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Effect of gender and stroke rate on joint power characteristics of the upper extremity during simulated rowing

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Abstract
Males typically have greater upper body strength than do females, which is likely to impact on the rowing techniques adopted by each sex. The aim of this study was to quantify energy contributions and compare the joint power production of upper extremity joints between the sexes. Seven males and eight females performed 60 s trials at five different stroke rates. External forces were measured at the handle and stretcher, while kinematics were recorded by motion analysis. Joint moments were derived by inverse dynamic calculations, followed by the calculation of joint powers and gross mechanical energy expenditure. Male rowers expended more total external energy per stroke and made a larger percentage contribution of angular shoulder energy to their total external energy expenditure. As stroke rate increased, the contribution from elbow and angular shoulder energy contributions decreased for both males and females. Female rowers decreased their angular shoulder contribution at a slower rate than did males as stroke rate increased. The overall percentage of work done on the stretcher was higher for male rowers, and this difference further increased at higher stroke rates. The results of this study suggest that specific upper body conditioning may be particularly important for female rowers.

Keywords: *Biomechanics, energy contributions, ergometer rowing*

Introduction

Rowing is a sport that requires athletes to generate, and maintain, a relatively high power output for the duration of a competitive race. Studies exploring rowing characteristics investigate power production to quantify technique in a way that can be used by athletes and coaches to improve performance. The average power produced in one stroke is the result of a complex segmental coordination of the body's joint powers (Mokha, Ludwi, Wood, & Mokha, 2004). Power has been found to be a predictor of rowing performance (Bourdin, Messonnier, Hager, & Lacour, 2004; Ingham, Whyte, Jones, & Nevill, 2002), with mean propulsive power per kilogram of body mass one of the many variables enabling differentiation between rowers of varying skill (Smith & Spinks, 1995).

Most rowing research has focused on the peak, mean, and instantaneous power developed throughout the stroke. Peak power output has been reported to predict an athlete's performance (Bourdin et al., 2004; Ingham et al., 2002) and provides feedback to coaches and athletes on stroke performance as a whole. However, these measures of power fail to identify exactly what joints are contributing to the power being generated and cannot assist with the implementation of strength and conditioning programmes.

Four studies partitioned the contribution of larger body segments to total power (Kleshnev, 1996, 2000; Tachibana, 2002; Tachibana, Yashiro, Miyazaki, Ikegami, & Higuchi, 2007). However, with the use of simplified joint force methods instead of mechanical joint power calculations, the power developed and transferred by joint moments was neglected in these studies. It appears no investigation has quantified the contribution of individual joints to total power output.

Stroke rate is the number of strokes performed in a unit of time, usually expressed as strokes per minute. Different crews adopt a variety of stroke rates during competition, often with the same successful outcome (Martin & Bernfield, 1980). Furthermore, coaches frequently incorporate low stroke rates during training sessions for detailed attention to an athlete's technique. When a task is altered, as when changing the cadence at which it is performed, joint-specific

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changes to power output are likely to follow (Ettema, Lorås, & Leirdal, 2009; Martin & Brown, 2009). At faster stroke rates, the relative time spent developing force at the handle decreases (Martin & Bernfield, 1980) with a consequent reduction in power coming from the arm pull (Kleshnev, 1996). However, it is currently unknown how this reduction in power during the arm pull is partitioned within the joints of the upper extremity and whether there are joint-specific changes at various stroke rates.

It is expected that power output will be different between the sexes, although when observed relative to lean body mass, mean rowing power is similar between males and females (Lutoslawska, Klusiewicz, Sitkowski, & Krawczyk, 1996; Tachibana et al., 2007). This being the case, it is not yet understood whether there are gender-specific contributions to the power developed at different joints. Compared with males, reduced strength capabilities in females are more pronounced in the upper body (Wilmore, 1974). This lack of upper body strength in females (McGuigan & Ratamess, 2009; Weyant, 2001) could alter the relative joint power contribution to total stroke power.

The aims of this study were to quantify joint energy contributions to total external energy expenditure and compare joint powers of the upper extremity at various stroke rates and between the sexes. We hypothesize that the energy contribution of the upper extremity during the drive phase of rowing will be reduced in females compared with males across all joints and stroke rate conditions.

Methods

Participants

Fifteen rowers, all of whom reported being free of injury at the time of testing and familiar with simulated rowing, participated in the study. Male participants were club ($n = 2$), state ($n = 3$), and national ($n = 2$) rowers, while the female participants were state ($n = 5$) and national ($n = 3$) rowers. Rowers' characteristics are presented in Table I. Males were taller ($P = 0.001$) and heavier ($P = 0.014$) than females, while age and training frequency were similar across the sexes ($P > 0.1$). Athletes were informed of the procedures and signed a consent form before participating. The study received approval from the University of Sydney's Human Research Ethics Committee.

Table I. Participant characteristics (mean $\pm$ *s*).

	Males ($n = 7$)	Females ($n = 8$)
Age (years)	21.7 $\pm$ 5.4	20.9 $\pm$ 2.5
Height (m)*	1.85 $\pm$ 0.1	1.74 $\pm$ 0
Mass (kg)*	79.66 $\pm$ 8.3	66.72 $\pm$ 9.3
Training frequency (h $\cdot$ week^{-1})	18.2 $\pm$ 4.9	16.5 $\pm$ 5.2

*Significant difference between males and females ($P < 0.05$).

Protocol

Participants carried out five 60 s bouts of rowing on a Concept II sliding ergometer (Concept2, Model D, Morrisville, VT, USA) with the damper setting positioned at level 1 (the lowest drag setting). The five trials consisted of a combination of stroke rates: 18, 24, 30, and 36 strokes per minute and "race" pace (SR.18, SR.24, SR.30, SR.36, and SR.race respectively). Race pace was described to the participants as being the stroke cadence commonly used during a 2000 m competitive race, not the fastest they could physically row. Familiarization with the test equipment was done immediately before testing during a 5 min warm-up (Schabort, Hawley, Hopkins, & Blum, 1999; Soper & Hume, 2004).

Data were collected for 60 s under each condition when participants were asked to exert maximal effort while maintaining the nominated stroke rate and proper technique. A 5 min active recovery period, in which participants self-selected a comfortable and easy pace, separated each trial. The order in which the stroke rates were tested was randomly assigned. The digital display on the sliding ergometer was partially covered to provide participants with stroke rate feedback only.

Kinetic analysis

The simulator was instrumented to measure external forces generated by the participant at the hands and feet. A custom-built foot stretcher (Luescher Teknik Specialist Sports Technology, Melbourne, VIC, Australia) equipped with four force sensors (9251A, Kistler Instrumente AG, Switzerland; non-linearity $< 1\%$, hysteresis $< 0.5\%$) collected three-dimensional forces being applied to the stretcher. Force applied at the handle was measured with a strain gauge (Model UMM-K200, Dacell, Korea; non linearity $< 0.1\%$, hysteresis $< 0.1\%$) connected in series with the handle chain. The foot stretcher force sensors were zeroed before each trial. Air resistance was assumed to be negligible and accordingly given no value. The same was assumed for the friction force generated by movement of the simulator along the slides (Consiglieri & Pires, 2009).

Kinematics analysis

Before testing, reflective markers were fixed with double-sided adhesive tape (3M, Pymble, NSW, Australia) to the skin of the participants at anatomical landmarks of the upper body. Markers were positioned on the left and right ulnar and radial styloid processes, the left and right lateral and medial epicondyles of the humerus, the left and right acromion processes, and the left and right bicep using a method described previously (Greene, Sinclair, Dickson, Colloud, & Smith, 2009). Markers were also placed on the simulator at the top and bottom of the foot stretcher, on the two ends of the handle, at the centre of the flywheel, and on the chain force transducer. As recommended by Gorton and colleagues (Gorton, Hebert, & Gannotti, 2009), the same technician placed all markers on each participant.

The three-dimensional movement of reflective markers was captured by a motion analysis system (Cortex Motion Analysis, Version 1.0, Santa Rosa, CA, USA) comprising 14 digital cameras at a sampling frequency of 100 Hz. Joint centres were quantified as a function of time for a two-dimensional human body model using Kintrak software (Version 6.2, University of Calgary, Calgary, Alberta, Canada). The wrist joint centre, used to define the forearm, was defined as the midpoint between the radial and ulnar styloid markers. The elbow was defined as a hinge joint with its joint centre located midway between the medial and lateral humeral epicondyle markers. The shoulder joint centre was located 50 mm below the acromion marker in the anatomical position, with rotation possible about the three axes of motion and translation allowed in the antero-posterior direction. This antero-posterior translation of the shoulder reflects movement of the shoulder girdle forward and backward with respect to the trunk segment (Figure 1). The means of the left and right joint centres were used for the two-dimensional sagittal plane model. The kinematic data were filtered using a dual-pass Butterworth filter with a cut-off frequency of 5 Hz for position, 4 Hz for velocity, and 3 Hz for acceleration data (Giakas & Baltzopoulos, 1997).

Inverse dynamic modelling

The joint centre and kinetic data of the upper extremity were processed by custom software (Matlab, Mathworks, Natick, MA, USA) to output all the kinematic and kinetic variables required for this study. Joint moments were determined from an upper limb inverse dynamics analysis (Winter, 1979) using a two-dimensional dynamic linked segment model (Greene et al., 2009). Segment masses were estimated from percentages of total body mass, specific to male and female athletes, reported by Kreighbaum and Barthels (1985). Segment centre of mass and moment of inertia properties were derived from Winter (1979). Joint moments derived from the inverse dynamic calculations were multiplied with individual joint angular velocity values to determine joint power output.

Analysis of results

For each rowing condition, ten full strokes were analysed that were collected after the participants had reached the requested stroke rate (Hartmann, Mader, Wasser, & Klauer, 1993; Millward, 1987). The beginning of each stroke was defined by the catch where the simulator handle reached its maximum negative displacement relative to the simulator fan axle. A stroke's completion was defined by the handle's return to the catch position. Each stroke was normalized to 100% of a single rowing cycle to enable the time series means of groups to be compared.

The primary variable was a discrete value of gross energy expenditure per stroke expressed as a percentage of the total external energy expended. The gross energy expenditure values were determined by integration of the absolute value of the power time series curve for each joint. Gross energy expenditure was determined for the elbow and shoulder (angular and antero-posterior) movements and for the contribution of the handle and stretcher to total external energy. The energy applied to the handle and to the stretcher was calculated by integrating the product of force and velocity at the handle and stretcher respectively. The total external energy was determined by the summation of handle and stretcher energies per stroke.

The time series of joint power output at the elbow and shoulder (angular and antero-posterior) acted as

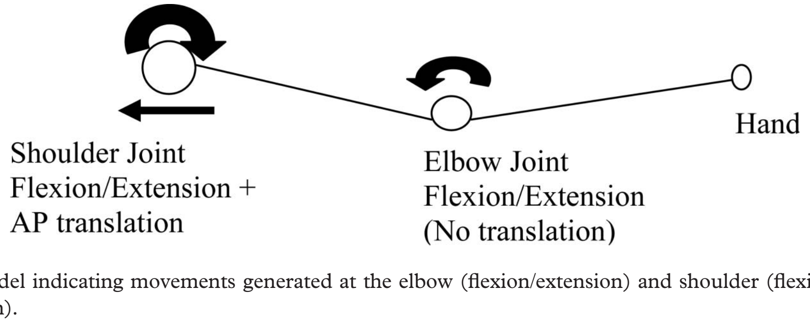

Figure 1. Upper arm model indicating movements generated at the elbow (flexion/extension) and shoulder (flexion/extension and antero-posterior [AP] translation).

a secondary variable. The time series for every stroke of each participant was normalized to the average total external power developed for that stroke.

Statistical analysis

Statistical differences in the magnitude of gross energy expenditure per stroke were assessed using a three-way analysis of variance (SPSS, Version 16.0) with a between-participant gender factor (male, female) and a within-participant factor of stroke rate (five stroke rates) and stroke number (ten strokes). The P-value to determine significance was set at 0.1 (Sterne & Davey Smith, 2001). To reduce the chance of a type I error, a Bonferroni adjustment was applied for comparisons between primary variable data. Differences between the sexes in joint power output characteristics as a function of time were assessed using 95% confidence intervals (Ho, Smith, & O'Meara, 2009).

Results

The stroke rates adopted during trials are presented in Table II. No significant differences were observed between the sexes ($P > 0.1$). The total external energy expenditure during a single stroke is shown in Figure 2. Differences between the sexes were observed ($P < 0.001$), with the males producing greater magnitudes of external energy than the females. We observed an interaction between stroke rate and gender ($P = 0.083$). This interaction illustrates that with faster stroke rates the males increased, and females decreased, the total external energy expended during a stroke ($P = 0.064$). This difference arose because the males showed both increased force production and stroke length at higher velocities (4.2% increase in force and 4.5% increase in length between 18 and 36 strokes per minute). In contrast, the females decreased force at higher velocity (8.9% decrease) and achieved only a small increase in stroke length (1.5%), resulting in an overall decline in energy expenditure.

Gross energy expenditure values (means and standard deviations) for the upper extremity are displayed in Table III. Shoulder angular energy expenditure as a percentage of total external energy per stroke is displayed in Figure 3. A main effect of gender was observed ($P = 0.001$), with the male rowers generating a larger proportion of their overall work through rotation of the shoulder. Stroke rate changed the contribution of shoulder angular energy to total energy ($P = 0.053$), whereby percentage contributions decreased in a linear fashion as stroke rate increased. Interactions between stroke rate and gender highlight differences in the involvement of shoulder angular energies ($P = 0.027$), illustrating that as stroke rate increased the relative shoulder angular energy contribution decreased at a faster rate

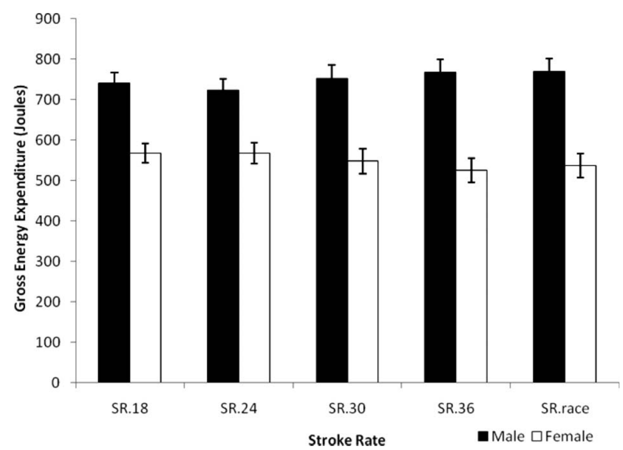

Figure 2. Total external energy expended per stroke for males and females across all stroke rate conditions (18, 24, 30, 36 strokes per minute and race pace). Means and standard errors are shown.

Table II. Comparison between the requested stroke rate and the actual stroke rate adopted by participants during the test (mean ± s).

Requested stroke rate[a]	Actual stroke rate (strokes per minute) Males	Females
SR.18	19.53 ± 1.92	19.04 ± 1.06
SR.24	24.39 ± 0.98	23.89 ± 0.91
SR.30	30.43 ± 1.38	29.88 ± 0.65
SR.36	36.41 ± 0.68	35.50 ± 0.90
SR.race	38.72 ± 4.77	38.27 ± 3.14

[a]18, 24, 30, 36 strokes per minute and race pace.

Table III. Gross energy expenditure values for the upper extremity (mean ± s)

		Gross energy expenditure (% total external energy)		
Stroke rate[a]	Sex	Elbow	Angular shoulder*	AP shoulder
SR.18	M	2.16 ± 0.53	12.81 ± 1.78	6.99 ± 2.17
	F	2.29 ± 0.35	8.30 ± 1.98	5.99 ± 1.03
SR.24	M	1.99 ± 0.55	12.12 ± 1.15	6.68 ± 1.98
	F	2.17 ± 0.42	8.17 ± 1.89	6.0 ± 1.20
SR.30	M	1.94 ± 0.50	12.0 ± 1.47	6.44 ± 1.85
	F	2.26 ± 0.32	7.97 ± 1.78	6.2 ± 1.12
SR.36	M	1.96 ± 0.59	11.85 ± 1.92	6.34 ± 1.76
	F	2.12 ± 0.42	7.44 ± 2.20	6.12 ± 1.22
SR.race	M	1.87 ± 0.53	11.06 ± 1.86	6.37 ± 1.88
	F	2.06 ± 0.55	8.49 ± 1.98	5.65 ± 2.15

[a]18, 24, 30, 36 strokes per minute and race pace.
*Significant difference between the sexes across all stroke rates ($P = 0.001$).

in males than females. A main effect of stroke number was identified within the strokes analysed for the contribution of shoulder angular energy to total external energy and was shown to decrease over time ($P < 0.001$). There were no significant differences in the relative contribution of antero-posterior shoulder energy between the sexes, for stroke number or with changes to stroke rate ($P > 0.1$).

Elbow energy contributions to total external energy during a stroke are presented in Figure 4. Stroke rate had a main effect on the contribution of elbow energy to total external energy ($P = 0.005$), showing that as stroke rate increased the contribution decreased.

The means and standard deviations for the handle, stretcher, and total external energies are shown in Table IV. There was a main effect of stroke rate ($P = 0.008$) explained by a quadratic relationship

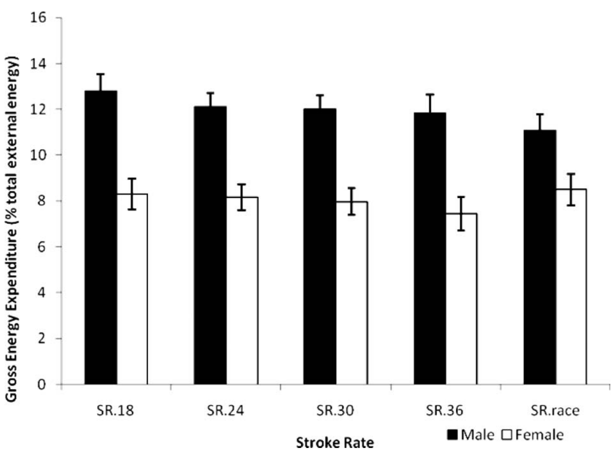

Figure 3. Angular shoulder energy expenditure per stroke for males and females across all stroke rate conditions. Means and standard errors are shown.

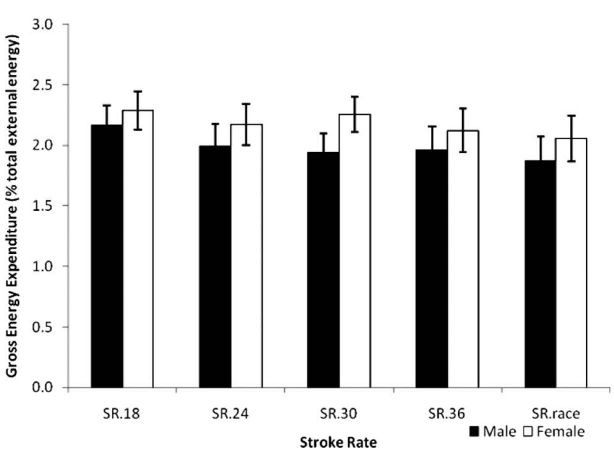

Figure 4. Elbow energy expenditure per stroke for males and females across all stroke rate conditions. Means and standard errors are shown.

($P = 0.009$), where the percentage contribution of stretcher energy to total energy expended per stroke declined as stroke rate increased from 18 to 30 strokes per minute, before rising again at the higher stroke rates (Figure 5). There was no overall significant main effect for gender in the contribution of stretcher energy to total external energy output ($P > 0.1$). However, there was a significant interaction between gender and stroke rate ($P = 0.014$) with males exhibiting larger energy contributions from the stretcher that became more apparent at higher stroke rates. A main effect of stroke number was identified within the strokes analysed for the contribution of energy expended at the stretcher to the total external energy ($P < 0.001$), with the stretcher's contribution increasing over time.

Total external energy expenditure is the sum of energy applied to the stretcher and to the handle. Therefore, changes in the relative proportion of energy applied to the stretcher and handle are equal in magnitude. As the proportion of total energy applied to the stretcher increased with stroke number, the proportion of energy applied to the handle therefore decreased ($P < 0.001$).

The angular velocity, joint moment, and joint power curves for angular shoulder movement at 18 and 36 strokes per minute are shown in Figure 6 and 7, respectively. At 18 strokes per minute, the males extended their shoulders faster than did the females during the mid drive phase. The females demonstrated a later onset of rapid shoulder extension at the end of the drive phase. At the beginning of the recovery phase, the females exhibited faster shoulder flexion with the differences between the sexes disappearing after this initial movement. Joint extensor moments were larger in the male rowers from 5% to 25% stroke time. Males then exhibited higher flexor moments for the duration of the recovery phase. Males generated larger joint power values from 5% to 25% stroke time. At the end of the drive phase, power absorption was observed for the females while the males were still generating power from angular shoulder movement.

At 36 strokes per minute, the males exhibited a faster shoulder extension during the mid drive phase, while females had a delayed peak shoulder extension velocity at the end of the drive phase. Females then demonstrated a faster peak shoulder flexion during the recovery phase. Male rowers exhibited larger joint extensor moments from 10% to 38% stroke time and then exhibited higher flexor moments for most of the duration of the recovery phase. Differences in joint power were evident during the mid drive phase where males generated a greater power. Males then absorbed more power than the females at the end of the drive phase and generated more power for the first half of the recovery phase.

Table IV. Energy expenditure at the simulator handle and stretcher and total gross external energy expenditure. Mean ± SD.

		Gross energy expenditure (% total external energy)		
Stroke rate[a]	Gender	Handle	Stretcher	Total external gross energy expenditure (J)*
SR.18	M	62.18 ± 4.13	37.82 ± 4.13	740.14 ± 74.72
	F	62.60 ± 3.26	37.40 ± 3.26	567.37 ± 65.54
SR.24	M	63.85 ± 4.00	36.15 ± 4.00	723.72 ± 87.86
	F	63.73 ± 2.60	36.27 ± 2.60	566.37 ± 57.88
SR.30	M	63.63 ± 3.77	36.37 ± 3.77	752.44 ± 117.21
	F	64.89 ± 2.01	35.11 ± 2.01	547.32 ± 41.92
SR.36	M	62.16 ± 3.76	37.84 ± 3.76	766.37 ± 117.47
	F	64.81 ± 2.29	35.19 ± 2.29	524.62 ± 35.88
SR.race	M	62.25 ± 4.63	37.75 ± 4.63	768.57 ± 93.06
	F	65.06 ± 2.60	34.94 ± 2.60	536.33 ± 79.82

[a]18, 24, 30, 36 strokes per minute and race pace.
*Significant difference between the sexes across all stroke rates ($P < 0.001$).

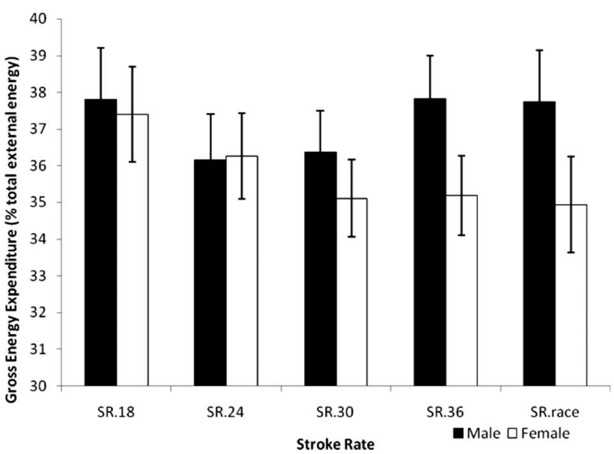

Figure 5. Stretcher energy expenditure per stroke for males and females across all stroke rate conditions. Means and standard errors are shown.

Discussion

The aims of this study were to quantify joint energy contributions to total external energy expenditure and compare joint powers of the upper extremity at various stroke rates and between the sexes. The primary finding was that the proportion of angular shoulder energy expenditure to total energy was lower in the female participants across all stroke rate conditions. No differences in the contributions of antero-posterior shoulder or elbow energies were found between the sexes. It might therefore be the angular shoulder contribution that explains the smaller arm power in females found by Kleshnev (2000) in his on-water investigation of power partitioning of larger body segments.

Rowing performance is determined largely by anthropometry (Barrett & Manning, 2004) and aerobic capacity (Ingham et al., 2002). However, these variables cannot entirely explain the differences in finishing times between male and female rowers (Yoshiga & Higuchi, 2003). Differences between the sexes in the contribution of angular shoulder energy to total external energy expended in the present study may help to explain the subtleties concerning differences in male and female rowing performance.

In the upper extremity, only the contribution of angular shoulder energy was shown to change as stroke rate was altered. In line with a study by Ettema et al. (2009), this reveals that the relative contribution of joint energy to total external energy is joint specific and in some cases remains unchanged (Ericson, 1988).

The present results show that at 36 strokes per minute, the summation of upper body energies is responsible for 20.15% of total external energy in males and 15.68% of total external energy in females. For a similar stroke rate, between 30 and 35 strokes per minute, Tachibana et al. (2007) found that on a simulator the arm pull contributed 10.7% and 10.5% to total power for males and females respectively. With participants using a broad range of stroke rates on-water, Kleshnev (2000) found that upper body contributions to total power were 24% and 21.3% for males and females respectively. The two aforementioned studies did not incorporate individual net joint moments into their calculations of segment powers and thus the results of this study can be interpreted as being more reflective of the actual power developed within the upper extremity.

At higher stroke rates, males were found to apply a greater relative contribution of total external energy to the stretcher than did females. This has implications for on-water rowing, as changes in the balance between forces applied at the stretcher and the pin cause boat velocity fluctuations within a rowing stroke, resulting in power losses to the water (Affeld, Schichl, & Ziemann, 1993). In addition, boat speed efficiency is reduced at very high or very low stroke rates (Sanderson & Martindale, 1986), suggesting

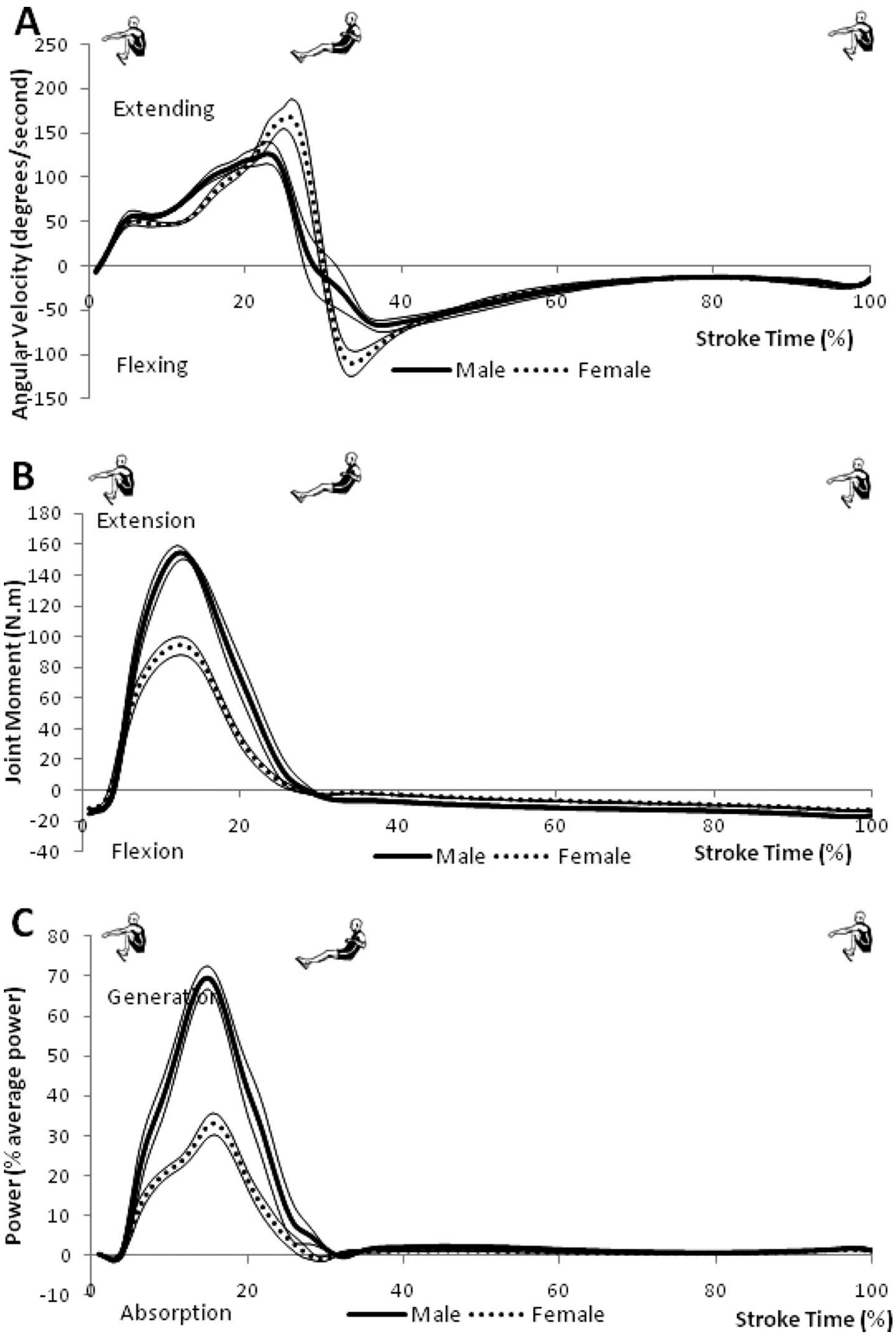

Figure 6. Ensemble mean angular velocity (A), joint moment (B), and joint power (C) curves for angular shoulder movement at 18 strokes per minute. Power is expressed as a percentage of the average total external power output during a stroke. The 95% confidence intervals are shown above and below the respective female and male data. Rower figures indicate stages of the stroke: catch, finish, and the next catch.

that the quadratic trend found between stretcher contribution and stroke rate in this study may have further associations with on-water performance. Testing a similar range of stroke rates to the ones used in this study, Hofmijster and colleagues (Hofmijster, Landman, Smith, & Van Soest, 2007) reported a linear reduction of velocity efficiency with increasing stroke rate. This trend was explained by higher accelerations of the rower relative to the boat.

Combining data across the sexes and stroke rates, we showed that, on a Concept II sliding ergometer, handle energy contributed approximately 64% to total external energy expenditure, while stretcher energy contributed approximately 36% (Table IV). Colloud and colleagues (Colloud, Bahuaud, Doriot, Champely, & Chèze, 2006) also reported that the horizontal movement of the handle was the largest contributor to total external power on a simulator

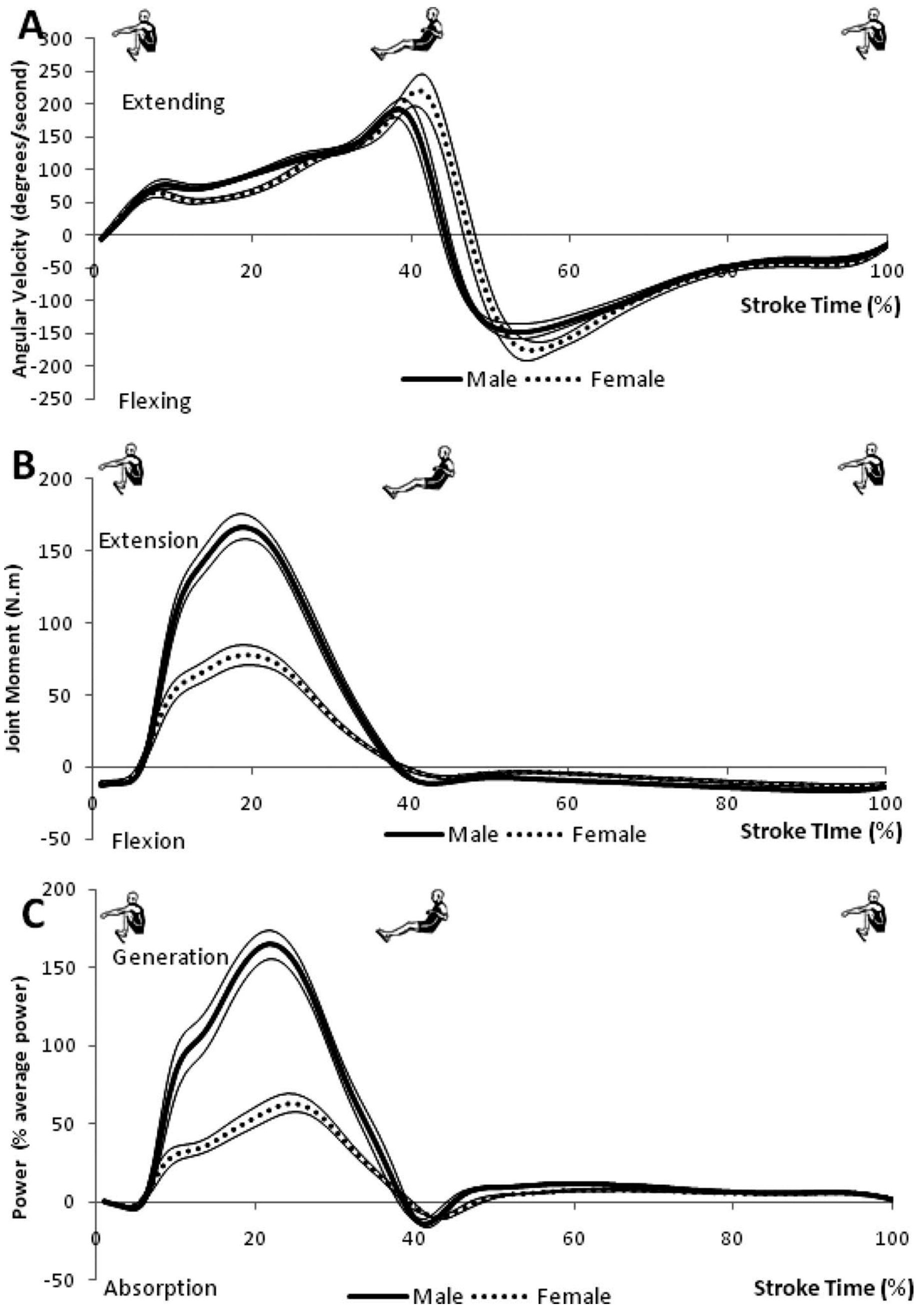

Figure 7. Ensemble mean angular velocity (A), joint moment (B), and joint power (C) curves for angular shoulder movement at 36 strokes per minute. Power is expressed as a percentage of the average total external power output during a stroke. The 95% confidence intervals are shown above and below the respective female and male data. Rower figures indicate stages of the stroke: catch, finish, and the next catch.

and found that at its maximum value represented 75% of the total external power developed. The practicality of these results and their transference to on-water rowing must be approached with caution as differences in handle force have been found between simulator and on-water data (Kleshnev, 2005). For example, the mass of the Concept II sliding ergometer is approximately 35 kg, whereas a single scull is closer to 19 kg (Hooper, 2006). These differences in mass alter the acceleration properties of the rowing movement (Hooper, 2006) and thus have the potential to modify power production when rowing on-water compared with simulator training.

Stroke-to-stroke variability in the energy contribution to total external energy at the handle and stretcher and during angular shoulder movement revealed inconsistencies within the strokes analysed. Both the energy at the handle and at the shoulder showed reductions in their contributions to total external energy as time passed. This implies that fatigue affected the upper limb musculature responsible for angular shoulder movement and reduced the ability to produce a continuous power contribution (Simões, Veloso, & Armada-da-Silva, 2006).

Time series curves of joint power are useful to determine where gender-specific differences exist within a stroke. Variations observed between males' and females' angular shoulder energy contributions require joint power, joint moment, and joint angular velocity curves to explain this finding in more detail. Joint power values are determined from the joint angular velocity and joint moment data with females often exhibiting smaller moments as a result of their smaller muscle volume (Holzbaur et al., 2007). Within a training session of long duration, rowers often utilize low stroke rates, whereas for shorter training sessions focusing on race techniques, they employ higher stroke rates to better simulate competition. At both 18 and 36 strokes per minute, the angular shoulder joint power between males and females differed primarily as a result of a larger extensor moment during the mid drive phase.

The effect size was relatively small when comparing elbow and antero-posterior shoulder energy contributions between the sexes. Further research with a larger sample size may enable a greater understanding of any potential differences at these joints. The present research was conducted using male rowers from a single training squad, and female rowers from two squads. It is therefore possible that the findings of this study could reflect techniques developed by coaching interventions rather than through inherent differences between the sexes. A further limitation to our study is that it was conducted on a simulator and not on-water. Differences in various kinematic (Lamb, 1989) and kinetic variables (Martindale & Robertson, 1984) indicate that our results may only represent the energy profiles obtained when rowing on a simulator. Further research is required for joint energy contributions to be determined on-water. The results were expressed as ensemble averages and thus may have missed some important individual differences in the production of mechanical energy. However, the 95% confidence intervals were invariably small, indicating that most rowers followed a similar pattern of power production.

Conclusions

The total external energy expended during a stroke was greater for males than females. As a percentage of total external energy, only the contributions from angular shoulder movement provide a difference between the sexes, with males exhibiting larger relative shoulder rotations than females. Changes to stroke rate altered the energy contributions from both angular shoulder and elbow movements. Interactions between gender and stroke rate demonstrated that with faster stroke rates males increase, while females decrease, the total external energy expended during a stroke. At faster stroke rates, females generate a higher percentage of external energy at the handle than the stretcher, while males exhibit a quadratic relationship whereby the largest contribution of energy at the handle occurs only at moderate stroke rates. Within the strokes analysed, the contribution of shoulder angular movement as a percentage of total external energy decreased with time. Although no significant differences were found for the contribution of antero-posterior shoulder energy to total external energy, it should be noted that at around 6% the involvement from this movement is an important contribution that should be factored into training programmes.

Our results demonstrate that changes in the contribution of joint energies to the total external energy expended during a stroke are joint specific. Furthermore, energy contributions are different between males and females at specific joints of the upper extremity, and rowing at slower stroke rates during training does not necessarily replicate the techniques adopted at stroke rates closer to those employed during a race. The results of this study should be considered when training rowers for competition. It is suggested that both males and females require specific training programmes focused on shoulder muscular endurance to minimize the effects of fatigue evident in this study. Females also require the implementation of upper extremity strength and conditioning programmes. These programmes, centring on the muscles involved in shoulder rotation, may alter the percentage contribution of angular shoulder energy and thus affect their total external energy expenditure.

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