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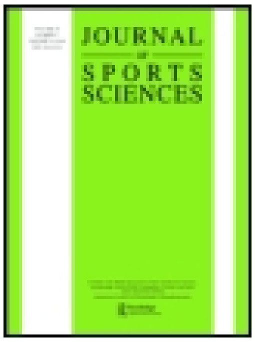

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Comparing para-rowing set-ups on an ergometer using kinematic movement patterns of able-bodied rowers

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ABSTRACT

While numerous studies have investigated the biomechanics of able-bodied rowing, few studies have been completed with para-rowing set-ups. The purpose of this research was to provide benchmark data for handle kinetics and joint kinematics for able-bodied athletes rowing in para- rowing set-ups on an indoor ergometer. Able-bodied varsity rowers performed maximal trials in three para-rowing set-ups; Legs, Trunk and Arms (LTA), Trunk and Arms (TA) and Arms and Shoulders (AS) rowing. The handle force kinetics of the LTA stroke were comparable to the values for able-bodied literature. Lumbar flexion at the catch, extension at the finish and total range of motion were, however, greater than values in the literature for able-bodied athletes in the LTA set-up. Additionally, rowers in TA and AS set-ups utilised more extreme ranges of motion for lumbar flexion, elbow flexion and shoulder abduction than the LTA set-up. This study provides the first biomechanical values of the para-rowing strokes for researchers, coaches and athletes to use while promoting the safest training programmes possible for para-rowing.

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KEYWORDS
Joint kinematics; injury risk; stroke length; pull force; para-athlete

Introduction

Para-rowing is a competitive and recreational sport that is growing in popularity throughout the world (Lewis, 2011). Individuals with mobility impairment experience improved health and wellness and increased levels of community integration, quality of life, psychological well-being and life satisfaction when they participate in sports (Campbell & Jones, 1994; McVeigh, Hitzig, & Craven, 2009; Tasiemski, Kennedy, Gardner, & Taylor, 2005). Sport participation can also help counter or offset health complications associated with mobility challenges, e.g., wheelchair athletes have reported to have reduced and delayed onset of shoulder pain in comparison to nonathletic wheelchair users (Fullerton, Borckardt, & Alfano, 2003).

Like most sports, rowing is associated with some injury, with low back injury and low back pain the most severe and chronic of rowing injuries (Hickey, Fricker, & McDonald, 1997; Hosea & Hannafin, 2012; Rumball, Lebrun, Ciacca, & Orlando, 2005). Shoulder, chest and wrists injuries are also common in rowers, representing <5%, 10–25% and 15–20% of injuries, respectively, (Hickey et al., 1997; Rumball et al., 2005). There is also evidence of a gender prevalence in some rowing injuries, e.g., rib stress fractures, costochondritis, costovertebral joint subluxation and intercostal muscle strain occur more frequently in female rowers than male (Karlson, 1998; Rumball et al., 2005; Wajswelner, Bennell, Story, & McKeenan, 2000). In an effort to mitigate injuries among para-rowers, it is useful to understand how the para-rowing set-ups change the basic ergometer rowing stroke. However, existing research on the para-rowing set-ups and the impact on stroke mechanics are lacking.

The rowing stroke is defined by the “drive” and “recovery” phases. The “drive” phase begins at the “catch”, the point at which the rower raises their hands, inserts the oar blades into the water and begins to apply a push force to the foot stops, and pull force to the handle. As the drive phase continues, the rower actively propels the boat forward until the rower reaches the “finish” position where legs and back are fully extended, arms flexed and adducted tight to the body, and the blade is removed from the water. The “recovery” begins at the “finish” as the rower returns to the “catch” position, while keeping the blades off the water and moving the sliding seat towards the stern. The kinematic portion of rowing studies often focuses on identifying the position of body segments, and how the position of those segments changes in terms of the stroke cycle. However, kinematic assessment is problematic (Hildebrand, Drenk, & Kindler, 1998; Lamb, 1989; McGregor, Bull, & Byng-Maddick, 2004) due to the difficulty of recording motion across open water. Dryland rowing on an ergometer achieves almost the same motion patterns as on-water rowing. The equipment has a flywheel, which, in the absence of oars, provides air resistance (drag) against which the rower pulls during the “drive” phase (Lamb, 1989).

Researchers have identified that extreme postures and large compression/shear forces of the lumbar spine are prime contributors to the lower back injury and pain associated with able-bodied rowing (Caldwell, McNair, & Williams, 2003; Hosea & Hannafin, 2012; Stallard, 1980). A number of studies have identified hyperflexion of the torso at the catch position as the point during the stroke cycle where the rower is at the greatest risk of injury (Howell, 1984; Morris, Smith, Payne, Galloway, & Wark, 2000; Rumball

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et al., 2005; Teitz, Kane, Lind, & Hannafin, 2002). In rowers and the general population, lower back injury risk has been highly correlated with peak compressive forces and torso flexion (Stallard, 1980; Teitz et al., 2002). Fatigue has been documented to exacerbate hyperflexion of the lumbar spine during ergometer rowing, and this increased flexion has postulated to increase the risks for lower back injury (Teitz et al., 2002). McGregor, Patankar, and Bull (2008) determined that males and females rowing an ergometer performed different movements in the sagittal plane. Specifically, women were observed to have a greater range of motion for both femoral and pelvic rotation with no differences in lumbar rotation (McGregor et al., 2008).

Para-rowing programmes provide coaching and rowing opportunities for people with physical and/or intellectual disabilities. There are currently three classes of para-rowing: Legs, Trunk and Arms (LTA), Trunk and Arms (TA) and Arms and Shoulders (AS) rowing. The international body that governs rowing, Fédération Internationale des Sociétés d'Aviron (FISA), defines the para-rowing categories as follows (FISA, 2010). Participants in LTA rowing utilise similar equipment as able-bodied athletes, have a verifiable and permanent disability but maintain a certain degree of function in LTA. This category includes individuals with functional, intellectual or visual disabilities. TA athletes row with their trunk, shoulders and arms. TA participants use a fixed seat, instead of a sliding seat. Participants of this class typically have significantly lower function or mobility of the lower limbs, but full function of the torso and upper body. TA rowers are strapped to the fixed seat at the pelvis and around the thighs. The thigh strap is placed just above the knees and secured to the boat or the ergometer to prevent any flexion or extension of the knee during rowing. Individuals participating in this class may have neurological or other physical impairment that limits the use of their lower limbs. The AS category of para-rowing is characterised by motion of the AS for propulsion. Athletes in this class have minimal or no trunk or leg function, and thus require the added stability of a fixed seat back, to which the torso of the AS rower is strapped across the thoracic region. The three categories of para-rowing facilitate the inclusion of most individuals with disability by offering rowing shells that are specifically designed to fit the functional abilities of athletes with stability and safety in mind.

There is relatively little literature related to para-rowing and none addressing the biomechanics of the para-rowing strokes. The research team was approached by a local para-rowing team to conduct research into this topic, with the longer-term goal of aiding coaches to make decisions on oar rigging and optimal strapping arrangements for para-rowers. The documentation of how the set-ups change the natural, observed rowing ergometer stroke is useful as a starting point to these larger theoretical questions. The purpose of this research is to increase the collective knowledge around observed postures and forces in para-rowing set-ups, and consider possible differences between male and female movement strategies in the para-rowing set-ups.

Method

Participants (n = 17; 9 male and 8 female) were from a varsity level rowing team and had no current musculoskeletal injury or recent history of low back pain. Participants signed consent forms prior to any testing and the study was approved by the Laurentian University Research Ethics Board. A Concept2 Model C indoor rowing ergometer was used for all trials and the WinTech rowing para-7800L fixed seat was used and clamped into position on the ergometer's rail for TA and AS conditions. Ergometer resistance was set at the recommended drag units [DU] for each athlete in each para-rowing set-up as defined in Table 1 (Lewis, 2011). All participants were able-bodied athletes who were familiar with the Concept2 Model C ergometer, but had no previous experience with para-rowing set-ups.

Table 1. Drag resistance units set on the Concept2 Model C air break ergometer through the PM4 monitor software.

	LTA	TA	AS
Male rowers			
Light weight (<160 lbs)	120	135	165
Heavy weight (>160 lbs)	130	140	175
Female rowers			
All	110	125	150

Participants were asked to complete three 10-stroke trials for each of the three rowing configurations (LTA, TA and AS). Trials were separated by 3 min of rest and participants also completed a 5-min familiarisation period with each new configuration. The participants were asked to complete each 10-stroke trial at maximal effort at a set stroke rate (strokes per minute (spm)): LTA trials at 24 spm, TA trials at 30 spm and AS trials at 36 spm. Stroke rates were determined after discussion with adaptive coaches, and were chosen to represent a race pace for these athletes.

During the rowing tasks, participants wore 41 reflective spherical markers at specific bony landmarks, as required by the motion capture tool kit module of the computer simulation JACK^{TM} (Siemens). The 0.025-m-diameter markers were affixed to the skin, or clothing, of the participants via double-sided adhesive discs. The LTA and TA ergometer set-ups utilised the full marker set. The AS rowing set-up utilised a reduced marker set containing 39 markers; the markers located at the 10th thoracic vertebrae and the right side back positions were removed to accommodate the fixed seat back. The three–dimensional (3D) motion of each participant was recorded using six infrared Vicon cameras at a sampling rate of 60 Hz. All markers were digitised into three-dimensional coordinate data by the Peak Motus software (version 9.0) and filtered using a Butterworth digital filter set at an optimal cut-off frequency.

The digital data was exported as a C3D file for import into JACK^{TM}. The JACK^{TM} programme used an individual's anthropometric measurements and C3D coordinates to create a 16-segment full-body virtual manikin of each rower. The stroke length was calculated and normalised, on a scale of 0% (minimum displacement of oar handle) to 100% (maximum displacement of ergometer handle). Pull force (N) was measured and recorded from an "S"-type strain gauge (Intertechnology Inc., Stainless Steel S Type Load Cell Reverse Transducers Model 9363) that connected the ergometer handle to the chain that drives the ergometer flywheel. The rower's pull force signal during the drive phase of the stroke was collected (600 Hz) in synchrony with the motion capture Peak Motus system.

The virtual manikin was then animated and kinematics quantified at the discrete points of catch and finish positions of the drive phase of each stroke using the JACK animation tool window and the posture analysis tool. Additionally, stroke length was calculated based on the anterior–posterior displacement of the hands from the catch to the finish position. The Task Analysis Toolkit (TAT) in the JACK™ programme was used to record and output the following values: knee flexion, lumbar flexion/extension, elbow flexion/extension and shoulder abduction. Outcome measures from the TAT-reported joint kinematics were analysed using a mixed repeated measures Analysis of Variance (ANOVA) for the effect of set-up (LTA, TA and AS), sex (male and female) and trial (three). The main effect of trial was not significantly different, and thus, the data was averaged across the three trials. The final mixed repeated measures ANOVA included a between-participant factor of sex and a within-participant factor of set-up. Follow-up *t*-tests and custom contrasts were done when significant main effects or interactions were found.

Results

The handle pull force demonstrated significant set-up and sex main effects for both peak pull force and mean pull force. Male participants produced significantly more peak and mean pull force than females. Expectedly, rowers in the LTA set-up were able to produce significantly more peak and mean pull forces than in the TA and AS set-ups, and significantly more peak and mean pull force in the TA than the AS set-up. Additionally, there was a significant interaction between set-up and sex for the mean pull force only ($F(_{2,14})$ = 11.88, p = 0.001). Follow-up custom contrasts, to evaluate this interaction, revealed that the difference between the two sexes was significantly different when comparing both LTA to AS (p = 0.001) and TA to AS (p = 0.017), while there was no significant difference between sex for mean pull force at LTA versus TA (Figure 1).

Kinematic data representing stroke length, and catch/finish angles at specific joints are represented in Table 2. There was no main effect of sex found for any joint angles reported here, nor any interaction effect of set-up by sex on the joint angles. Several significant main effects for set-up were observed and are reported in the following. Significant main effects were noted for stroke length in set-up ($F_{(2,\ 14)}$ = 252, p = 0.001) and sex ($F_{(1,\ 15)}$ = 6.18, p = 0.025). Follow-up *t*-tests indicated that participants rowing in the LTA set-up had a significantly greater stroke length than both the TA and AS set-ups, and likewise, TA was significantly greater than AS. As expected due to height differences, male participants used a significantly longer stroke length than female participants during the ergometer rowing trails. There was a main effect of set-up for both catch and finish lumbar angles ($F_{(1,15)}$ = 18.9, p = 0.001, $F_{(1,15)}$ = 5.4, p = 0.035). When rowing TA, participants used significantly greater lumbar angle at the catch (37° vs. 29°) and finish (−42° vs. −39°) positions.

A significant main effect was observed between set-ups for elbow angle at the finish of the stroke ($F_{(2,\ 14)}$ = 14.7, p = 0.001) but not the catch position. Follow-up *t*-tests using Bonferonni correction factor (required p < 0.017) identified significant differences (p = 0.001 and p = 0.006) between AS versus LTA and TA. Rowers using the AS set-up used significantly greater amounts of flexion of the elbow joint (11° and 7° more than for LTA and TA, respectively) at the finish position.

Range of motion for shoulder abduction increased significantly across para-rowing set-ups at both catch and finish positions (Figure 2). There was a significant main effect of set-up observed for the abduction angle of the shoulder at the catch position ($F_{(2,14)}$ = 13.6, p = 0.001). Follow-up *t*-tests (criterion p < 0.017) determined significant differences between TA versus LTA and AS set-ups (p = 0.001, p = 0.001), while the difference between LTA and AS was not significant (p = 0.09). Significant main effects of set-up were observed for the abduction angle of the shoulder at the finish of the stroke as well ($F_{(2,\ 14)}$ = 19.9, p = 0.001). Follow-up *t*-tests (criterion p < 0.017) indicated that the angle of shoulder abduction at the finish of the stroke increased significantly from the LTA to TA set-ups (p = 0.014), LTA to AS set-ups (p = 0.001) and TA to AS set-ups (p = 0.006).

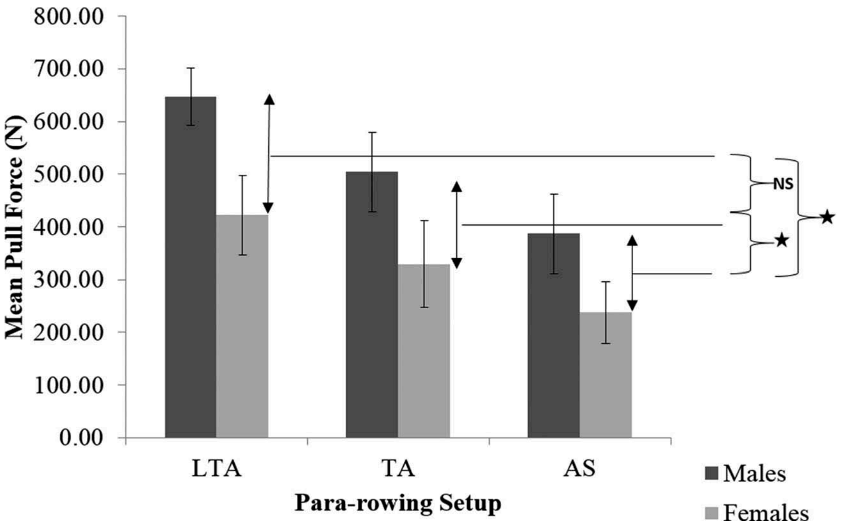

Figure 1. Sex and set-up interaction for mean handle pull force (N). Difference in mean pull force (N) between sexes was significantly different when comparing LTA to AS and TA to AS set-ups. Custom contrasts with Bonferonni correction for multiple comparisons determined significance at p < 0.017(*), NS=no significance.

Table 2. Summary of the kinematic data collected for male and female participants in the three para-rowing set-ups.

	LTA		TA		AS	
Variable	Male	Female	Male	Female	Male	Female
Stroke length (cm)	139 ± 11	132 ± 13	105 ± 11	94 ± 9	77 ± 7	66 ± 8
Lumbar (Catch,deg)	29 ± 7	28 ± 5	35 ± 6	38 ± 5	-	-
Lumbar (Finish,deg)	−38 ± 7	−39 ± 4	−42 ± 8	−41 ± 3	-	-
Elbow (Catch,deg)	5 ± 4	5 ± 8	4 ± 5	2 ± 2	7 ± 5	4 ± 5
Elbow (Finish,deg)	132 ± 10	133 ± 6	135 ± 10	137 ± 5	144 ± 5	142 ± 6
Shoulder (Catch,deg)	69 ± 6	66 ± 8	76 ± 6	74 ± 6	71 ± 5	71 ± 6
Shoulder (Finish, deg)	33 ± 7	41 ± 6	41 ± 17	49 ± 9	53 ± 5	58 ± 8

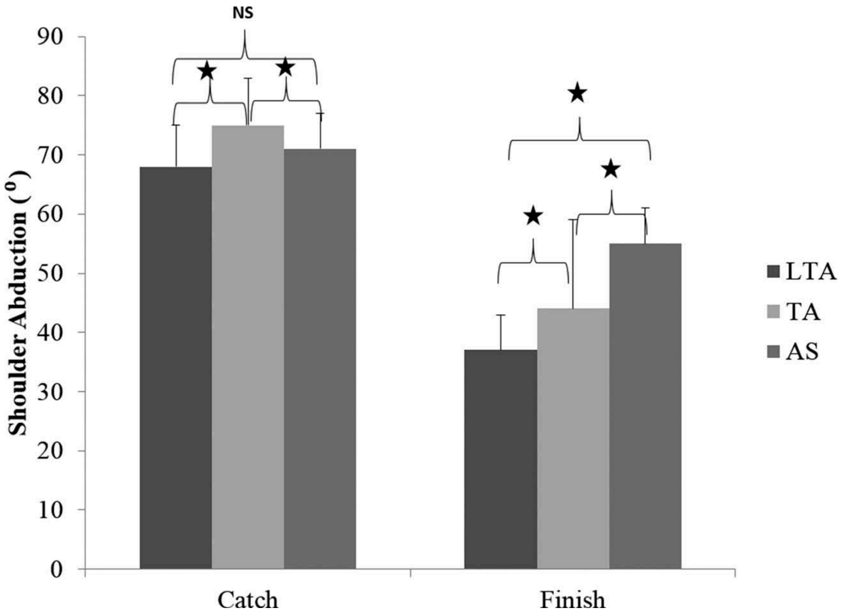

Figure 2. Significant main effect of set-up on shoulder abduction angle at the catch and finish positions of the stroke. Significant follow-up t-tests ($p < 0.05$) demarcated with a star. NS=no significance.

Discussion and implications

The purpose of this research was to document the postures and stroke kinetics of able-bodied athletes rowing with equipment set-ups that athletes with disabilities would use: TA and AS, and to determine if there any differences between the sexes within those set-ups. While our primary interest is in the novel study of the fixed seat set-ups, TA and AS, inclusion of the LTA set-up allows us to compare our results with ergometer studies previously reported in able-bodied literature. This is especially important due to using an unconventional method of data analysis by processing the kinematic motion patterns in JACK simulation software. As expected, our results generally agree with earlier studies supporting the validity of our methods and analyses. Measures of handle force, length of stroke and trunk motion were all within the ranges previously reported in the literature (McGregor et al., 2004, 2008; Sforza, Ferrario, Casiraghi, Galante, & Lovecchio, 2012; Tanaka, Ide, & Moreno, 2007). Males in our study produced 1035 N of peak handle force, in comparison to previously reported values of 1050 N for an elite male rower (Decoufour, Barbier, Pudlo, & Gorce, 2008), 1045 N for 10 heavyweight national team men (McGregor et al., 2008) and 897 N for 12 novice men (Steer, McGregor, & Bull, 2006). Similarly, females in our study produced 696 N of peak handle force, as compared to previously reported values of 796 N for 13 heavyweight national team women (McGregor et al., 2008) and 716 N for national team, heavy and lightweight women (Holsgaard-Larsen & Jensen, 2010). The average stroke length of participants in the LTA set-up in our study was 135 cm, which is similar to previously reported stroke lengths of 130 cm for novice rowers (Tanaka et al., 2007) and 139 cm for novice male rowers (Steer et al., 2006). Total average range of lumbar flexion and extension motion at the lower back for the LTA set-up in our study, 67°, was greater than previously reported values (Bull & McGregor, 2000; Sforza et al., 2012; Tanaka et al., 2007). This study was unable to differentiate between lumbar and pelvic motion due to processing the data in JACK software, and as such, some of this difference may be related to joint angle definition. Given the above comparisons, we are confident that the method utilised here has produced kinematic and kinetic values that are comparable to previous ergometer studies. More accurate estimates and joint definitions should be explored with a 3D kinematic analysis. However, moving the data into JACK supported a longer-term goal of evaluating seat and strapping design and oar rigging variables. A further limitation exists in our use of able-bodied rowers. Our primary interest lies in determining the impact of set-up on motion patterns, regardless of the abilities of the user. As such, it is likely that a para-rower would not achieve the same joint positions recorded here. However, the utility of having a maximal benchmark from which to produce coaching recommendations is still useful.

The main purpose of this work was to document the impact that TA and AS set-ups had on rower kinematics and kinetics using able-bodied participants to ensure some uniformity of movement. As would be expected to happen when portions of the kinetic chain are limited (i.e., fixing the seat and strapping segments) stroke lengths decreased by set-up (from LTA to TA by 25% and LTA to AS by 47%). Generally, LTA or able-bodied rowers achieve maximal performance by increasing the length of their strokes while applying techniques that maximise leg drive, followed by the back. When parts of that kinetic chain are lost in the TA and AS set-ups, able-bodied rowers in this study changed movements at the lower back, elbows and shoulder in comparison to the LTA set-up. Rowers using the TA set-up used a significantly greater range of lumbar motion than that reported in the able-bodied literature by increasing the joint angle not only at the catch position preferentially, but also at the finish position. Since the force profile at the handle peaks early in the rowing drive phase, the increased amount of trunk flexion observed in TA set-up, combined with large handle forces, may place the lumbar spine at increased risk of injury. This is of particular concern when we consider that the flexion–relaxation (FR) phenomenon, in which erector spinae musculature turns off, occurs at significantly lower values of lumbar flexion during seated postures compared to standing (Callaghan & Dunk, 2002).

In the absence of erector spinae activity, the surrounding passive spinal tissues and possibly the deeper muscles (Andersson et al., 1996) must provide the major resistive force against the moment produced at the lumbar spine due to trunk flexion. Dickey et al. (2003) suggest that FR phenomenon is a complex, neurophysiological interaction that cannot solely be explained by reflexive actions. Colloca and Hinrichs (2005) highlighted that understanding the load sharing that occurs between active and passive structures when FR occurs is important to understand the causes of low back pain and injury. Although not statistically significant, females in this study appeared to primarily lengthen the TA stroke via excessive trunk flexion at the catch. This finding parallels the work of McGregor et al. (2008), in which women used greater anterior pelvic rotation in a theorised effort to optimise the length of the rowing stroke. Once restricted in the TA set-up in this study, it is reasonable to assume that females used a similar kinematic strategy to produce a powerful stroke. To confirm this suspicion, a more detailed analysis of both lumbar and pelvic joint angles during para-rowing is required. Interaction effects observed for the mean handle pull force also support the notion that females perform maximal rowing differently than males. Comparison of the drop in mean pull force between sexes at each of the different set-ups suggests that there was a non-significant difference between males and females only when comparing the TA to AS set-ups. The significant sex by set-up interaction was also observed in the estimated values of low back compression not reported here (Cutler, Merritt, Eger, & Godwin, 2015). Since females reportedly use a different mechanism (primarily anterior rotation of the pelvis) for achieving optimal rowing patterns (McGregor et al., 2008), it can be speculated that removing the involvement of the trunk from the rowing stroke had a greater impact on males than females, resulting in greater decreases to pull force.

Another observed kinematic change was that shoulder abduction angle increased significantly, at the catch and finish positions, as mobility decreased by set-up. Previously, biomechanics literature has not identified shoulder abduction angle changes in any aspect of rowing performance. Therefore, this change is considered to be a unique feature to para-rowing set-ups, and should be investigated in more depth as it relates to the design of the fixed seat and strapping used in TA and AS rowing. Indeed, Smoljanovic, Bojanic, Pollock, & Radonic (2011) found that competitive AS rowers seek to maximise their stroke lengths to achieve performance by reaching over the restrictive chest strap with their shoulders and upper back (Smoljanovic et al., 2011). This movement would most likely occur via a shoulder abduction and internal rotation movement. Our study suggests that the change in shoulder abduction angle to accomplish this is especially apparent at the catch position of TA rowing where abduction angle is 7° greater than in the LTA set-up. Additionally, flexion of the elbow at the finish position was observed to increase as the rower became more restricted by the set-up. The results of this study suggest that participants increase upper extremity postures joint angles (shoulder and elbow) at the finish to increase stroke length and/or force production.

In the context of injury risk, hyperflexion of the lumbar spine and extreme spinal postures are often cited as mechanisms for low back injury in able-bodied rowing. Our results suggest that able-bodied rowers in the TA rowing set-up used significantly more trunk flexion at the catch of the stroke as compared to able-bodied rowing, which will place the lumbar spine at greater risk of injury. These technique changes are not unlike the changes observed in novice rowers, who attempt to maximise force production by leveraging the handle with their backs, rather than driving with their legs (Tanaka et al., 2007). Increases in range of motion of both the shoulder and elbow may increase the risk of injury as well. In able-bodied rowers, increased shoulder flexion angle excursion was associated with rib stress fractures (Vinther et al., 2006). Smoljanovic et al. (2011) also identified that the unique conditions created by chest straps in the AS set-up may place significant stress on the upper thoracic region of para-rowers. Increased flexion of the elbow at the finish of the stroke observed in the TA and AS set-ups results in significant ulnar deviation, and may increase the risk of wrist injury.

When considering handle force kinetics, this work demonstrated that participants produced significantly less handle force by set-up, decreasing from LTA > TA > AS, respectively. It has been established that handle force is inversely proportional to stroke rate (McGregor et al., 2004), which was increasing proportionally across these set-ups (24 spm, 30 spm and 36 spm, respectively). In addition, it is logical to assume that as the number of links in the kinetic chain decrease, the body's ability to produce force will also decrease. In LTA rowing, the legs are the major force producers, representing nearly half of total rowing power, followed by the trunk which produces one third and the AS which represent approximately one fifth of total rowing power (Kleshnev, 2000). Based on the proportions described by Kleshnev (2000) of body segment contribution to rowing power, it would be reasonable to see peak and average force production decrease by as much as 50% going from LTA to TA and 80% LTA to AS. However, the results of this study identify that average handle force decreased by approximately 22% for LTA to TA and 42% for TA to AS rowing. The kinematics portion of the study suggest that this smaller than expected drop in force production might be accounted for by using more extreme joint ranges in TA and AS set-ups. At this time, there are no studies that have reported handle forces for rowers in the TA and AS set-ups. However, from the results of this study, researchers and practitioners can begin to conceptualise the contributions of various body segments to force generation in the para-rowing set-ups.

Conclusions

This is the first study to report kinetic and kinematic changes associated with para-rowing set-ups. The recognition that athletes in para-rowing set-ups are likely to alter their range of motion in key joints should alert coaches working with adaptive athletes of possible injury and suggest ways to modify rigging or stroke parameters to minimise injury risk. When there is a perceived injury risk, the results of this study can be used to assist coaching regarding the high-risk elements. For example, AS athletes could be coached to reduce shoulder abduction postures at the catch and elbow flexion at the finish, while TA athletes could also minimise extreme lumbar flexion at the catch. These observations also align with Smoljanovic et al.'s (2011) recommendation to reduce hinging over the chest strap or provide the athlete with an orthosis to distribute the mechanical load over a wider area of the thoracic region. Finally, there were significant differences in pull forces between men and women in this, and a previous, study that estimated low back compression values (Cutler et al., 2015). A study designed to tease out the exact mechanism of difference between males and females should be designed such that practical questions relating to drag factors, and rigging strapping designed for females can be answered.

Disclosure statement

No potential conflict of interest was reported by the authors.

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