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Research article

A biomechanical assessment of ergometer task specificity in elite flatwater kayakers

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Abstract
The current study compared EMG, stroke force and 2D kinematics during on-ergometer and on-water kayaking. Male elite flatwater kayakers (n = 10) performed matched exercise protocols consisting of 3 min bouts at heart and stroke rates equivalent to 85% of VO_2peak (assessed by prior graded incremental test). EMG data were recorded from *Anterior Deltoid* (AD), *Triceps Brachii* (TB), *Latissimus Dorsi* (LD) and *Vastus Lateralis* (VL) via wireless telemetry. Video data recorded at 50 Hz with audio triggers pre- and post-exercise facilitated synchronisation of EMG and kinematic variables. Force data were recorded via strain gauge arrays on paddle and ergometer shafts. EMG data were root mean squared (20ms window), temporally and amplitude normalised, and averaged over 10 consecutive cycles. In addition, overall muscle activity was quantified via iEMG and discrete stroke force and kinematic variables computed. Significantly greater TB and LD mean iEMG activity were recorded on-water (239 ± 15 vs. 179 ± 10 µV.s, $p < 0.01$ and 158 ± 12 vs. 137 ± 14 µV.s, $p < 0.05$, respectively), while significantly greater AD activity was recorded on-ergometer (494 ± 66 vs. 340 ± 35 µV.s, $p < 0.01$). Time to vertical shaft position occurred significantly earlier on-ergometer ($p < 0.05$). Analysis of stroke force data and EMG revealed that increased AD activity was concurrent with increased external forces applied to the paddle shaft at discrete phases of the on-ergometer stroke cycle. These external forces were associated with the ergometer loading mechanism and were not observed on-water. The current results contradict a previous published hypothesis on shoulder muscle recruitment during on-water kayaking.

Key words: Kayaking, ergometry, electromyography, stroke force, stroke kinematics.

Introduction

The development of sports specific ergometers over the last 25 years has revolutionised the training and testing of elite athletes worldwide. Ergometers are primarily designed to simulate biomechanical movements and physiological stresses associated with a specific sport, allowing exercise to be performed in an indoor environment (Dal Monte et al., 1988). In order to validate ergometer usage in laboratory testing of athletes, a quantitative assessment of task specificity must be established. Literature validating task specificity of various ergometer designs, using cardio-respiratory (de Campos Mello et al., 2009; Kenny et al., 1995; Van Someran et al., 2000) or biomechanical variables such as kinematic and force data (Elliott et al., 2002; Lamb, 1989) exist. The development of reliable, commercially available air-braked kayak ergometers has led to their usage in training and testing of elite flat-water kayakers. Investigations into the validity of on-ergometer versus on-water testing for metabolic and cardio-respiratory variables (VO_2, heart rate and blood lactate) have concluded that while kayak ergometers accurately simulated physiological demands of short-term high-intensity kayaking, a biomechanical assessment was required to determine how accurately kayak ergometers simulated the on-water scenario (Van Someran et al., 2000; Van Someran and Oliver, 2001).

Surface electromyography (EMG) has been used for over 30 years as an effective technique for assessing muscle recruitment patterns during complex movements (De Luca, 1997) and more recently Nowicky et al. (2005) used EMG data in an assessment of rowing ergometer design. Nowicky et al. (2005) concluded that a direct biomechanical comparison to on-water rowing would further clarify the accuracy with which land-based ergometers simulated on-water rowing. Several laboratory based kinesiological EMG studies investigating kayaking (Capousek and Bruggemann, 1990; Trevithick et al., 2007; Yoshio et al., 1974) have been documented. Trevithick et al. (2007) investigated recruitment patterns of eight shoulder muscles in recreational kayakers and concluded that further research examining muscle recruitment patterns on-water kayaking was warranted, in order to establish if patterns observed during on-ergometer kayaking truly reflect the on-water scenario. Capousek and Bruggemann (1990) used EMG analysis during kayak-specific strength exercises and movement patterns to determine the most active muscles during the kayak stroke; reporting that *Anterior Deltoid* was the most active of the muscle groups investigated. To date, no literature validating the biomechanical task specificity of a kayak ergometer has been published. In addition, no quantitative analysis of EMG data during on-water kayaking has been reported.

The aim of this study was to validate the biomechanical task specificity of a commercially available kayak ergometer by analysing and comparing EMG, stroke force and 2D kinematic data during on-ergometer and on-water kayaking. We hypothesised that on-water and on-ergometer kayaking would not differ significantly in duration, timing and magnitude of muscle activation, stroke force or kinematic data.

Methods

Participants

Ten (n = 10) male international flat-water kayakers volunteered to perform this study (mean ± SD; age 20 ± 3yr,

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height 1.80 ± 0.06 m, body mass 73.5 ± 6.2 kg). Personal best times for 500m were <110s for senior and <120s for junior kayakers. Prior to participation, enlisted kayakers completed a detailed medical questionnaire and underwent a medical examination by a qualified practitioner which included anthropometric, pulmonary and haematological assessments, in order to rule out any subclinical or medical contraindications to maximal exercise testing.

Experimental design

The study protocol consisted of three separate assessments and was approved by the University Health Sciences Research Ethics Committee. Initially, a graded incremental test to volitional exhaustion was performed on a kayak ergometer to assess VO_2, lactate and heart rate response profiles. Incremental test data were subsequently used to set individual exercise intensity (85% VO_2peak) for task specificity trials. The first trial was on-ergometer; the second was on-water. Time duration between task specificity trials was between 1 and 7 days and all trials being performed between 09:00 and 11:00 to reduce the potential for circadian variability. Participants were instructed to refrain from intense physical exertion in the 24 hour prior to all testing sessions, in order to minimise the risk of fatigue impacting on subsequent measurements. During task specificity trials, exercise intensity was matched using heart and stroke rate data attained during incremental testing and all individuals acted as their own control.

Kayakers performed their graded incremental test and on-ergometer task specificity trial on an air-braked, drag adjustable Dansprint kayak ergometer (Dansprint, Hvidovre, Denmark). The ergometer consisted of a fixed flywheel connected to a carbon shaft via a retractable cord attached at either end (see Figure 3a). Distance from seat to foot-bar was adjusted to match each individual's seat position in the kayak; hand position on the carbon shaft was also adjusted to match on-water paddling position. Ergometer drag setting was adjusted for body mass via a flywheel damper to equate to on-water drag forces associated with body mass displacement (www.dansprint.com). For the purposes of the current study, flywheel resistance was placed at setting 3 for kayakers up to 75kg, setting 5 for kayakers between 75 and 85kg and setting 7 for kayakers over 85kg. Power output per stroke (W), mean power output (W) and stroke rate (strokes·min^{-1}) were displayed on the ergometer's display monitor, allowing exercise intensity to be accurately controlled during incremental testing. Kayakers performed the on-water task specificity trial in a standard Nelo Olympic flat-water kayak (Nelo, Porto, Portugal). Kayak dimensions adhered to strict International Canoe Federation guidelines for flat-water racing; mass and length were 12kg and 5.2m, respectively. The seat used during the study was a fixed US model, identical to the seat on the kayak ergometer. Spray decks over the cockpit were not used as contact with EMG recording electrodes on *Vastus Lateralis* risked causing movement artefacts during paddling.

Maximal incremental test protocol

Gas exchange variables during incremental testing were recorded using a Quark b^2 (Cosmed, Rome, Italy) breath-by-breath metabolic analyser. Prior to each incremental test this unit was calibrated for O_2 and CO_2 using room air and a standardised alpha-certified gas (15% O_2, 5% CO_2 and balance N_2, BOC, Surrey, UK), and volumetrically using a 3L gas calibration syringe (Cosmed, Rome, Italy). A Polar S120 heart rate monitor (Polar, Kempele, Finland) consisting of a coded transmitter belt and monitor, recorded heart rate data during incremental testing. Blood lactate data immediately upon completion of each incremental exercise element was assessed using a YSI 1500 lactate analyser (Yellow Springs Instruments, Ohio, USA) from capillary blood samples collected from the ear-lobe following sterile lancing. The CV% of the YSI 1500 sport lactate analyser, computed using a known standard (5 mmol·L^{-1}) on a daily basis, was 0.83%.

Kayakers performed a 10-min warm-up on the ergometer at a power output between 70 and 90W followed by 5-min self-stretching. Following baseline data collection for 3 min the initial exercise intensity (mean power) for all kayakers was 90W. Target power output for successive increments increased by 20W every 3 min in a stepwise fashion to volitional failure. Heart and stroke rate data were recorded every 30s during the final 2 min of each increment. Metabolic data, recorded on a breath-by-breath basis, were averaged over 15s intervals using Quark b^2 software, mean data for metabolic variables recorded during the final 90s of each increment were used during data analysis. Maximal VO_2 (mL·kg^{-1}·min^{-1}) recorded in any 15s interval during the entire incremental test was recorded as the kayaker's VO_2peak.

Task specificity trials

Task specificity trials both on-ergometer and on-water consisted of a 3 min bout of exercise at heart and stroke rates equivalent to 85% of individual kayaker's VO_2peak. Prior to trail commencement, a task specific 10 min warm-up at heart rate equivalent to 50% of individual kayaker's VO_2peak was performed. Heart rate data were recorded and monitored throughout the trials using a Garmin Forerunner telemetric heart rate monitor (Garmin, Kansas, USA) and stroke rates were controlled via a digital metronome which kayakers listened to using a standard MP3 player and headphones. Kayakers were instructed to maintain the pre-determined stroke rate throughout and to gradually increase their heart rate over the initial 2 min until target heart rate had been attained. They then maintained heart rate and stroke rate as close as possible to their individual targets for the final minute of the task specific exercise bout.

EMG data

EMG data were recorded on the right side of the body from four muscles involved in the kayak stroke cycle: *Triceps Brachii (long head)* (TB), *Anterior Deltoid* (AD), *Vastus Lateralis* (VL) and *Latissimus Dorsi* (LD). Prior to electrode application, kayakers were seated and designated recording sites shaved, abraded and subsequently cleaned with isopropyl alcohol in order to reduce skin impedance to less than 20kΩ. Pairs of Ag/AgCl circular bipolar, pre-gelled surface electrodes (Paediatric Red Dot, 3M, Minnesota, USA) were applied to the midpoint of the palpated muscle belly approximately halfway between the motor endpoint area and the distal part of the muscle, longitudinally to the muscle fibres. A fixed inter-electrode distance of 20mm was maintained in order to minimise potential cross-talk from adjacent muscles. All reference electrodes were placed over electrically neutral sites and all recording electrodes and leads were fixed to the skin using strapping (Prowrap, Meuller Sports Medicine, Wisconsin, USA) to minimise potential movement artefacts. Surface electrode positions were marked with a permanent marker and digital photographs recorded to ensure correct electrode replacement during the subsequent task specific trial.

Raw EMG data were recorded via a 14 bit AD converter (ME6000, Mega Electronics, Koupio, Finland), band-pass filtered between 8 to 500Hz, pre-amplified and converted from analogue to digital at a sampling rate of 1 kHz. These data were transmitted from an integrated memory card (compact flash memory, 256Mb) to computer via wireless telemetry and subsequently synchronised to the 2D video kinematic data. Synchronisation of EMG and video data using an audio-sync trigger (Mega, Koupio, Finland) facilitated identification of onset of each stroke cycle on the EMG recording.

Isometric maximal voluntary contractions (MVC) were performed prior to all task specificity trials to normalise EMG data against a maximal reference for each muscle (see Table 1 for specific joint position and action). Joints were positioned at the appropriate angle and all isometric actions were resisted by an adjustable chain attached to fixed horizontal climbing bars (Hintermeister et al., 1998). Kayakers were instructed to push maximally and hold for 5 s. Each isometric MVC was repeated three times with a rest period of 55 s between successive actions.

Kinematic data

2D video kinematic data were recorded during task specificity trials using a 50 Hz digital video camera (JVC, Yokohama, Japan) positioned orthogonally to the sagittal plane of the kayaker at a distance of 15 to 20m. Video data were transferred in real-time to computer via firewire connection for subsequent processing and analysis using Matlab (Mathworks, Massachusetts, USA). The height of the kayak seat above the water line was measured and used to mark a reference line (virtual water line) along the length of the ergometer relative to the seat. A paddle reference point was set up by adding an extension element to the end of the ergometer shaft equating to each kayaker's actual paddle length (range 215 to 221cm). Onset of stroke cycle was identified as the first video frame on paddle entry into the water (on-water trials) or the first video frame in which the paddle reference point crossed below the virtual water line (on-ergometer trials). To quantify the time duration of the draw phase and the draw/transition ratio, the end of the draw phase was identified as the first video frame when the paddle fully emerged from the water (on-water trials) or the first video frame when the paddle reference point crossed above the virtual water line (on-ergometer trials).

Stroke force data

Laser trimmed strain gauge amplifiers (RS Components, Northants, UK) and discrete strain gauge elements were integrated in a Wheatstone bridge array with temperature compensation onto two identical commercially available carbon kayak shafts (Jantex, Sokolovce, Slovakia). Separate quad strain gauge arrays were fitted at fixed distances of 20cm either side of the midpoint of both shafts, facilitating assessment of stroke force data during left and right paddle strokes via resultant bending moments. The integration of one shaft onto the kayak ergometer and the addition of commercially available carbon paddles (Jantex Alpha M+; Jantex, Sokolovce, Slovakia) to the other shaft facilitated assessment of stroke force profiles during both on-water and on-ergometer task specificity trials. Paddle shafts were adjusted to match the length and angle of the kayaker's normal paddle set-up. All shafts were calibrated with 10 and 20 kg loads prior to both trials. Strain gauge data recording bending moments on left and right sides of the shaft resultant from the applied propulsive force were amplified (Dataq, Ohio, USA) and data logged at a frequency of 100Hz under software control (Windaq Pro Data Acquisition Software V2.0, Dataq, Ohio, USA). The onset of each stroke cycle was identified as the point at which force increased above a 10N threshold (Benson et al., 2011).

Data reduction and statistical analysis

All EMG, force and kinematic data were transferred to Matlab (Mathworks, Massachusetts, USA) for data reduction. Raw EMG data for each kayaker were root mean squared at a resolution of 20ms for 10 consecutive stroke cycles within the last 30s of each on-water or on-ergometer task specificity trial. Overall muscle activity per stroke was initially quantified using integrated EMG (iEMG) or area of rms amplitude per stroke (Nowicky et al., 2005). Each stroke cycle was then amplitude normalised to individual pre-trial isometric MVC actions and temporally normalised (cubic spline fitting) to eliminate variations in stroke to stroke duration. EMG data were finally expressed as group mean ensembles for 10 consecutive cycles, every 2% of stroke cycle duration,

Table 1. Presented are the joint positions and actions for specific isometric MVC trials performed on investigated muscle prior to task specificity trials.

Muscle	Joint position	Action
Triceps Brachii	0˚ shoulder flexion 90˚ elbow flexion	Elbow extension
Latissimus Dorsi	0˚ elbow flexion, 30˚ shoulder abduction and internally rotated	Shoulder extension and internal rotation
Anterior Deltoid	0˚ elbow flexion 45˚ shoulder flexion	Shoulder flexion
Vastus Lateralis	90˚ knee flexion in a seated position	Knee extension

Table 2. Presented are group mean (SEM) data for exercise intensity, EMG activity, stroke force and stroke kinematic variables. Asterisk infer a significant difference between conditions.

	Variable	On-ergometer	On-water
Exercise intensity (n = 10)	Heart rate (beats·min^{-1})	174 (3)	175 (3)
	Stroke rate (strokes·min^{-1})	81 (2)	82 (2)
EMG activity (n = 10)	iEMG of TB (µV.s)	179 (10) **	239 (15)
	iEMG of LD (µV.s)	137 (14) *	158 (12)
	iEMG of AD (µV.s)	494 (66) **	340 (35)
	iEMG of VL (µV.s)	82 (9)	83 (6)
Stroke force (n = 7)	Peak force (N)	223 (19)	238 (22)
	Time to peak (s)	.16 (.02)	.18 (.01)
	Time to peak (%)	11.8 (1.1)	13.4 (.3)
	RFD_{peak} (N·s^{-1})	1215 (153)	1098 (84)
	RFD_{50} (N·s^{-1})	1165 (116) **	1833 (119)
	Stroke impulse (N.s)	67 (4)	79 (8)
Stroke kinematics (n=10)	Angle of entry (˚)	134 (2)	133 (2)
	Time to vertical (s)	.16 (.02) *	.19 (.02)
	Draw time (s)	.40 (.01)	.40 (.01)
	Draw/transition ratio (%)	57.8 (1.4)	58.0 (1.3)

* inferring $p < 0.05$, ** inferring $p < 0.01$.

normalised relative to isometric MVC. For statistical analysis, mean rmsEMG data were averaged for each 10% segment of the stroke cycle. Stroke force data were also averaged over the same 10 consecutive stroke cycles and temporally normalised to attain a group mean stroke force ensemble at each 2% of stroke cycle duration. Data were subsequently analysed to attain measures of peak force (N), absolute time to peak force (s), normalised time to peak force (%), rate of peak force development (RFD_{peak} in N.s^{-1}) as outlined by Benson et al. (2011). An additional rate of 50% peak force development (RFD_{50} in N.s^{-1}) was also calculated in order to compare early stroke force development across conditions. Integration of the stroke force profile in the first 30% of the stroke cycle quantified the draw impulse (Ns). Paddle shaft angle at stroke cycle onset, time to vertical position, draw phase time and draw/transition ratio were all computed from kinematic data.

All data are presented as group mean ± SEM and normality was assessed using Kolmogorov-Smirnoff tests. Statistical analyses of iEMG data were performed using 2-way repeated measures ANOVA (trial x stroke cycle interval), *post-hoc* Tukey tests quantified detected differences. Comparison of iEMG, stroke force and kinematic data across conditions (on-water vs. on-ergometer) were performed using paired Student's T-tests. Statistical analyses were performed using Sigma Stat (Systat Software, Chicago, USA) and $p < 0.05$ inferred statistical significance.

Results

Group physiological characteristics

The group had a mean ± SEM VO_2peak of 56.4 ± 1.7 mL·kg^{-1}·min^{-1}, BMI of 22.5 ± 0.4 kg·m^{-2} and percentage body fat of 11.6 ± 0.4 %. During incremental testing mean maximal power output at volitional failure was 203 ± 13 W. For each incremental test; heart rate, blood lactate, VO_2 and stroke rate data were plotted against power output (W). Subsequently, lactate threshold (T_{Lac}) defined as the point of inflection on the lactate curve was determined graphically (Beaver et al., 1986). The mean load, HR and BLa at T_{Lac} were 140 ± 11 W, 171 ± 4 beats·min^{-1} and 3.0 ± 0.2 mmol·L^{-1}, respectively. Mean heart and stroke rates equivalent to 85% of the group VO_2peak were 174 ± 2 beats·min^{-1} and 81 ± 2 stroke·min^{-1}, respectively. The exercise intensity at which the group performed matched on-water and on-ergometer trials could thus be considered close to their aerobic-anaerobic threshold as defined by T_{Lac}. During the task specificity trials, no significant differences were observed in heart or stroke rate data recorded during the final minute of exercise (see Table 2). CV% for heart and stroke rate data (on-ergometer and on-water) was 0.8 and 1.0%, and 2.9 and 3.4%, respectively.

Kinematics of the stroke cycle

Kinematic analysis of the paddle shaft angle at entry, time to vertical position, time of draw phase and transition phase are presented in Table 2. Time to vertical paddle position occurred significantly earlier comparing the on-ergometer trial to the on-water trial (0.16 ± 0.02 vs. 0.19 ± 0.02 s, $p < 0.05$). No significant differences were observed between exercise conditions for angle of paddle at entry, draw time or draw/transition ratio.

In order to better interpret the results of the current study, a brief description of the kinematics of the kayak stroke cycle is necessary. The kayak stroke cycle is a contralateral movement of the upper body with four distinct phases (a draw and transition phase for both right and left sides). The cycle begins when the paddle blade enters the water initiating the draw phase, where the paddle is pulled through the water. The draw phase ends when the paddle blade is removed from the water. Once the paddle exits the water, a transition phase occurs where the kayaker moves from the end of one draw phase to the start of the draw phase on the opposite side. Once the opposite draw phase is completed, a second transition phase brings the kayaker back to the original side for the onset of the next stroke cycle.

Muscle activity during the stroke cycle

2D kinematics synchronised to EMG data facilitated observation of the distinct phases of the stroke cycle during which each investigated muscle was active. Both TB and LD were highly active during the draw phase of the stroke

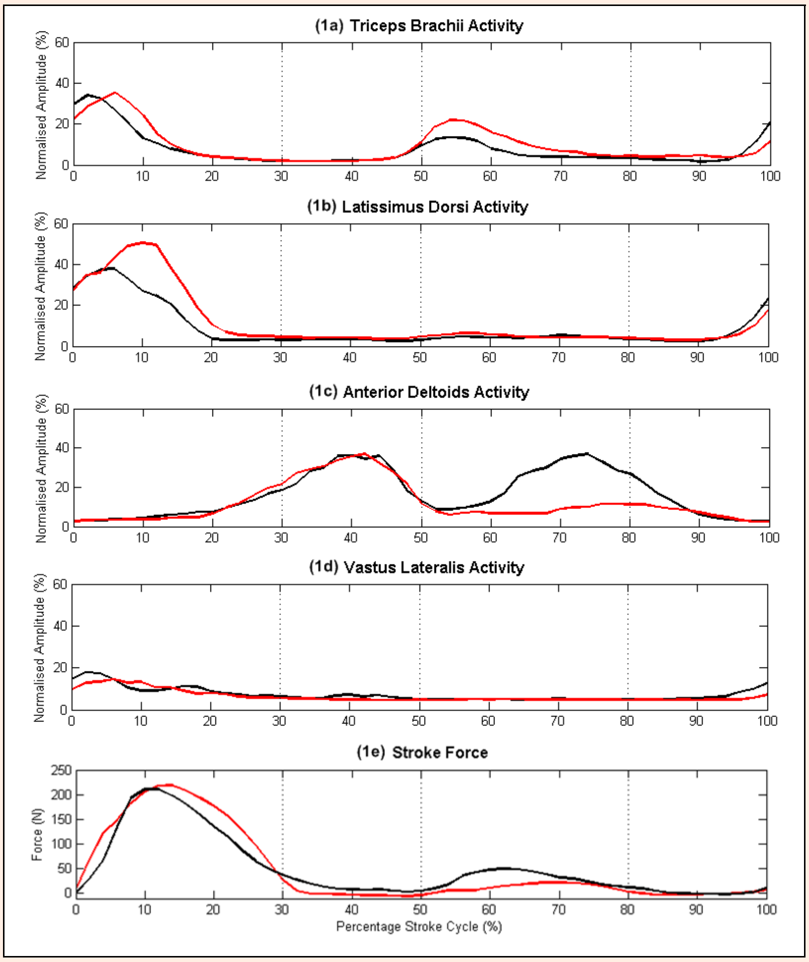

Figure 1. Group mean ensemble EMG traces (1a to 1d) and group mean stroke force profiles (1e) recorded during on-water (red) and on-ergometer (black) kayaking. The dashed vertical lines separate the approximate phases of the stroke cycle; draw phase (0-30%), transition phase (30-50%), opposite draw phase (50-80%) and opposite transition phase (80-100%).

cycle. In addition, VL was active during the draw phase. Activity in AD initiated as the paddle exited the water and increased throughout the transition phase. An additional phase of TB activity was observed during the opposite draw phase as the opposite paddle was drawn through the water, however, the level of activity observed during this phase varied greatly between kayakers and between conditions. Activity in AD was also observed towards the end of the opposite draw phase and during opposite transition phase of the stroke cycle, however, this phase of activity was significantly greater during on-ergometer kayaking, see Figure 1.

Due to variations in the number of peaks and phases of muscle activity observed between kayakers and across conditions, overall muscle activity per stroke cycle was initially quantified using integrated EMG (iEMG) or area of rms amplitude per stroke cycle (Table 2). Comparison of mean iEMG data across conditions revealed significantly greater muscle activity during on-water kayaking for both TB ($p < 0.01$) and LD ($p < 0.05$), no significant differences were observed for VL. Mean AD iEMG activity was significantly greater during on-ergometer kayaking ($p < 0.01$). In order to quantify where in the stroke cycle these differences occurred, EMG data was normalised to MVC and averaged for 10% intervals of the stroke cycle to produce group ensembles (Figure 2). A 2-factor repeated measures ANOVA (trial x stroke cycle interval) performed on these data revealed significant differences at discrete intervals within the stroke cycle. Mean TB activity was significantly greater during on-water kayaking at both the 60 and 70% intervals ($p < 0.01$ and $p < 0.001$, respectively, Figure 2a). Mean LD activity was significantly greater during on-water kayaking at the 20% interval ($p < 0.001$, Figure 2b). Pronounced differences however, were observed in AD, mean iEMG activity during on-ergometer kayaking was significantly greater than on-water at the 70, 80 and 90% intervals ($p < 0.001$, $p < 0.001$ and $p < 0.05$, respectively, Figure 2c).

Stroke force analysis

Due to minor technical problems during on-water trials (water interference with strain gauge array), only 7 full sets of stroke force data were attained. Therefore all statistical analysis was performed on a sub-group ($n = 7$). Quantitative results for stroke force data are presented in

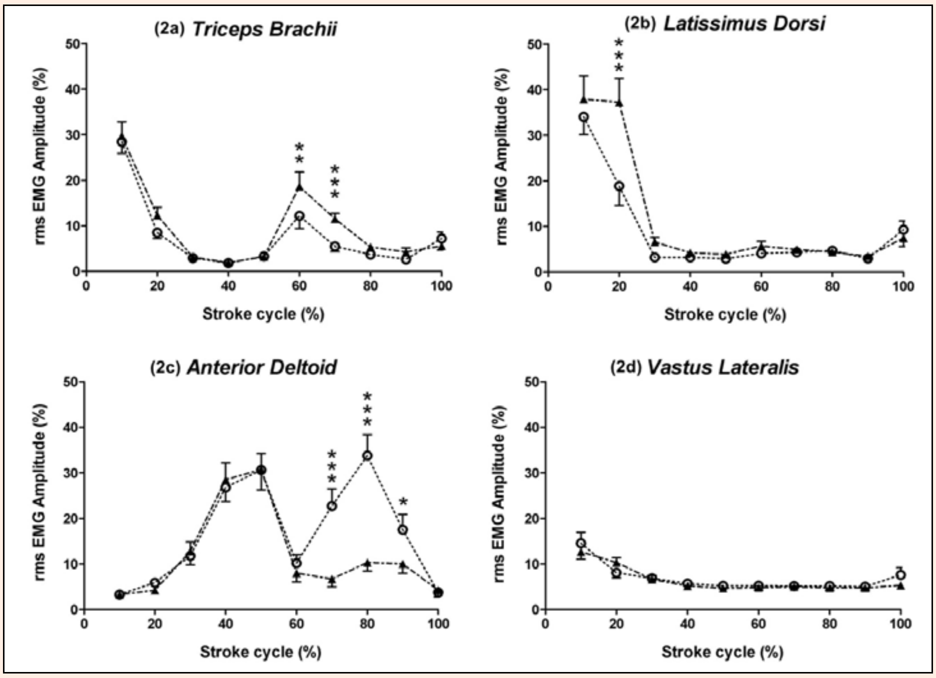

Figure 2. Group mean ± SEM (n=10) EMG profiles for on-ergometer (open circles) and on-water kayaking (closed triangles) stroke cycles. Each point represents the mean rmsEMG amplitude for 10% of the stroke cycle normalised to maximal rmsEMG amplitude recorded during isometric MVC. Asterisk infer difference between conditions at specific 10% intervals within stroke cycle (* inferring $p < 0.05$, ** inferring $p < 0.01$, *** inferring $p < 0.001$).

Table 2. Peak forces were greater during on-water kayaking (238 ± 22 vs. 223 ± 19 N); however this difference did not attain statistical significance ($p < 0.06$). Peak force occurred later in the draw phase (table 2), however, this difference also failed to attain statistical significance ($p < 0.16$). Analysis of rates of force development revealed that mean RFD_{50} was significantly greater on-water ($p < 0.01$) compared to on-ergometer. This can clearly be seen from Figure 1e as slower development of force in the early portion of the on-ergometer compared to on-water draw phase. In contrast to RFD_{50}, mean RFD_{peak} was greater during the on-ergometer stroke cycle. The draw impulse (N.s) which quantified the overall forces applied during the draw phase revealed that greater forces were applied on-water (79 ± 8 vs. 67 ± 4 N.s, respectively), however, this difference was not statistically significant ($p < 0.11$). Although not quantified, a noticeable difference in forces occurred during both the transition and opposite draw phases of the stroke cycle. During the transition phase, no detectable force was recorded on-water, the paddle is not in the water during this phase and minimal external forces are being exerted through the shaft. However, a noticeable force was recorded during the equivalent phase on-ergometer; see Figure 1e from 30 to 50% stroke cycle. This difference also manifest itself during the opposite draw phase, where a larger displacement of the shaft (by the opposite draw impulse) was observed on-ergometer.

Discussion

The aim of this study was to compare EMG, 2-D kinematics and stroke force profiles both on-water and on-ergometer in order to assess the accuracy with which the ergometer simulates the biomechanical demands of on-water kayaking. Significant differences in muscle activity patterns, stroke force and kinematic data suggest that the two biomechanical tasks are not perfectly matched. Some differences in muscle activity may be explained by subtle changes in kinematics during the draw phase. This is most likely the case with LD activity, where significantly earlier time to vertical position ($p < 0.05$, see Table 2) appears to have altered LD recruitment pattern during on-ergometer kayaking. Other more striking differences in muscle activity, such as those observed in AD during the latter stages of the ergometer stroke are most likely explained by the additional external forces associated with the ergometer loading mechanism being applied to the paddle shaft.

Increased AD activity manifest itself as a significant second phase of recruitment occurring between 60 and 90% of the stroke cycle, a pattern not evident during on-water kayaking, see Figures 1c and 2c. The most probable explanation for this difference was the ergometer loading mechanism exerting additional forces on the paddle shaft (Figure 3a). In order to maintain constant tension on the pulleys connecting the paddle shaft and ergometer flywheel, an elastic chord exerts a recoil force. A recent analysis of strain gauge data from a stationary position has quantified this force at 20 ± 4N (unpublished data), however, during dynamic movement both the direction and magnitude of this force constantly changed. Trevethick et al. (2007) previously suggested that this recoil force aided in the transition phase of the stroke cycle, resulting in less shoulder muscle activity than would be expected during on-water kayaking. With

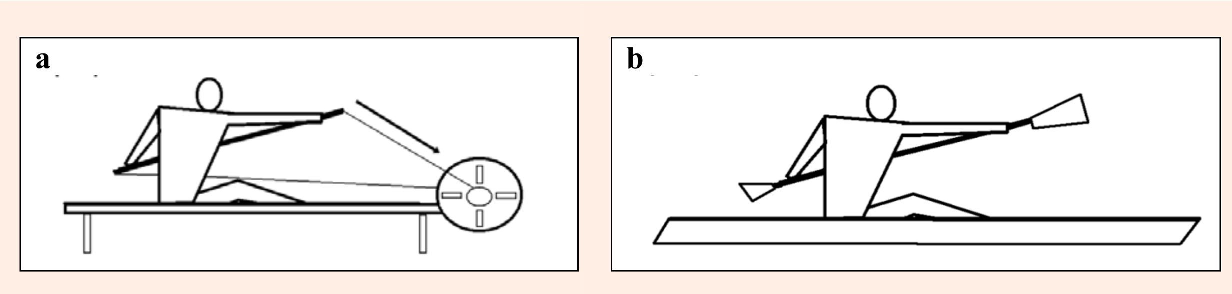

Figure 3. Diagrammatic representation of a time-point at the start of the opposite transition phase during the on-ergometer (a) and on-water (b) stroke cycle. The arrow in Figure 3a represents the elastic recoil force being applied to the paddle shaft which AD must work against. No such external force occurs on-water during this phase of the stroke cycle.

regards to AD activity, the results of the current study clearly contradict this hypothesis. During the latter stages of the stroke cycle (60 to 90%) the shoulder moves from abduction into forward flexion. As the opposite draw phase concludes, the shoulder is in its most flexed and forward position in order to maximise forward reach for the subsequent stroke (Logan and Holt, 1985). Both kinematic and strain gauge data would suggest that the ergometer is exerting a downward recoil force on the paddle shaft at this point. No such downward force is exerted during the equivalent phase of the on-water stroke. In order to maintain optimal shoulder and arm position during these latter stages of the on-ergometer stroke cycle, the kayaker must resist this downward force via significant increases in AD recruitment, evident at the 70 ($p < 0.001$), 80 ($p < 0.001$) and 90% ($p < 0.05$) intervals.

Stroke force profiles recorded during both test conditions highlighted that propulsive forces are generated during the draw phase of the kayak stroke cycle. During this phase, the shoulder is extended and internally rotated, facilitating the pulling motion of the paddle through the water (Logan and Holt, 1985). Since LD is responsible for both shoulder extension and internal rotation, LD is considered a major propulsive muscle involved in the kayak stroke. Previous studies have reported that LD plays a primary role in generating propulsive forces during both kayak (Yoshio et al., 1974; Trevithick et al., 2007) and freestyle swimming stroke cycles (Pink et al., 1991) and the current results are in agreement with this literature. The phase of LD activity in the current study was concurrent with the propulsive forces generated during the draw phase. In addition, time to peak LD activity closely matched time to peak stroke force for both conditions. Peak forces occurred later during the on-water stroke cycle (13.4 ± 0.3 vs. 11.8 ± 1.1 % of cycle) and peak LD activity also occurred later during on-water kayaking (Figure 1b). Moreover, significantly higher mean LD activity recorded in the 20% interval during on-water kayaking ($p < 0.001$) may explain the greater propulsive forces being generated in the latter stages of the on-water draw phase (15 to 30% of stroke cycle, Figure 1e).

It is widely accepted that the maximum absolute acceleration occurs at and around the vertical paddle position (Mann and Kearney, 1980). The kinematic and stroke force data from the current study are in agreement with this literature, since a close relationship between time to peak force and time to vertical paddle position existed during both on-ergometer and on-water trials (Table 2). Significantly earlier time to vertical position observed on-ergometer may be a result of the recoil forces pulling the shaft forward on the opposite side earlier than during the on-water scenario. It is possible that this subtle change in stroke kinematics may have led to both the earlier peak forces and the significantly earlier peak LD activity observed during the on-ergometer draw phase; see Figure 1e and 1b, respectively.

During the draw phase of the stroke cycle TB was also highly active. Prior to and directly at the onset of the draw phase, concentric contraction of TB ensure that maximal forward arm reach is attained (Logan and Holt, 1985). As the draw phase progresses however, the elbow joint is flexed (Baker et al., 1999; Tokuhara et al., 1987). Since TB is an elbow extensor, it may seem counter-intuitive to observe TB activity here, but progressive elbow flexion during the draw phase is actively resisted through an eccentric action of TB. Tokuhara et al. (1987) reported that skilled kayakers do not recruit their elbow flexors during simulated arm pulling movements, even though elbow flexion occurs during the movement. In a multi-articular movement, the resultant propulsive force is limited by the weakest joint force within a multi-joint system (Kumamoto and Takagi, 1980). Since forces generated via shoulder extension exceed forces capable of being generated via elbow flexion, the optimal strategy for force development during the draw phase is one where forces are generated via shoulder extension and transmitted to the paddle via the elbow joint. Thus inhibition of elbow flexor recruitment and increased elbow extensor recruitment produce greater propulsive forces during the draw phase of the kayak stroke (Tokuhara et al., 1987).

In addition to the initial draw phase, TB was also active during the opposite draw phase, although significant differences in the level of activity were observed between exercise conditions, see Figure 2a. In order to effectively perform the opposite draw phase, the recovery arm acts as a support and aids in the forceful entry and pull of the opposite paddle through the water. Trevithick et al. (2007) reported that both *Upper Trapezius* and *Supraspinatus* were also active during the opposite draw phase of the kayak stroke cycle. The current results suggest that TB activity is also necessary to support the opposite draw phase, however, the reason why this phase of TB activity was significantly greater during on-water kayaking remains to be fully elucidated. It is possible that once again, recoil forces acting on the shaft are forcing kayakers to alter their muscle recruitment patterns. Differences in force profiles suggest that the ergometer is applying additional loads to the kayak shaft during this phase (50 to 70% of the stroke cycle). In order to maintain optimal joint position, it is possible that increased elbow flexion (via reduced TB activity) provides resistance to the recoil forces pulling the shaft forward earlier than required. Regardless of the exact mechanism, it is worth noting that the two best kayakers (based on personal best times) both showed markedly greater TB activity during the opposite draw phase compared with other members of the group, both on-water and on-ergometer. This suggests that enhanced recruitment of TB during this phase of the stroke cycle may improve stroke biomechanics and thereby increase kayak velocity.

Logan and Holt (1985) reported that prior to the onset of the stroke cycle, the thoracic vertebrae are rotated anteriorly and the knee and hip joints are at their maximal degree of flexion. These joint articulations are made in an effort to maximally rotate the trunk and shoulders in the anterior direction, optimising the forward reach necessary for paddle entry. At the onset of the draw phase, the knee extensors are recruited in order to forcefully extend the knee joint from the maximal flexed position (Logan and Holt, 1985). This action aids in pelvic rotation and horizontal hip adduction, both of which enhance the rotational component that is desired in the trunk (Logan and Holt, 1985). Activity in VL was observed during the draw phase of the stroke cycle both on-ergometer and on-water (Figures 1d and 2d), in agreement with previous investigations evauating the role of VL in aiding body segment rotation (Logan and Holt, 1985; Mann and Kearney, 1980). While mean iEMG activity in VL in the current study was lower than activity observed in upper body musculature (Table 2), the role of contralateral knee extension and flexion in enhancing pelvic and trunk rotation should not be underestimated. This point is highlighted by the fact that almost all elite kayakers have a strap on their footrest to enhance contralateral leg movements (Logan and Holt, 1985; Sanders and Baker, 1998).

Differences in the rate of force development in the initial stages of the draw phase were observed between the two exercise conditions. RFD_{50} was significantly greater during the on-water draw phase (1833 ± 119 N.s^{-1} vs. 1165 ± 116 N.s^{-1}, $p < 0.01$). This difference is highlighted by a change in the slope of the ergometer stroke force profile at approximately 5% into the stroke cycle (Figure 1e). A similar finding was reported for initial stroke force development comparing dynamic and stationary rowing ergometry (Benson et al., 2011; Kleshnev and Kleshneva, 1995) and it was proposed that a disparity between handle and footstretcher forces may explain the altered stroke force development on stationary ergometers (Kleshnev and Kleshneva, 1995). In a similar fashion, it is possible that a disparity between initial force development at the shaft and opposing resistive forces at the flywheel may exist. A minor delay in transmission of forces from the shaft to the flywheel via the connecting ropes may impede optimal force development in the first 5% of the stroke cycle. During the on-water scenario, it appears no such delay in force generation occurs. Once the paddle enters the water, propulsive force can be generated effectively though the paddle shaft without any transmission delay.

One of the main outcomes of the current study is that the recoil force associated with the ergometer loading mechanism appears to affect activity patterns in TB, LD and most notably in AD. In the case of LD activity, the subtle changes to stroke kinematics (earlier time to vertical position) brought about by this recoil force, are most likely responsible for the altered activity patterns observed on-ergometer. In the case of TB and especially AD activity, it seems more likely that the altered recruitment patterns are as a result of the kayakers working to maintain optimal stroke kinematics. An ongoing study assessing the effect of varying kayak ergometer recoil forces on 3D kinematics and muscle activity patterns suggests that an increase in recoil force results in greater AD activity without any noticable change in 3D kinematics of the upper limb (unpublisded data).

Study limitations must be considered before drawing definitive conclusions from the current results. Firstly, the biomechanical data presented only represents one sub-maximal exercise intensity. Kayakers exercised at a sub-maximal workload equivalent to 85% of their VO_2peak, an exercise intensity in close proximity to their aerobic-anaerobic threshold as assessed by T_{Lac}. Athlete and coach testimony suggests that the majority of ergometer training involves intervals of specific time duration, performed at sub-maximal workloads equivalent to the aerobic-anaerobic threshold. As such, this exercise intensity was chosen as it represented the most relevant intensity from a training perspective. A previous assessment of kayak ergometer task specificity concluded that simulated kayaking did not closely reflect open-water kayaking in the assessment of sub-maximal cardio-respiratory responses to exercise (Mitchell and Swaine, 1998). However, Van Someran et al. (2000) assessed cardiorespiratory variables at maximal exercise intensity and detected no significant differences between on-water and on-ergometer kayaking. The results of the current study are in agreement with Mitchell and Swaine (1998), however, it remains to be seen if biomechanical differences are also evident during maximal exercise. Previous literature has reported stroke rates of 118 ± 4 (Mann and Kearney, 1980) and 96 ± 5 strokes.min^{-1} (Sanders and Kendal, 1992) during high intensity kayaking. The target stroke rates used in the current study (81 ± 2 strokes.min^{-1}) were markedly lower. A recent study by Sealey et al. (2011) reported that increasing stroke rate can alter the stroke kinematics in outrigger canoeing. It is possible therefore, that at higher stroke rates, differences between on-ergometer and on-water kayaking are not as significant as those observed in the current study. Further analysis of EMG, stroke force and kinermatic data, across a range of exercise intensities and stroke rates is warranted in order to fully assess biomechanical task specificity of the kayak ergometer. In addition, the current study did not randomise the order of task specificity trials. In considering the group's level of proficiency and the fact that participants were regularly exercising both on-ergometer and on-water as part of their overall training, the authors opinion was that biomechanical data collected from this elite group would not be compromised by a trial familiarisation or training effect. Regardless of this fact, the possibility that non-randomisation played some minor unquantifiabe role in the effects observed cannot be ruled out. Finally, the number of available EMG channels limited our investigation to just four involved muscles. Kayaking is a complex multi-joint movement incorporating recruitment of many different muscles and analysis of recruitment patterns from other shoulder, arm and trunk muscles is warranted in order to provide a more complete assessment of kayak ergometer task specificity.

Conclusion

The results of the current study confirm that while the kayak ergometer may replicate the metabolic and cardiorespiratory demands of on-water kayaking (Van Someran et al., 2000), it does not perfectly replicate the biomechanical demands of the sport. While the 2D kinematics appear closely matched (with the exception of time to vertical), measures of muscle activity and force production highlight that significant differences clearly exist between the two tasks. The most striking of these differences was the significantly greater AD activity recorded during on-ergometer kayaking. It is unclear as to whether this increased recruitment of AD during discrete phases of the stroke cycle has any implication for long term training. It should be noted that regardless of the findings of the current study, the kayak ergometer will remain a highly useful tool in the training and testing of elite kayakers. Therefore further research comparing EMG from other active muscles and at varying exercise intensities is warranted, in order to provide a more complete assessment of the biomechanical task specificity and potential training implications for ergometer usage.

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Key points

- When exercising at fixed heart and stroke rates, biomechanical differences exist between on-ergometer and on-water kayaking.
- Ergometer kayaking results in significantly greater *Anterior Deltoid* activity but significantly lower *Triceps Brachii* and *Latissimus Dorsi* activity, compared with on-water kayaking.
- The altered muscle recruitment patterns observed on-ergometer are most likely a result of additional forces associated with the ergometer loading mechanism, acting upon the paddle shaft.

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