculated from the profile of the stroke-by-stroke power output as well as from the profile of the forces generated at the feet. These variables may be useful in determining whether biofeedback principles can be used during simulated rowing under standardized laboratory conditions that will ultimately lead to enhanced 'on water' performances.

Acknowledgements

The authors thank the NZ Kiwi Lottery Board and the Hillary Commission (NZ Sports Science and Technology Board) for providing funds to purchase and modify the rowing ergometer, and Dr Will Hopkins for valuable statistical advice.

References

- Åstrand, P.-O. (undated). Work Tests with the Bicycle Ergometer. Sweden: Monark-Crescent AB.
- Bartko, J.J. (1966). The intraclass correlation coefficient as a measure of reliability. *Psychological Reports*, **19**, 3-11.
- Cumming, G.R. and Alexander, W.D. (1968). The calibration of bicycle ergometers. *Canadian Journal of Physiology and Pharmacology*, **46**, 917–919.
- Gautier, G.M. (1985). Visually and acoustically augmented performance feedback as an aid in motor control learning: A study of selected components of the rowing action. *Journal of Sports Sciences*, **3**, 3-26.
- Hahn, A.G., Tumilty, D.Mca., Shakespear, P., Rowe, P. and Telford, R.D. (1988). Physiological testing of oarswomen on Gjessing and Concept II rowing ergometers. *Excel*, 5, 19-22.
- Henry, J.C., Clark, R.R., McCabe, R.P. and Vanderby, R. (1995). An evaluation of instrumented tank rowing for objective assessment of rowing performance. *Journal of Sports Sciences*, 13, 199-206.
- Koutedakis, Y. (1987). Ergometry: Use of rowing ergometer. *Rowing*, June, pp. 17–18.
- Lakomy, H.K.A. (1984). The measurement of power output during simulated rowing. *Journal of Physiology*, 361, 3P.

- Leger, L. and Thivierge, M. (1988). Heart rate monitors: Validity, stability, and functionality. *Physician and Sports Medicine*, 16, 143-151.
- Macfarlane, D.J., Fogarty, B.A. and Hopkins, W.G. (1989). The accuracy and variability of commercially available heart rate monitors. *New Zealand Journal of Sports Medicine*, 17, 51-53.
- Mason, B.R., Shakespear, P. and Doherty, P. (1988). The use of biomechanical analysis in rowing to monitor the effect of training. *Excel*, **4**, 7–11.
- Painter, R., Cunningham, D.J.C. and Petersen, E.S. (1987). Analysis and isopnoeic comparisons of flow profiles during steady-state breathing in man, in hypercapnia, hypoxia and exercise. In *Concepts and Formalizations in the Control* of Breathing (edited by G. Benchetrit, P. Baconnier and J. Demongeot), pp. 313-324. Manchester: Manchester University Press.
- Rodriguez, R.J., Rogriguez, R.P., Cook, S.D. and Sandborn, P.M. (1990). Electromyographic analysis of rowing stroke biomechanics. *Journal of Sports Medicine and Physical Fitness*, **30**, 103-108.
- Smith, J. (1983). Measurements of force. *Rowing USA*, October/November, pp. 6-8.
- Smith, R.M. and Spinks, W.L. (1989). Matching technology

to coaching needs: On-water rowing analysis. In VII International Symposium of Biomechanics in Sports, pp. 277-287. Melbourne: Footscray Institute of Technology.

- Smith, R.M. and Spinks, W.L. (1995). Discriminant analysis of biomechanical differences between novice, good and elite rowers. *Journal of Sports Sciences*, 13, 377-385.
- Steinacker, J.M., Lormes, W. and Stauch, M. (1991). Sport specific testing in rowing. In *Advances in Ergometry* (edited by N. Bachl, T.E. Graham and H. Löllgen), pp. 443-454. Berlin: Springer-Verlag.
- Telford, R.D., Hooper, L.A. and Chennells, M.D. (1980). Calibration and comparison of air-braked and mechanically braked bicycle ergometers. *Australian Journal of Sports Medicine*, **12**, 40-46.
- Wilson, J.-M.J., Robertson, D.G. and Stothart, J.P. (1988). Analysis of lower limb muscle function in ergometer rowing. *International Journal of Sport Biomechanics*, 4, 315-325.
- Wing, A.M. and Woodburn, C. (1995). The coordination and consistency of rowers in a racing eight. *Journal of Sports Sciences*, 13, 187-197.
- Zatsiorsky, V.M. and Yakunin, N. (1991). Mechanics and biomechanics of rowing: A review. *International Journal of Sport Biomechanics*, 7, 229-281.