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The effect of ergometer design on rowing stroke mechanics

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The effect of rowing ergometer design upon power delivery and coordination patterns of the rowing stroke was analyzed for 14 elite rowers. Rowers were tested in three ergometer conditions: the fixed stretcher Concept2c ergometer, the Concept2c ergometer mounted on sliding rails, and the sliding stretcher RowPerfect ergometer. Ergometers were instrumented to measure the external force generated at the handle and the foot stretcher and a nine-segment inverse dynamics model used to calculate joint and overall power delivery. Peak power generation and absorption at the knee joint was significantly greater, and total power delivered to the ergometer delayed on the fixed stretcher ergometer when compared to the sliding stretcher ergometers. No differences were found in the mechanical energy delivered to the handle of the three ergometers; however, greater joint mechanical energy production of the lower limb reduced mechanical efficiency when rowing the Concept2c fixed ergometer. The fixed foot stretcher on the Concept2c fixed ergometer acts to increase the inertial forces that the rower must overcome at the catch, increasing the moment and power output at the knee, and affecting the coordination pattern during the recovery phase.

Although a high proportion of race training is completed on water, rowing ergometers are commonly used for performance testing, technique coaching, crew selection, and bad weather training (Soper & Hume, 2004a). Ergometers have, to a certain extent, been shown to simulate both the biomechanical and metabolic demands of on-water rowing (Christov et al., 1988; Lamb, 1989; Dawson et al., 1998; Schabort et al., 1999; Elliott et al., 2002) and also allow for the standardization of testing, which is not entirely possible on water because of environmental variability (Jürimäe et al., 2002).

While previous studies have compared fixed and sliding stretcher ergometer conditions for power output and reliability (Soper & Hume, 2004b), stroke parameters and force output (Bernstein et al., 2002), and muscle activation and Electromyography (EMG) (Nowicky et al., 2005), the effect of ergometer design upon joint coordination and the timing of joint mechanical energy and power production is yet to be investigated.

Three ergometer designs are widely in use within the rowing community today. These are the Concept2c fixed (C2F) ergometer (Concept2c Inc., Morrisville, Vermont, USA), the Concept2c sliding (C2S) ergometer (Concept2c Inc.) and the RowPerfect (RP) rowing simulator (Care RonPerfect Bv, Hardenberg, The Netherlands). All three are air-braked ergometers with the rowing handle attached by a chain to the flywheel complex and the rower free to move in the anterior-posterior direction on the sliding seat. Where these ergometers differ is in the fixed or sliding nature of their stretcher and flywheel assembly.

The C2F ergometer has a foot stretcher fixed to the frame, which is stationary relative to the floor. This ergometer remains stationary throughout the rowing stroke and the rower's center of mass moves in the anterior-posterior direction on the seat about a fixed point. The C2S ergometer (mass 35 kg) is mounted on a set of slides, allowing the whole ergometer to move in the anterior-posterior direction throughout the stroke, rather than providing a static base as in the traditional C2F. The RP ergometer consists of a flywheel complex that is mounted on a slide, and like the seat, is free to move in the anterior-posterior direction. The flywheel complex consists of the air-braked flywheel with the oar handle attached, as well as the foot stretcher. The flywheel complex has a mass of approximately 17.5 kg, which is comparable to that of a boat section and oars carrying one oarsman (Bernstein et al., 2002). The interaction between the rower and the ergometer is shown in Fig. 1.

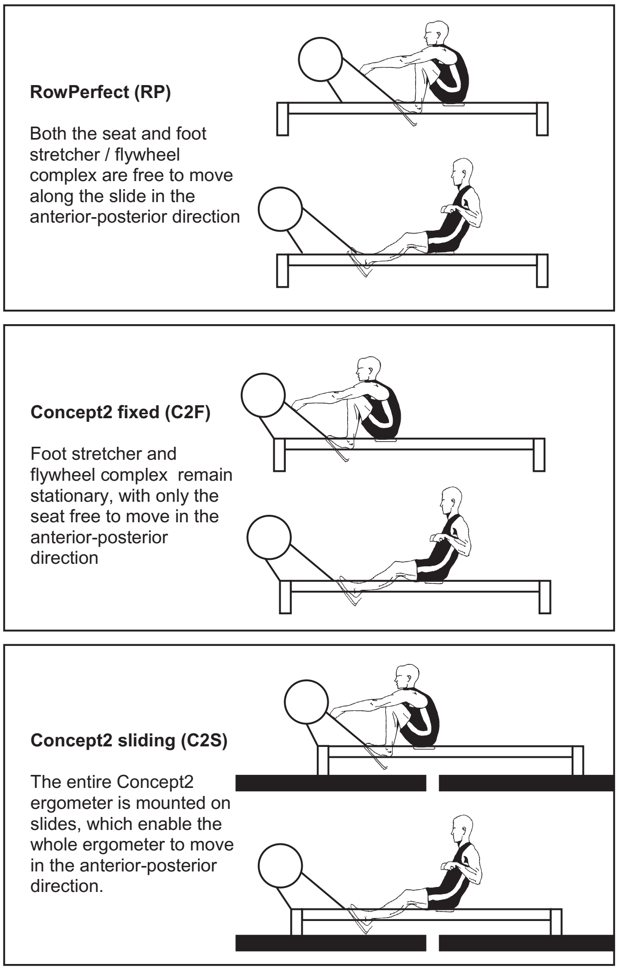

Fig. 1. Representation of the RowPerfect, Concept2c fixed and Concept2c sliding rowing ergometers, and the interaction between the rower and the ergometer.

All rowers, regardless of performance level, encounter and are familiar with rowing ergometers as a regular part of their training regime. However, owing to the differing designs of these three major ergometers and the limited understanding of joint mechanical energy and power contributions, there exists some dispute in the literature and the rowing community as to how these ergometers compare in regard to the technical and force parameters of the rowing stroke, and the potential to best replicate on-water rowing.

The aim of the study therefore is to explore the joint mechanical energy and power production throughout the drive and recovery phases, as well as the joint and segment coordination sequences to provide an insight into the effect of three ergometer conditions upon the efficiency and technical parameters of rowing.

Materials and methods

Experimental design

To test the hypothesis that there will be no differences in the primary dependent variables among the three ergometer conditions, 10 consecutive strokes were analyzed from the subjects rowing on each of the ergometers at 32 strokes/min. The two factors, ergometer condition and stroke, were used in a repeated measures statistical analysis. The primary dependent variables were (1) the sum of joint mechanical energy expenditure per stroke, (2) the sum of external mechanical energy expenditure per stroke, and (3) the ratio of the sum of external mechanical energy expenditure per stroke to the sum of joint mechanical energy expenditure per stroke.

Subjects

Fourteen elite male rowers (age 25.1 ± 4.5 years; height 1.98 ± 0.07 m; mass 91.3 ± 7.5 kg) provided written informed consent to participate in the study. Participants consisted of both heavyweight and lightweight rowers made up of Olympic and international representatives ($n = 10$) national, state and university competitors ($n = 4$), including four specialist scullers, six sweep oar rowers, and four who trained for both sweep rowing and sculling. Training frequencies ranged from 7–11 sessions per week and their average Concept2c 2000-m performance time was 6 min 9 s ± 13 s, with a range of 5 min 46 s–6 min 34 s. The University of Sydney Human Ethics Review Committee approved this study.

Participants were tested at 32 strokes/min on all three ergometer conditions. The flywheel resistance was set on the RP ergometer using a 400-mm diameter wind disc, a setting commonly used by elite rowers and for the C2F and C2S at level 4, which is used for heavyweight testing of Australian National Rowers. Subjects were provided with visual information feedback of stroke rate via a digital display mounted on the ergometer (Speed Coach, Nielsen-Kellerman, Marcus Hook, Pennsylvania, USA) and were instructed to perform their usual rowing technique, especially in terms of stroke length and to maintain a power output corresponding to their average power output during a maximal 2000-m ergometer test. The ergometer digital display was covered to prevent the rowers from using it.

All rowers had previous experience with all the ergometer conditions used and were familiar with the test procedure. A short period (5 min) of familiarization was conducted immediately prior to testing to allow subjects to prepare for the testing session. All rowers were experienced in maximal ergometer rowing for 2000 m. Participants then performed 1 min of rowing at a power output corresponding to their average power output for a maximal 2000-m test. This is approximately 80% of their maximal propulsive power; a compromise between maximal and mid-race power output and similar to values reported in the literature (Hartmann et al., 1993; Schabort et al., 1999; Ingham et al., 2002; Jürimäe et al., 2002; Hofmijster et al., 2008). All ergometers were tested during the same testing session. Ergometer order was randomly assigned for each rower with sufficient rest periods provided between trials.

Force data collection

All ergometers were instrumented identically to measure the external forces generated by the rower at the hands and feet. Two foot stretchers were constructed, each fitted with two force transducers (Model 9067, Kistler Instrument Corp., AG Winterthur, Switzerland; linearity ≤ 0.5%, hysteresis ≤ 0.5%) to record three-dimensional (3D) reaction forces and the center of pressure in line with the long axis of the foot stretcher. A unidimensional force transducer (Model TLL-500, Transducer Techniques Inc., California, USA; linearity 0.24%, hysteresis 0.08%) was connected in series at the chain-handle attachment. The force transducers were calibrated against a force platform (Model 9281A, Kistler Instrument Corp.) and checked prior to each session using a known weight. The instrumentation of each foot stretcher had a mass of 3.8 kg.

Kinematic data collection

The kinematics of the rowing stroke were recorded using a 3D motion analysis system (Motion Analysis Corporation, Santa Rosa, California, USA) to provide an accurate joint center data for the sagittal plane model of the rower. To record the 3D body motion, reflective markers were attached to specific anatomical landmarks on the participant encompassing 13 joints and 15 body segments. Fifty-two markers (15 mm diameter) were placed for an initial static trial with 12 of these being removed for the following rowing trials (Greene et al., 2009). The static trial was necessary to define joint centers and segment coordinate systems using KinTrak software (Version 6.2, University of Calgary, Canada, 2001). The 3D trajectories of the joint centers were then calculated for each rowing trial. The shoulder joint center was identified using the methods of Veeger (2000) and the hip joint center using those of Bell et al. (1990). The motion of the ergometer and its handle was defined by seven reflective markers attached to the top and bottom of the foot stretcher, the chain force transducer, the handle extremities, and the center of the flywheel.

Nine video cameras (Expertvision 3D, Motion Analysis Corporation) provided input for the motion analysis system. Motion capture software (EVaRT 4.0, Motion Analysis Corporation) enabled synchronized recording of 3D motion and force channels, which were sampled at 60 Hz and 120 Hz, respectively. The first five strokes (~15 s) were sufficient for the subject to reach the desired stable stroke rate. Kinematic and force data were recorded for the last 45 s of each 1-min trial to ensure the capture of 10 full strokes for analysis.

The spectra of position and force data were analyzed to determine optimum cutoff frequencies for the raw data according to the method of Giakas and Baltzopoulos (1997). The outcome of this analysis was a second-order Butterworth filter with a cutoff frequency of 5 Hz for position and 10 Hz for force data.

Inverse dynamics modeling

Using a two-dimensional nine-segment whole-body model, the net joint forces and moments were calculated in a custom program (Buck et al., 2000) based on the inverse dynamics method described by Winter (1990). The nine segments were linked by hinge joints, with an exception being the shoulder joint where the sliding of the joint was also taken into account, resulting in 19 degrees of freedom for the model.

Segment masses were estimated using parameters from Kreighbaum and Barthels (1985). The position of segment centers of mass and moment of inertia properties were derived from Winter (1990) except for the trunk segment center of mass, which was from Zatsiorsky and Yakunin (1991).

The first part of the inverse dynamics analysis started from the handle force, extending through the upper limb, and down the trunk to the hip joint. The trunk segment, with embedded reference frame, was defined as a rigid body running from 50 mm anterior to C7 along the spinal longitudinal axis to the L4/L5 disc centroid. The L4/L5 disc centroid was estimated using the iliac crests as the most lateral part of the torso at the caudal level, and mid-distance between the anterior and posterior skin surface along the iliac line as the anterior-posterior coordinate (McGill et al., 1988). The contribution of the shoulder joint force to the trunk moment was calculated by considering the location of the sliding joint center with respect to the C7 – L4/L5 trunk segment.

A second inverse dynamics calculation was initiated starting from the foot stretcher force extending up the lower limb to estimate the net hip moment. The root mean square (RMS) error between the two estimates of hip moment was used as a measure of the validity of the overall inverse dynamics method. The RMS error between the net hip moments of the "stretcher up" and "handle down" inverse dynamics method was calculated at RMS error 4.9 ± 4.0 Nm, less than 5% of the peak-to-peak amplitude of the hip joint moment.

Analysis of results

Ten full strokes were analyzed from each rowing trial. Two events, the catch and the release, were identified for each stroke. The catch occurred when the handle was at its most anterior horizontal displacement and the release at the most posterior handle position. Each stroke was normalized to 100% stroke (catch to next catch). All 10 strokes were used to form an average stroke profile for each rower, and then ensemble force-time stroke profiles were calculated to represent the mean with 95% confidence intervals included to indicate variability across subjects (Winter, 1984).

Data were analyzed during both the drive and recovery phase of the stroke. The drive phase occurred between the catch and the release when most of the power was delivered to the handle by the rower. The entire stroke was examined to ascertain any effects that the ergometer designs may have upon the rower during the recovery phase, as the rower slides back toward the catch position. Joint power production was calculated using the joint moment multiplied by the angular velocity.

Statistical tests

Multivariate analysis of variance with repeated measures (SPSS for Windows, SPSS Inc., Chicago, Illinois, USA) was used to test the significance of any observed differences in the means among the ergometer conditions. The degrees of freedom were adjusted (Huyn–Feldt) if the data failed Mauchly's test of sphericity. *A priori* contrasts (simple for group, polynomial for stroke) and post-hoc pairwise comparisons were used and the 0.05 level adopted for statistical significance. A Bonferroni adjustment was made for pairwise comparisons and multiple dependent variables. Time series data were compared using 95% confidence intervals to determine the periods where curves fell within similar ranges, and when data showed differences in the phases of the curves. The 95% confidence intervals of all ergometers were used in the between-group analysis; however, the 95% confidence intervals were only displayed for the C2F ergometer to enhance the clarity of the figures.

Results

External power production from the handle began to rise later and then peaked later for the C2F than it did for the other two ergometers (Fig. 2). Mean power production across subjects on the RP and C2S ergometers lay outside the 95% confidence intervals of the C2F during the first 10–15% of the stroke, with the power production being lower on the C2F during this period as a result of delayed power delivery. The RP and C2S ergometers reach peak power output earlier in the drive phase and also display smaller magnitudes of peak power when compared to the C2F, with significant differences in magnitude being shown between C2S and C2F ($P = 0.04$). Later in the drive phase (25–40% of the stroke), the C2F power curve remained significantly

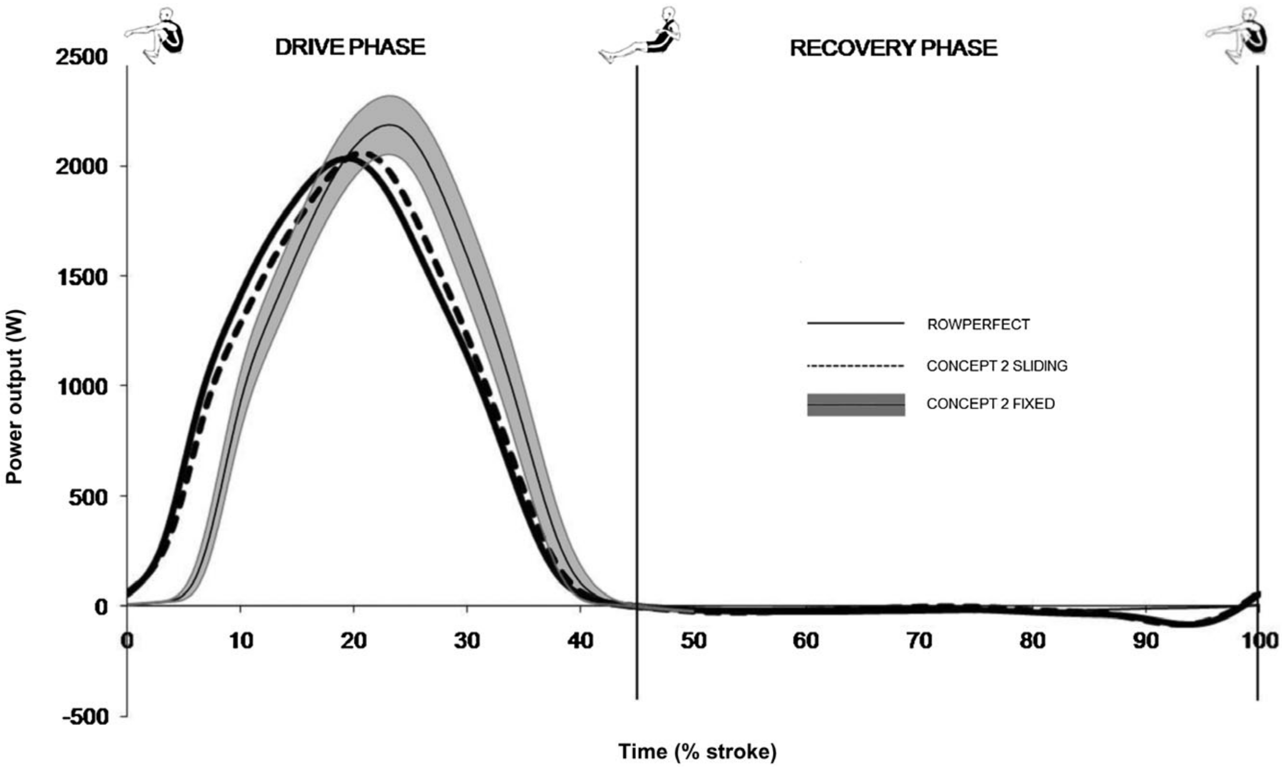

Fig. 2. External power output throughout the entire stroke. The figure depicts the normalized stroke profile of ensemble means for power output, calculated as the sum of handle power and foot stretcher power. The shaded area depicts the 95% confidence interval for the C2F ergometer. The 95% confidence intervals are shown only for the C2F ergometer condition to improve clarity of the figures. Rowing figures depict the catch, release, and the new catch position.

elevated when compared to the RP and C2S ergometers. Total area under the curve showed no significant difference between the three conditions, indicating that subjects were rowing at the same average power output even though the only stroke rate was specifically controlled (RP = 479.89 ± 51.47 watts; C2F = 473.81 ± 48.11 watts; C2S = 476.96 ± 50.19 watts).

The power generated at the knee joint shows a significant difference in the peak power production during the drive phase between the C2F and C2S ($P = 0.001$; Fig. 3). The knee joint power for RP and C2S lie outside the 95% confidence intervals of the C2F through greater power production on the C2F between 8% and 20%, greater absorption on C2F between 25% and 35%, and a different pattern of power output between 55% and 100%.

Joint moments at the knee were significantly greater at the catch on the C2F ergometer when compared to the RP and the C2S ($P = 0.01$; Fig. 4). Knee moment curves remained in phase for all three ergometer conditions during the drive phase, despite extension moments being elevated during the early portion (0–20% of stroke) and flexion moments being greater during the latter portion (25–35% of stroke) on the C2F. During the recovery phase however, knee moments on the C2F shifted out of phase in comparison to those developed on the RP and C2S, with peak flexion moment occurring earlier on the C2F. Rowers showed no significant differences in the angular velocity of the knee joint between ergometer conditions (data not shown) indicating that differing power outputs across the knee are the result of differences in joint moment, not velocity at the knee.

Rowers display significantly larger hip moments on the C2F ergometer at the catch when compared to the RP ($P = 0.02$; Fig. 5). The RP ergometer lies below the 95% confidence intervals of the C2F throughout almost the entire first 30% of the stroke and between 55% and 100% of the stroke. The C2S ergometer is comparable in shape and magnitude to that of the C2F and around the catch, yet lies outside of the 95% confidence intervals of the C2F between 22% and 32% of the stroke, and between 60% and 95% of the stroke. Again, rowers showed no significant differences in the angular velocity of the hip joint between ergometer conditions (data not shown).

The magnitude of horizontal trunk acceleration on the C2F is markedly increased in comparison to both the RP and C2S ergometers. The rate of positive acceleration is greater on the C2F throughout the drive phase as the rowers move away from the catch position, with substantially greater peak acceleration in the later drive phase (30% of the stroke). The trunk acceleration during the

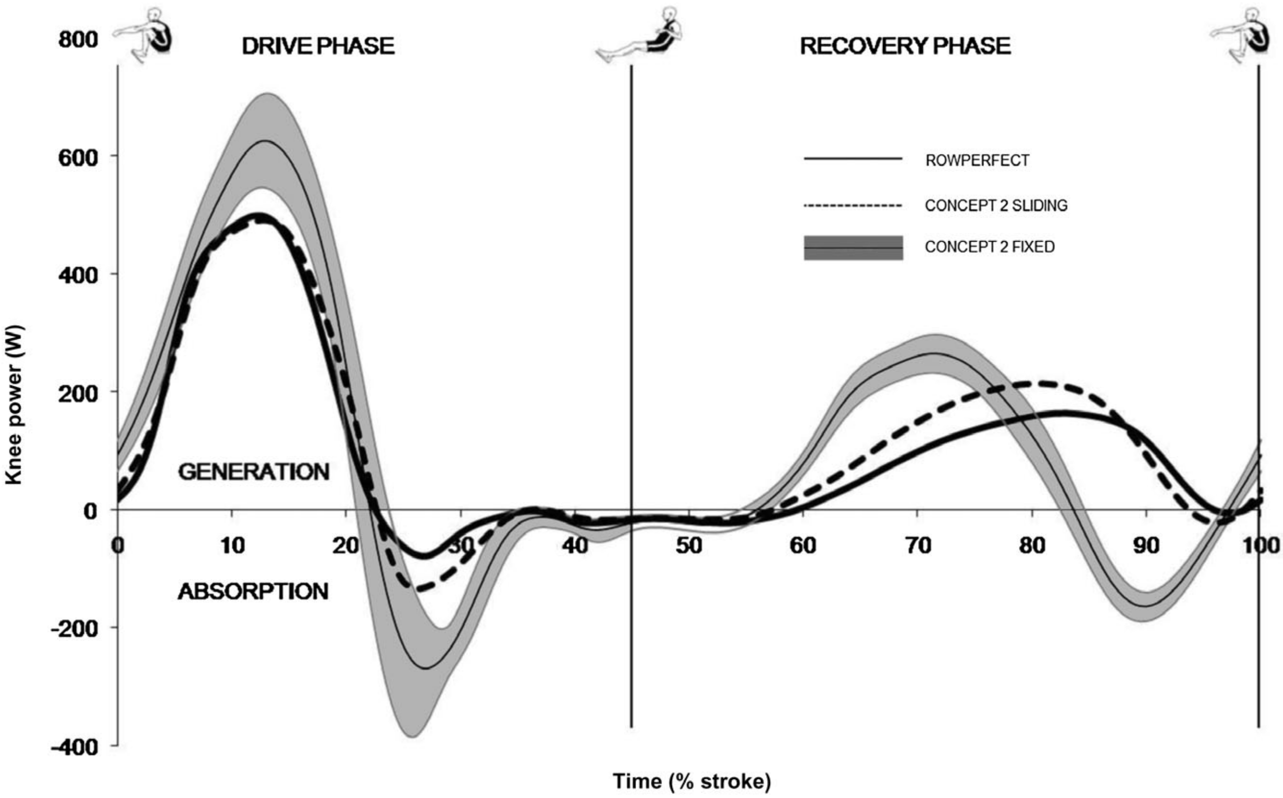

Fig. 3. Knee power output throughout the entire stroke. The figures depict the normalized stroke profiles of ensemble means for knee joint power output. The shaded area depicts the 95% confidence interval for the C2F ergometer. The 95% confidence intervals are shown only for the C2F ergometer to improve clarity of the figures. Rowing figures depict the catch, release, and the new catch position.

Table 1. Total joint mechanical energy and external mechanical energy per stroke delivered to the handle and the foot stretcher (mean ± SD)

	Ergometer type		
	RowPerfect	Concept2c sliding	Concept2c fixed
Sum joint mechanical energy per stroke (J)	1450.7 ± 231.9	1461.3 ± 240.8	1632.6 ± 236.4*
Sum external mechanical energy per stroke (J)	899.8 ± 96.5	888.4 ± 90.2	894.3 ± 94.1
Joint–external ratio per stroke (%)	63.6 ± 12.8	62.4 ± 12.8	55.9 ± 10.7*

*Significant at $P \leq 0.05$ C2F vs RP and $P \leq 0.05$ C2F vs C2S.

recovery phase also demonstrates elevated rates of both positive and negative trunk acceleration on the C2F (data not shown).

Over the entire stroke encompassing the drive and recovery phases, total joint mechanical energy production was significantly greater for the C2F ergometer compared to both the RP ($P = 0.006$) and C2S ($P = 0.011$; Table 1). No differences, however, were found in the external mechanical energy delivered to the three ergometer types. The ratio of work done across the joints in relation to that delivered to the handle and stretcher was calculated to give a measure of mechanical efficiency. Significant differences were shown between the C2F and the RP ($P = 0.006$), and between the C2F and the C2S ($P = 0.012$). The rowers delivered a smaller percentage of their joint mechanical energy to the C2F ergometer when compared to the RP or C2S.

The amount of mechanical energy per stroke produced across individual joints was calculated for both the drive and recovery phases of the stroke (Fig. 6). Knee joint mechanical energy production was significantly greater during both stages of the stroke on the C2F ergometer compared to both the RP ($P = 0.044$; $P = 0.025$) and the C2S ($P = 0.011$; $P = 0.001$; Fig. 6a and b). The hip and ankle joints showed no significant differences during the drive phase, but mechanical energy production was significantly greater at both joints during the recovery phase on the C2F compared to the RP ($P = 0.023$ and $P = 0.022$; Fig. 6b). No significant difference existed between the RP and the C2S ergometers at any joint.

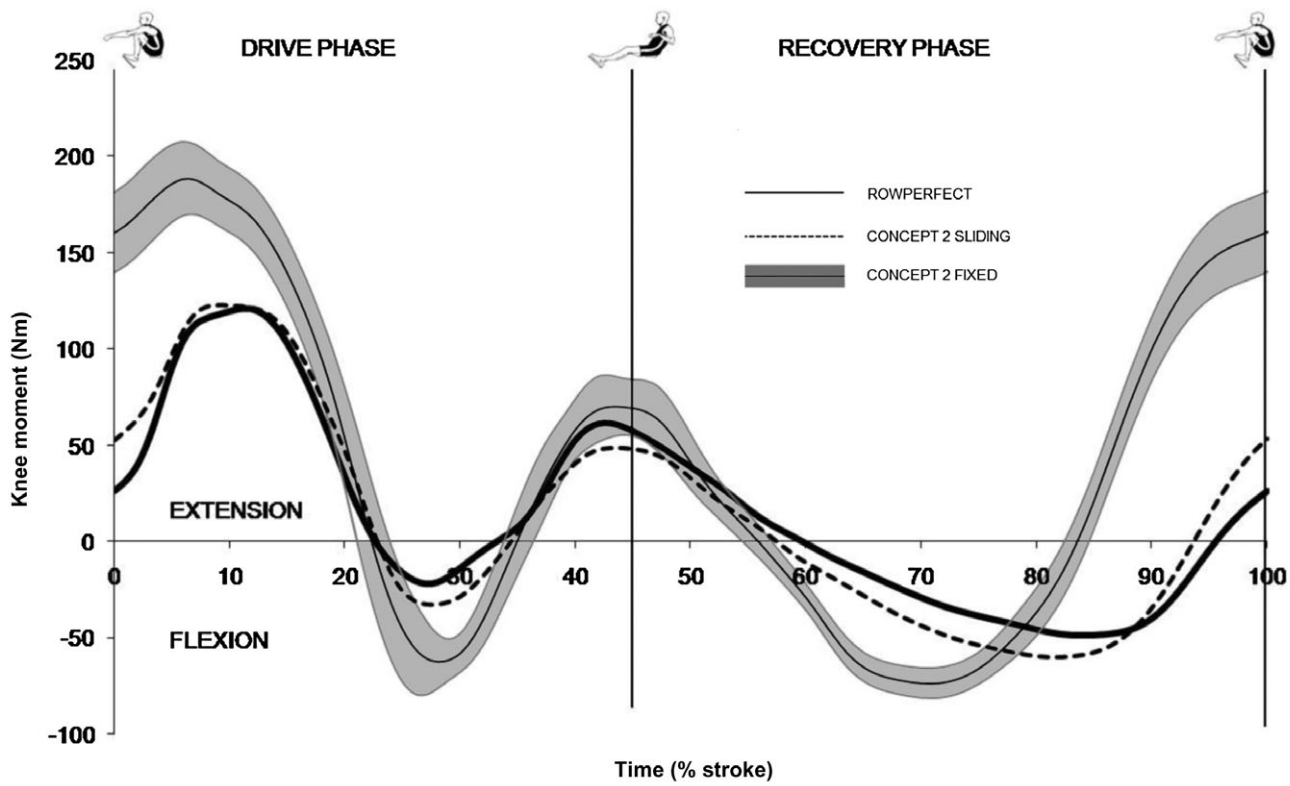

Fig. 4. Knee moments developed throughout the entire stroke. The figures depict the normalized stroke profiles of ensemble means for knee joint moment, with extension moments being positive, and flexion moments negative. The shaded area depicts the 95% confidence interval for the C2F ergometer. The 95% confidence intervals are shown only for one ergometer condition to improve clarity of the figures. Rowing figures depict the catch, release, and the new catch position.

Discussion

Mean propulsive power output, propulsive work consistency and stroke-to-stroke consistency and smoothness are all considered by Smith and Spinks (1995) to make significant contributions to successful rowing performance. Power output, and more specifically, peak power, is often used as the main identification criteria of a rower's mechanical energy production and technique efficiency, as well as having been reported to be the best predictor of 2000-m ergometer rowing performance (Bourdin et al., 2004).

Total power output of the rowers (Fig. 2), taking into account both the handle and the stretcher forces, shows that rowers on the C2F ergometer delay the delivery of power to the ergometer when compared to both the RP and C2F ergometers. It is not until approximately 15% of the stroke that the fixed ergometer power delivery is comparable to that of the other two ergometer conditions. Delayed power delivery to the ergometer can be attributed to the action of the fixed foot stretcher, where increased kinetic energy production is required by the rower in order to accelerate the rower's body mass before power can transfer through the body to appear at the handle (Bernstein et al., 2002). For a period of time around the catch, the power output from leg drive (extension) is largely devoted to accelerating the rower's mass, which is much larger when the feet push against a fixed stretcher. Colloud et al. (2006) described how the mechanism of the sliding foot stretcher allows a very different transfer of mechanical energy. The sliding stretcher design enables the center of mass (COM) of the combined fan assembly and lower limb to be accelerated in the opposite direction to that of the rowers body mass (Fig. 1), resulting in a lower net kinetic energy change as kinetic energy is proportional to the square of velocity. The results reported in Fig. 2 concur with those of Colloud et al. (2006) in highlighting a faster transfer of forces displayed at the handle while rowing a sliding ergometer. Zatsiorsky and Yakunin (1991) reported that the rowers COM and that of the boat are accelerated independently of each other on the water, similar to the configuration of the sliding stretcher, suggesting that the inertial loads experienced by the rower on the water are not as high as those on the C2F.

The energy expended by the rower during the stroke, and how effectively this is delivered to the boat, has a significant role to play in the performance of the rower. The greater the ratio of mechanical energy delivered to the handle and foot stretcher compared to that, which is produced by the joints, the more mechanically efficient the rower (Fukunanga et al., 1986). Significant

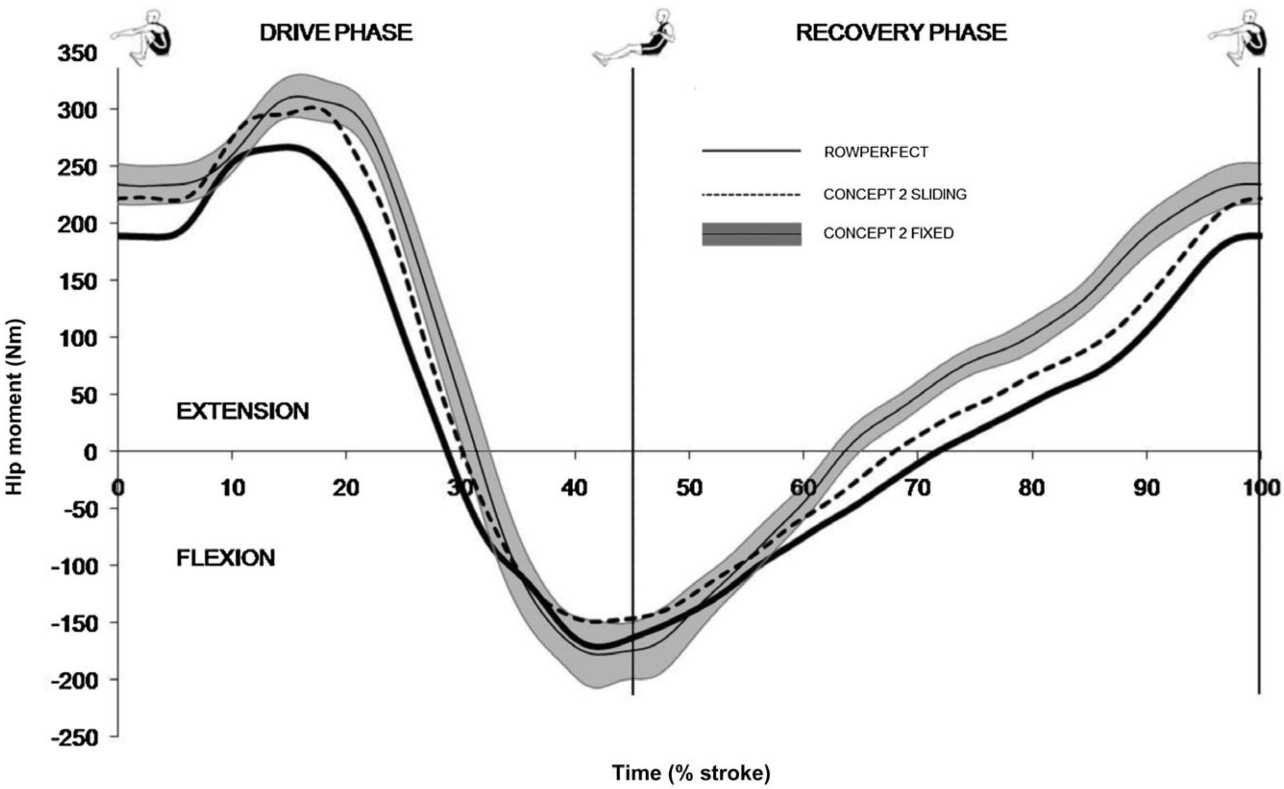

Fig. 5. Hip moments developed throughout the entire stroke. The figures depict the normalized stroke profiles of ensemble means for hip joint moment, with extension moments being positive, and flexion moments negative. The shaded area depicts the 95% confidence interval for the C2F ergometer. The 95% confidence intervals are shown only for the C2F ergometer to improve clarity of the figures. Rowing figures depict the catch, release, and the new catch position.

differences were found between fixed and sliding stretcher ergometers in the total mechanical energy production summed around all joints across the entire stroke (Table 1). Rowers are required to expend more total mechanical energy on the C2F, despite mechanical energy delivery to all three ergometers being comparable. Rowers on the C2F ergometer delivered a significantly lower proportion of their total joint mechanical energy production to the ergometer (55.9%) when compared to both the RP (63.7%) and the C2S (62.4%), demonstrating that the extra mechanical energy produced is not used to deliver power to the ergometer. These results are again in consensus with those of Bernstein et al. (2002), who reported increased segment kinetic energy for rowers on a fixed stretcher ergometer when compared to a sliding stretcher ergometer. Increased energy demand can once again be attributed to the greater mass of the rower being accelerated in relation to a fixed point on the C2F, as well as the rower having to accelerate in the opposite direction to reduce the velocity of their body mass to zero at the catch and then increase segment velocity away from the catch position.

Figure 2 shows that the magnitude of peak power output on the C2F was larger for all subjects when compared to the RP and the C2S ergometers. This increase in peak power delivered to the C2F ergometer once again results from the necessity to deliver power to the stretcher to accelerate the rower's entire mass in relation to a fixed point, leading to greater inertial resistance being experienced by the rower. This increased peak power corresponds to the significantly larger magnitudes of knee power production that are seen on the fixed ergometer compared to the sliding ergometers (Fig. 3). Increased power production and absorption occurs as a result of significantly larger flexion and extension moments at the knee joint (Fig. 4), which again arises as a result of the ergometer design. The elevated knee flexion moment and subsequent knee power absorption is due to the need to support body weight on the stretcher and subsequent movement of the stretcher reaction force moving from under the knee joint to above the knee joint from 22% to 35% of the stroke. Once again, the increased inertial force acting on the rower and increased trunk acceleration on the fixed stretcher ergometer requires a greater workload to be produced by the athlete.

During the drive phase, the pattern of knee power generation and absorption is similar among all three ergometer conditions, with early power generation and late power absorption, despite the reported differences in magnitudes. During the recovery phase however, it can be seen in Figs 3 and 4 that the pattern of power and

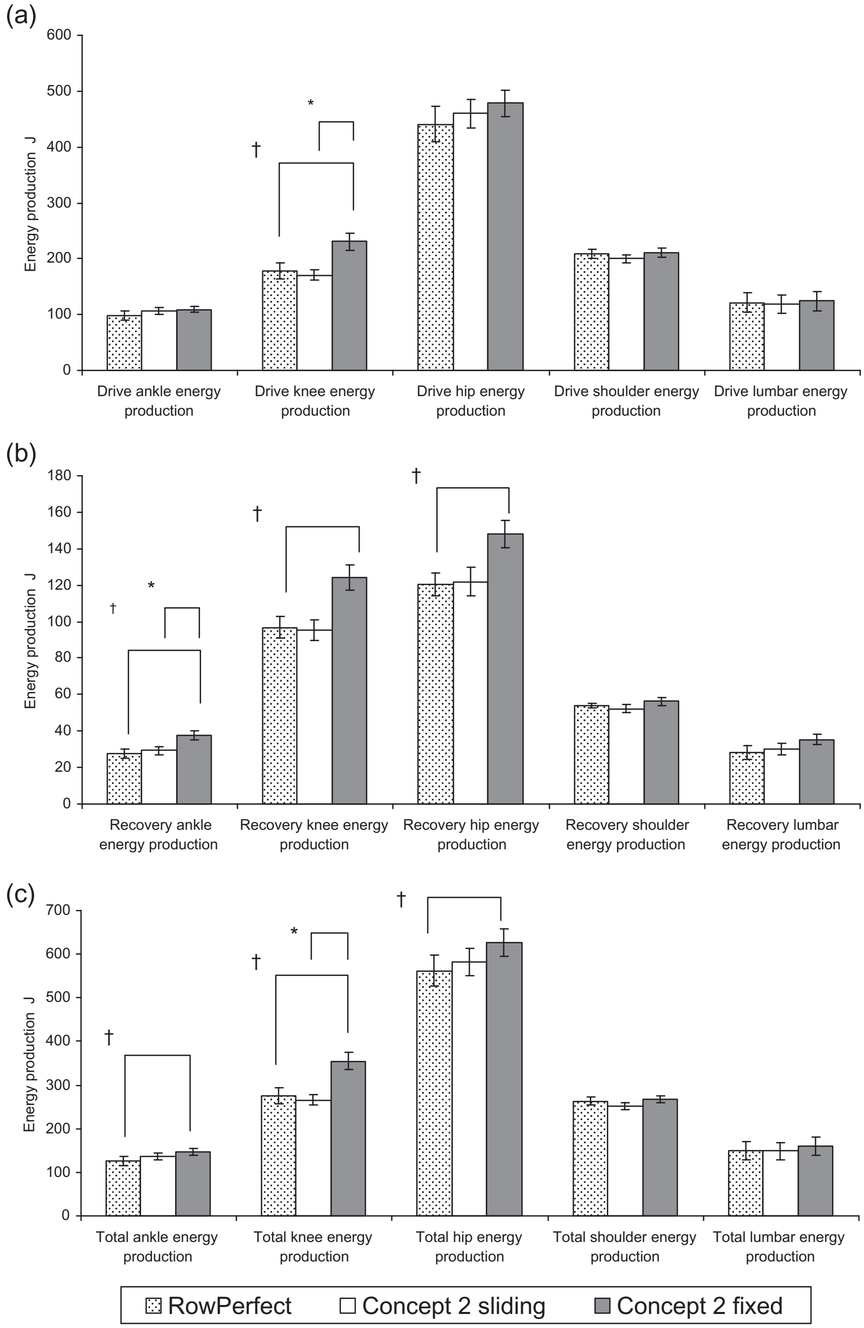

Fig. 6. Joint mechanical energy production throughout the different phases of the stroke (mean ± SD). The figures depict the normalized, ensemble means for joint mechanical energy production during the drive phase (a), recovery phase (b), and the entire stroke (c). †Significant at $P \leq 0.05$ C2F vs RP. *Significant at $P \leq 0.05$ C2F vs C2S.

moment production at the knee differs greatly between the fixed and the sliding ergometers. When rowing the fixed stretcher ergometer, rowers display greater magnitudes and earlier development of flexion moments as the rower generates power to actively pull their mass back toward the catch position. Elevated knee power absorption late in the recovery phase occurs as the result of an extension moment, which acts to slow the return of the rower toward the catch position, in preparation for the next stroke to begin. It is well understood that maximal velocity of the rowing boat occurs during the early part of the recovery phase (Martin & Bernfield, 1980; Affeld et al., 1993). Body movements and fluctuations of the rower during this period should be actively controlled, with the aim being to maximize the run of the boat in the water before initiating the return to the catch position, which causes a reduction in the velocity of the boat (McBride, 2005). Therefore, the differing pattern of knee activity and increase of both power generation and absorption of the rower on the C2F ergometer resulting from the increased inertial load on the C2F may bring into question the specificity of the fixed ergometer in replicating the magnitude, timing, and coordination of the on-water recovery phase.

In concurrence with the findings related to knee power production (Fig. 3) and knee moments (Fig. 4), the increased mechanical energy production during the rowing stroke on the fixed ergometer appears to focus specifically around the lower extremity (Fig. 6c). During the drive phase, rowers display significantly greater knee mechanical energy production on the C2F when compared to both the RP and C2S (Fig. 6a). Elevated joint mechanical energy production also occurs during the recovery phase, where a significant increase is seen not only at the knee joint, but also at the ankle and hip joints (Fig. 6b). Consequently, an increased mechanical energy demand is placed upon the lower extremity to accelerate the body away from the catch in the drive phase, or to first initiate and then slow down the return to the catch during the recovery phase.

When comparing the magnitude of both peak power output and peak knee power output, statistical differences were only found between the C2F and C2S ergometers, but not the C2F and RP. An explanation of which may come from the findings of Soper and Hume (2004b), who reported that power output on the C2F showed lower standard error measurements (SEMs) than on the RP, and was subsequently deemed to be a more reliable indicator of power output because of the C2F's inherent stability. The RP ergometer not only exhibits a sliding foot stretcher and flywheel complex, but it also exhibits a seat, which requires the rowers to balance their weight distribution during the rowing stroke. Such variables will increase the skill demands upon the rower and subsequently increase the SEMs displayed. Although the C2S ergometer also has the sliding foot stretcher mechanism, the whole ergometer is attached to a set of runners and free to move in the anterior-posterior direction. Because of its design, the C2S has a greater mass and a more constrained setup, resulting in less fluctuation and a greater degree of stability than the RP. This increased variation of results experienced within the sample may explain why significant differences were seen for the C2S, but not for the RP, despite their peak magnitude values being very similar.

Further research is required to gain a greater understanding of the on-water kinetics and kinematics, and subsequently how precisely ergometer rowing follows the mechanics of on-water rowing. Until a direct comparison of ergometer and on-water rowing has been carried out, it can only be suggested that the presence of the sliding foot stretcher may improve the specificity of stroke mechanics between ergometer and on-water rowing, providing a more accurate portrayal of the on-water stroke than the fixed stretcher ergometers.

Perspectives

The study has highlighted key differences that exist between the major ergometer designs widely used within the rowing community. The presence of a fixed foot stretcher increases the magnitudes of power generation and absorption throughout the rowing stroke, as a result of increased flexor and extensor moments developed by the muscles acting around the knee. Joint mechanical energy requirements of the knee and hip joints were subsequently increased on the fixed stretcher ergometer, suggesting a reduced mechanical efficiency while rowing the fixed stretcher ergometer. Given the large amount of time spent training and exercising on rowing ergometers, is important to quantify and consider the increased stresses applied to the rower as a result of rowing the fixed stretcher ergometer. Increased lower limb loads may have implications for joint overuse injury and fatigue development, and must be carefully considered in the development and prescription of training programs. As well as placing increased demands upon the rower, the changes in the joint activation patterns experienced by the rower on the fixed stretcher ergometer may, with further investigation and comparison of ergometer and on-water rowing, prove detrimental to the transfer of technique between ergometer and on-water rowing, which is important to both rowers and coaches alike.

Key words: biomechanics, simulator, mechanical energy expenditure, joint power, coordination.

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