Revealing complexities within flat-water kayaking:
injury prevention and biomechanical analysis.

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Abstract

Elite kayakers are required to perform repetitive movements that create strength and flexibility asymmetries in their bodies, making them susceptible to injury.

The first portion of this thesis is dedicated to investigating whether a supervised, corrective pre-habilitation programme of the kinetic chain, conducted twice a week for 10 weeks, would reduce these predisposing factors.

A group of 19 marathon paddlers were assessed before and after the intervention, with nine of them receiving the intervention. The 10-week intervention programme was found to significantly improve scapular position and kinesis, thoracic spine extension and single arm pulling ability, thus suggesting improved shoulder function and reduced risk of injury.

The second portion of the thesis involved novel biomechanical analysis of kayaking on the water and on a kayaking-ergometer. It is the first objective description of the three dimensional movements of the kayak in the literature. Sprint and marathon paddlers performed a 180 metre time trial using an instrumented paddle with an accelerometer and gyroscope attached to the boat for analysis of boat movement characteristics and paddler-generated forces. Similar patterns for paddle torque, boat acceleration and pitch were observed between male sprint paddlers and male marathon paddlers. However, the direction and timing of the roll and the yaw of the boat during the water phase of the kayak stroke differed between these groups of paddlers. In addition, substantial individual variation existed within the group of male marathon paddlers.

On the kayaking ergometer, activation patterns of the trunk and pelvic muscles were measured using electromyography during a maximal 200 metre time trial. Gluteus medius, lower trapezius and erector spinae were measured for the first time in maximal kayaking. The latissimus dorsi, pectoralis major and external oblique muscles were more active during the contralateral phase than has previously been reported. When these paddlers performed a single arm pull test on the same day, the muscle activation patterns changed, and muscle groups were active according to their anatomical function and what has previously been described.

First, variation of movement, flexibility and segmental training of the kinetic chain may be advantageous when incorporated with kayaking training to prevent shoulder injury risk factors in paddlers. Second, individual evaluation of three-dimensional boat kinematics and muscle recruitment timing provides objective insight into an individual's kayak technique, with potential benefits for improving technical performance and mechanical efficiency.

Declaration

I, **Julia Marguerite Fisher**, do hereby declare that the experiments presented in this thesis were conceived and executed by myself except where otherwise indicated.

Neither the substance, nor any part of this thesis has been submitted in the past, or is being, or is to be submitted for a degree in the University or any other University.

This thesis is presented in fulfilment of the requirements for the degree of Doctor of Philosophy in Exercise Science.

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List of abbreviations

General phrases

Anterior superior iliac spine	ASIS
Coefficient of variation	CV
Control group	CG
Distance of superior scapula spine from spine	*ds*
Distance of inferior scapula spine from spine	*di*
Difference in the heights of the superior scapulae spines	*h*
Electromyography	EMG
Erector spinae muscle	ES
External rotation	ER
External oblique muscle	EO
Four person kayak	K4
Gluteus medius muscle	GM
Internal rotation	IR
Intervention group	IG
Lateral scapula slide test	LSST

Latissimus dorsi muscle	LD, lats
Left	Lf.
Lower fibres of trapezius muscle	LT
Maximal voluntary contraction	MVC
One person kayak	K1
Pectoralis major	PM, pecs
Proprioceptive neuromuscular facilitation	PNF
Posterior superior iliac spine	PSIS
Range of motion	ROM
Right	Rt.
Root mean squared	RMS
Shoulder	sh.
Standard deviation	SD
Straight leg raise	SLR
Tukeys honestly significant difference test	HSD
Two person kayak	K2

Measurements

Acceleration g force	g
Angular degrees of movement	°

Meters per second	m/s
Newton meters	Nm
Percent of maximum value	% of max
Strokes per minute	spm
Stroke rate	SR

Chapter 1: Introduction

History of paddling

Originating in North America as a form of long-distance transport, paddling has become a popular sport using a variety of kayaks and aquatic conditions such as flat-water, rivers and the sea. It is a sport where efficiencies in biomechanics of the person, paddle and boat must be mastered within the principles of hydrodynamics for best performance.

International landscape of flat-water paddling

The two internationally raced disciplines of flat-water-kayaking are sprint and marathon distances. First included in 1924 Paris Olympic Games, flat-water sprint kayaking is raced in lanes across flat water much like rowing, and competed distances across 200 m, 500 m and 1000 m in single, two-person and four-person kayaks (K1, K2 and K4 respectively).

Flat-water marathon competitions are 30 km long, involving seven laps. There is a portage between each lap, during which the paddlers get out of their boats and have to run a short distance to a different put-in location. Unlike sprint events where participants are organised into lanes and where wave riding results in disqualification, marathon paddlers make use of drafting. It is more energy efficient to paddle on another boat's wave, compared to paddling alone on a stretch of water. The race structure of marathon paddling therefore incorporates strategies beyond paddling speed and endurance, and includes bunch riding tactics, take-out and put-in speed as well as running ability with the boat.

Technical training; involving individual attention to kayaking technique from a coach during on-water paddling sessions, as well as supervised strength training, is classically only adopted by sprint kayakers. In contrast, marathon paddlers seldom have the opportunities of one-on-one technical coaching on the water that sprint paddlers receive.

This trend is consistent with most peer-reviewed journal articles on kayak technique studying sprint kayaking. There is currently no objective analysis of marathon kayakers' technique in the literature.

The kayak stroke

In kayaking, the person and boat are propelled across open water by alternately submerging a paddle blade in the water (Plagenhoef, 1979; Mann & Kearny, 1980; Aitken & Neal, 1992; Timofeev *et al*. 1996; Sperlich & Baker, 2002; Begon *et al*., 2009; Michael *et al*. 2009; Rottenbacher *et al*., 2011; Brown *et al*., 2011). This pulling force from the stroke side arm is coupled with a pushing force from the aerial arm and together, with the integration of the whole body, the force applied overcomes the aero- and hydrodynamic drag and the athlete-paddle-boat system is accelerated forwards (Mann & Kearny, 1980).

When the stroke is transitioning from one side of the boat to the other, there is no paddle in the water. During this air phase, the athlete-paddle-boat system is only exposed to drag forces, and deceleration occurs. It is the combination of the acceleration and deceleration of the water and air phases respectively that contribute to the overall mean velocity of the boat and thus kayak performance.

Best performance in kayaking requires the highest mean velocity, and therefore the relationship of both acceleration and deceleration of the athlete-paddle-boat system must be considered when optimising kayaking biomechanics and performance.

Due to the unstable surface of the water and the slim design of kayaks, unilateral application of force results in accessory three-dimensional movements of the kayak, called pitch, roll and yaw (Mann & Kearny, 1980; Jackson, 1995; Pendergast, 2005; Begon *et al*., 2010; Brown *et al*., 2010; Vadai *et al*., 2013).

Although three dimensional accessory movements of the boat have been well-described in previous studies exploring kayaking biomechanics (Mann & Kearny, 1980; Jackson, 1995; Pendergast, 2005; Begon *et al*., 2010; Brown *et al*., 2010; Vadai *et al*., 2013), these variables have not been objectively quantified and reported on with regards to magnitude, direction or timing during the stroke cycle.

Mann and Kearny (1980), using only video analysis, made an early hypothesis that minimising acessory movements of the boat would increase the efficiency of the boat through the water. This was later confirmed by Jackson (1995) when he investigated the relationships of frictional and wave drag with the wetted surface area of the boat. Although steps have been made to understand the hydrodynamic interactions that are at play during kayaking, the precise optimal three-dimensional control of the boat has not yet been determined and the work by Mann and Kearny (1980) remain the basis of understanding kayaking biomehcniacs. Investigations into rowing performance by Baudouin and Hawkins (2002) support Jackson's (1995) findings, where reduced three-dimensional movements of the skull were associated with both improved efficiency and performance. From the current literature on kayaking biomechanics it can be concluded that it is advantageous to paddling efficiency to control and reduce the three-dimensional accessory movements of the kayak (Mann & Kearny, 1980; Jackson, 1995).

A novel aim of this thesis is to quantify the three-dimensional movements of a kayak on the water during maximal paddling, with reference to direction and timing of roll, pitch and yaw of the boat. Further, the study aims to investigate the relationships between paddle force, boat forward acceleration and boat kinematics. These findings will enable a greater understanding of their associations with one another. Testing elite sprint and elite marathon paddlers, addresses the complex interactions at play during maximal paddling in these two different groups.

The investigation of paddle force, boat forward acceleration and three dimensional kinematics during on-water paddling of sprint and marathon paddlers is presented in Chapter 3 of this thesis.

Paddle force: magnitude, timing and direction

It is agreed that force applied through the paddle to the water results in forward propulsion of the kayak (Plagenhoef, 1979; Mann & Kearny, 1980; Aitken & Neal, 1992; Timofeev *et al*., 1996; Sperlich & Baker, 2002; Michael *et al*. 2009; Rottenbacher *et al*., 2011; Brown *et al*., 2011). Strain gauges on the paddle shaft measure the effects of applied paddle force and have become a popular and relatively easy objective measurement of kayaking biomechanics (Aitken & Neal, 1992; Timofeev *et al*. 1996; Sperlich & Baker, 2002; Rottenbacher *et al*., 2011; Brown *et al*., 2011; Helmer *et al*., 2011; Strum *et al*., 2013). The interpretation of paddle force data is complex. Three components of paddle torque need to be considered; the magnitude, the timing in relation to the orientation (angle and depth) of the submerged paddle blade and the direction of the paddle blade’s movement through the water.

Attempts to quantify the contribution of the legs, pelvis and trunk during kayaking have been conducted by Begon *et al.* (2010). Although, this study was performed on an indoor ergometer, this poses a challenge as large differences exist between the use of a stable ergo compared to the unstable water. On the water, the narrowness of a kayak increases lateral instability, requiring a contribution from the pelvis to control for this instability. Specific biomechanical differences of the pelvis while paddling on the water compared to in the laboratory on land have not yet been determined objectively and requires further research.

In the aforementioned study, twelve elite male participants were found to have high individual variation for pelvic and scapular girdle rotation. This variation is likely even greater on the water, for the reasons mentioned above, and unique paddling techniques would render a different optimal contribution for the legs and pelvis for each paddler.

Lastly, the highest stroke rate tested by Begon *et al.* (2010) was 92 strokes per minute (spm). This is considerably below the average stroke rate for elite paddlers performing over 200 m, 500 m and 1000 m distances which has been reported at 138 ± 6.8 spm, 121 ± 6.4 spm and 113 ± 9.7 spm respectively (Baker *et al*., 1999; Brown *et al*., 2011). Changes in paddler kinematics with increasing stroke rates however, is yet to be determined.

With the consideration of the limitations to their study, Begon *et al.* (2010) concluded that the use of the legs in a pedalling motion is associated with improved paddling performance (Begon *et al*., 2010). This was attributed to the legs' role in transferring forces from the foot plate/bar through the body to the paddle, and in initiating the rotation of the pelvis and subsequent rotation of the trunk. Isometric contractions of the legs (where no movement but rather rigidity is gained) result in push and pull forces on the foot-rest and seat that play a role in maintaining balance and posture in the boat (Begon *et al*., 2010). Fully understanding the effect of these isometric forces at the footrest and seat requires the use of three-dimensional strain gauges synced with kinematic and electromyography on the legs and torso while paddling maximally on the water. This has yet to be investigated and would lead to further validation of the optimal role of the legs in kayaking.

Brown *et al.* (2011) utilised notational analysis (a subjective rating system) to document person, paddle and boat kinematics between international, national and club level paddlers during on-water competitions using video cameras positioned on the bank. It was concluded that the elite kayakers had greater leg drive, trunk rotation and width of strokes compared to national and club-level paddlers.

Optimisation of flat-water kayaking performance is further suggested to be achieved by timing the application of maximal paddle force so that the greatest force is applied when the resultant force (combination of vertical and horizontal components) is best aligned with the horizontal forward displacement of the kayak (Robinson *et al*., 2002; Michael, 2009; Brown, 2009). The beginning and end of the stroke is dominated by vertical (y) force components (downward and upward, respectively). In contrast, once the paddle is submerged, the component along the long axis of the boat (x) dominates. It is therefore encouraged that this power phase (greatest contribution from the horizontal force), is maintained for as long as possible (Robinson *et al*., 2002; Brown, 2009; Michael, 2009). This can be achieved by pulling the paddle diagonally away from the boat. Therefore, when objectively measuring paddle force, not only are the peak and average forces important but the time in the water phase, at which the maximum force occurs. Chapter 3 of this thesis will examine these aspects of paddle force.

The diagonal direction of the paddle blade can further contribute to efficiency, if the lift and drag components of propulsion are considered. Lift forces act perpendicular to the flow of the water relative to the paddle (Sanders, 1998), thus the wider the stroke the greater the contribution of lift to propulsion. In contrast, pulling the paddle directly backwards, in a narrower stroke, relies on contribution from drag for propulsion (Sanders, 1998) and is more energy expensive.

Kendal and Sanders (1993) investigated the paddle paths of seven national kayakers. Greatest variation found was in the amount of posterior displacement of the submerged paddle, ranging from no displacement to 18 cm of backward displacement. The best kayaker's (Olympic medallist) paddle blade showed a combination of slight backward displacement and width at the end of the pull phase (Kendal & Sanders, 1993). The pathway of the paddle was curved, and pulled diagonally away from the kayak, therefore utilising both lift and drag for propulsion of the boat through the water (Kendal & Sanders, 1993). The wider stroke, as observed in elite sprint kayakers by Brown *et al.* (2011) complements these findings.

An arced paddle pathway also allows for better use of trunk rotation around the longitudinal axis of the trunk so that a wider stroke offers greater opportunity for rotation compared to a pulling action along side the boat (Sanders, 1998). Therefore the driving contribution of the pull phase comes from both shoulder extension and trunk rotation. The wider stroke will also likely offer greater lateral stability as the relative base of support is increased.

Mann and Kearny (1980) tested two female and nine male internationally competitive paddlers on the water using a calibrated area of 12 meters with one camera capturing at 70 frames a second. Paddlers had 40 meters to accelerate their boats to a "competitive speed" before entering this area. Body markers were placed on the upper body and later digitised for body segment analysis. From this data an undesirable upward thrust of the wrist at initial water contact of the pull phase was idendified. The authors suggested that paddlers should transfer weight onto the pull side to reduce this upward thrust and maintain grip on the water, preventing inefficient posterior slipping of the paddle in the water. A wider stroke, as well as counter-balancing with the legs and seat, would be required to ensure the paddler maintains lateral stability when transfering weight towards the submerging paddle blade at the beginning of the pull phase.

As the paddle begins to exit the water, toward the end of the pull phase, the upward thrust from the water is reversed and the paddler is advised to shift their centre of mass away from the pulling side (Mann & Kearny, 1980). Changes in the centre of mass would interact with the lateral rolling of the boat, depending on the extent of the compensation. Measurement of intra-stroke deviations in the roll of a kayak has not yet been described in the literature. This thesis (Chapter 3) will endeavour to determine whether this phenomenon of rolling the boat towards the stroke side is adopted by elite sprint and marathon paddlers.

In conclusion, studies on kayaking biomechanics have revealed significant complexity in the relationships between boat speed and a range of biomechanical variables including paddle forces. It is clear that optimal kayak technique is far more complex than applying the largest possible paddle force to the water, but rather that a whole body contribution and co-ordination, including the legs, torso and upper-body, is required to optimise stroke technique and paddle performance within the properties of hydrodynamics.

Muscle recruitment patterns during kayaking

The two scenarios previously described of the paddle pathway (narrow and wide) would not only influence the lift and drag contributions but also require differing neuromuscular strategies to execute the two techniques.

In the first scenario, a narrower paddle stroke, Sanders (1998) discusses the likelihood that shoulder extension and elbow flexion would be responsible for pulling the paddle backwards alongside the boat. In the second scenario, a wider paddle stroke, the author refers to trunk rotation with less elbow flexion being the necessary movements adopted, as the arm would move laterally away from the body instead of alongside it, therefore levering the boat past the submerged paddle (Mann & Kearny, 1980; Sanders, 1998).

The latissimus dorsi (LD) muscle has been described as the prime mover during the water phase of sprint kayaking (Trevithick *et al*., 2007; Brown, 2009; Fleming *et al*.; 2012). This is unsurprising as its function described in Grant’s Atlas of Anatomy (Grant, 1943) is to pull the body towards an outstretched arm. During the period when the paddle blade is submerged, concentric contraction of the ipsilateral latissimus dorsi muscle would pull the boat towards the outstretched arm, as described for the function of this muscle group. This large triangular muscle, wrapping from the spine to the front of the humerus, also contributes to ipsilateral trunk rotation (McGill, 1991), thereby further assisting the water phase of kayaking where the trunk is rotated towards the stroke side (Plagenhoef, 1979; Mann & Kearny, 1980; Michael *et al*., 2009; Brown *et al*., 2011).

While testing elite sprinters' muscle activation during on-water paddling using electromyography (EMG), Brown (2009) found associations between the contralteral external oblique (EO) with boat speed and paddle torque production. Contraction of the EO causes trunk rotation to the opposite side (Kumar *et al*., 2012) and its relation to performance supports the contribution of trunk rotation to the paddle force in elite sprinters, who have been found to use a wider stroke (Brown *et al*., 2011).

Further, contributions of pectoralis major (PM), the lower fibres of the trapezius (LT), erector spinae (ES) and gluteus medius (GM) have not yet been described in the literature for paddling. The fourth study in this thesis provides the first measures of these muscles during a maximal paddling time trial.

Pectoralis major is responsible for adduction of the shoulder and therefore it is expected that it will be activated during the contralateral pull phase, at the same time as the LD on the opposite (stroke) side. The LT is responsible for scapula upward rotation during arm elevation and therefore is expected to be active during all phases, but to be most active under load, during the ipsilateral pull phase. The ES and GM muscles are considered to be stabilisers of the kayak stroke. Kamur and colleauges (2002) report that the ES contributes bilaterally to trunk rotation, assuming the role of a trunk stabiliser during rotation. The GM's function is to provide latereral stability to the pelvis (Gottschalk *et al*., 1989) by preventing the opposite ilium to drop. Both of these muscle groups are therfore likely to contribute to the lateral stability of the person and boat.

Previous studies on kayak technique have reported greatest variation in the backward displacement of the submerged paddle (Kendal & Sanders, 1993) and the amount of pelvic rotation (Begon *et al*., 2010). Given these findings, variation in the activation timing of muscles of the trunk (ES) and pelvis (GM) and lateral stability (roll) of the boat were of interest.

Strength training

Although it is established in the literature that trunk and pelvic rotation contribute to paddling efficiency (Kendal & Sanders, 1993; Brown, 2009; Begon *et al*., 2010) and that paddling performance on the ergometer has no relation to strength during pull and push strength tests (McKean & Burkett, 2009), kayakers strength training is biased towards push and pull movements (van Someren & Howatson, 2008; Garcia – Pallares *et al*., 2009).

Bench-press and bench-pull are the two most popular exercises for kayakers strength training and testing (van Someren & Howatson, 2008; Garcia – Pallares *et al*., 2009;

McKean & Burkett, 2009). The validity of these exerciese to kayaking performance remains questionable, and the complexity of the skills required for best kayaking performance perhaps supersedes pull and push strength.

During the execution of bench-press and bench-pull exercises the bench provides a stable base while both arms are used for the same movement at the same time involving no trunk or pelvic rotation nor leg drive. This is dissimilar to paddling, which is performed on an unstable surface involving unilateral arm movements and requiring the integration of leg, pelvic and trunk movements.

Further, during bench exercises, the weighted bar is brought to the chest by either pulling or pushing of the bar rather than the body moving towards the arms, as occurs during paddling (Mann & Kearny, 1980). The shoulder position achieved when the bar arrives at the chest can vary according the preferred technique. Commonly, the bar is pushed and pulled at shoulder level. These exercises can be performed with the bar arriving lower down the chest, closer to the xiphisternum or with the body inclined (angled upwards) or declined (downwards) from horizontal. These variations use different lever arms and therefore involve slightly different muscles to perform the task with resultant difference in joint and soft tissue loading. The variations in these exercises also have implications for the association between measurements of strength and kayaking performance, as well as for how shoulder strength is developed. In kayaking, the pulling arm transmits forces to the water while positioned lower than shoulder height and never comes to the chest but rather in an arc pathway away from the body as the torso rotates (described previously). The pushing arm in kayaking starts wide and comes towards the midline but due to trunk rotation, rarely crosses the midline.

The support from the bench during bench-press blocks scapula retraction and upward rotation. These movements of the scapula are necessary for the humeral head to remain centred in the glenoid fossa of the scapula during the shoulder abduction of bench press. The blocking of these movements by the bench can cause an anterior translation of the humeral head in the glenoid and thus place excessive strain on the anterior musculature of the shoulder, including the biceps brachii tendon, which is commonly injured in kayakers (Edwards, 1993).

Strength training focusing on bench-press and bench-pull exercises (where the bar touches the chest) encourages the pattern of elbow flexion (biceps brachi) and scapula downward rotation (rhomboids) during the pull and push training. This is not similar to efficient kayaking technique as described previously and may contribute to the development of a technique where the paddle is pulled by the biceps, remaining closer to the boat, using drag more than lift for propulsion as well as less trunk rotation.

Shoulder injuries

Excessive loading of anterior structures with poor scapula kinematics is a risk factor for shoulder injury and should be avoided (Kibler, 1991). Dr Walsh (quoted by Edwards, 1993) who was a physician for an international kayak team in the 1980s attributed shoulder injuries in kayakers to weight training rather than to on-water paddling. The author of this thesis, in her role as a physiotherapist for the National sprint kayak team, along with team management and coaches, have similarly observed that the bench press is the strength training exercise that elicits more shoulder pain than either paddling or other strength training modalities in the South African elite sprint kayaking squad.

When Cox and Nouwen (1989, reported on by Edwards, 1993) tested thirty international elite sprint kayakers they found that 53% of the kayakers had a shoulder injury at the time of testing. Twenty percent of shoulder injuries were attributed to biceps tendonitis, 20% due to a rotator cuff injury, 14% were shoulder bursitis, while 46% of the shoulder injuries were undiagnosed. Intrinsic risk factors for these shoulder injuries include limited range of movement and imbalances in shoulder function (Kugler, 1996; Donatelli *et al*., 2000; Kibler, 2006). More specifically, scapula malpositioning (Kebaeste *et al*., 1999; Smith *et al*., 2002) and dyskinesis (Warner *et al*., 1992; Smith *et al*., 2002; Burkhart *et al*., 2003; Cools *et al*., 2004; Kibler, 2006), posterior rotator cuff weakness (Kibler, 1998; Burkhart *et al*., 2003; Escamilla, 2009), decreased glenohumeral internal rotation range (Kibler, 1996; Burkhart *et al*., 2003) and a tight posterior joint capsule (Kibler, 1996 & 2006) may all contribute to shoulder injury risk.

Paddlers have been found to present with many of these risk factors. Most notably, McKean and Burkett (2009) reported decreased rotation range and weak scapula stabilisers relative pulling strength. The reduced strength of the scapula stabilising muscles compared to pulling strength is likely to cause abnormalities in the position and movement of the scapula and glenohumeral joint.

Furthermore, these risk factors can be exacerbated by extrinsic factors, such as side winds putting more strain on the one shoulder while paddling, asymmetrical boat kinematics, poor technique during weight training (Edwards, 1993; Kobler *et al*., 2010) and insufficient recovery between training sessions causing fatigue-related technique changes (Kobler *et* *al*., 2010). It is important that both intrinsic and extrinsic risk factors to injury are addressed in order to decrease their incidence.

Due to the high incidence of shoulder injuries in kayaking and the repetitive nature of the sport injury prevention strategies need to be employed by paddlers if they want to prevent limitation of participation and performance as well as long-term shoulder pathology. Prehabilitation, a term given to preventative rehabilitation, is therefore indicated for paddlers; with the aim of preventing the development or worsening of adaptations caused by training that increase their shoulder injury risk.

The first study in this thesis aims to determine if an integrated prehabilitation including full range exercises using normal kinematics, balanced strength and co-ordination between body segments would be successful in preventing intrinsic risk factors in a group of paddlers.

Conclusion: Holistic approach to kayaking performance

The evidence presented above describes a range of factors that contribute to kayaking performance. These are broadly grouped into injury risk factors and prevention, on-water boat and paddle biomechanics, and the neuromuscular strategies of the kayaking stroke.

The application of science to performance requires that these factors be measured, interpreted and understood, so that coaches and athletes may benefit from their application. The overarching aim of this thesis is to investigate these factors to better understand how they may impact on boat performance, as well as to recognise their clinical implications. The individual variation in the above-described factors is of particular interest in this thesis, since performance is so crucially determined by skill and technical execution. The specific research questions of each study are described in the following section.

This holistic, integrated and individualised approach to the scientific questions around kayaking related injuries and technique is aimed at elevating the standard of measuring and interoperating kayaking biomechanics and performance.

Research questions and hypotheses

The following specific research questions will be examined in the present thesis:

Question 1 (Study 1)

Can previously documented intrinsic risk factors to shoulder injury, found in elite paddlers, be mitigated by a supervised 10-week prehabilitation programme comprising of training control of full active ranges of the glenohumeral joint, thoracic spine and scapula under increasing loads, using kayak specific movement patterns?

Kayakers have been found to have a high incidence of shoulder injury (Edwards, 1993). The repetitive movements of kayaking on flat-water and the bias of strength training towards push and pull strengthening leads to particular adaptations of the shoulder girdles (Edwards, 1993). These acquired abnormalities, including decreased shoulder rotation range and weak scapula stabilisers (McKean & Burkett, 2009) likely predispose paddlers to shoulder injuries (Kugler, 1996; Donatelli *et al.*, 2000; Kibler, 2006). Other factors (extrinsic) such as selection of strength training exercises and the techniques of executing these exercise as well as paddling technique and conditions are also possible contributors to this high incidence of shoulder injury (Edwards, 1993).

We hypothesise that a supervised, kayak-specific, individualised prehabilitation programme will improve the intrinsic risk factors of shoulder injury in kayakers, including improved active shoulder rotation range, improved positioning and kinematics of the scapula and improved shoulder function when testing pulling ability.

Question 2 (Study 2)

How does three-dimensional orientation of the boat change over a stroke cycle during maximal kayaking for sprint and marathon kayakers?

Currently there are no objective reports in the literature of how the boat reacts to the unilateral application of paddle force to the water. However, previous research encourages the minimising of accessory three-dimensional movements of the kayak, such as roll, pitch and yaw, in order to achieve greater paddling efficiency (Mann & Kearny, 1980; Jackson, 1995; Begon *et al*., 2009; Michael *et al*. 2009). The three-dimensional intra-stroke deviations of the boat will be measured during the positive and negative acceleration phases using an accelerometer and gyroscope attached to the boats of sprint and marathon kayakers during maximal paddling.

We hypothesise that during the pull phase of the stroke, the boat will roll towards the stroke side as suggested by Mann and Kearny (1980). We hypothesise that the nose of the boat will dip down into the water at the beginning of the pull phase when the downward vertical componenents of the force are greatest (Robinson *et al*., 2002; Michael, 2009) and that the nose of the boat will lift again at the end of the pull phase, when the upward force from the paddle force vector dominates (Robinson *et al*., 2002; Michael, 2009). We hypothesise that the unilateral applied paddle force will cause the nose of the boat to yaw away from the stroke side.

The three-dimensional movement of the boat are the result of the magnitude, timing and direction of paddle force as well as the magnitude, timing and direction of the movement and force transfer from the paddler to the boat. Variability has previously been found in both paddle (Kendal & Sanders, 1993) and paddler (Begon *et al*., 2010) biomechanics of elite kayakers, and therefore, we hypothesise that there will be technical differences in the three-dimensional accessory movements of the boat.

Marathon paddlers receive less technical coaching, race longer distances and paddle in turbulent water conditions compared to sprint paddlers. Therefore, we hypothesise that differences will be found in the three-dimensional movement of the boat between marathon and sprint kayakers and further hypothesise that the variability of these findings will be greater within the group of marathon paddlers.

Question 3 (Study 3)

Do non-technically trained marathon paddlers' muscle recruitment strategies of the latissimus dorsi and external oblique muscles match those of elite sprint paddlers' during the kayak stroke, as previously described in the literature?

Kayaking is a technical sport where the whole body needs to be co-ordinated to transfer maximal power through the water to the paddle. Previous electromyographic investigation of elite sprint kayakers by Brown (2009) and Fleming et al. (2012) found that the ipsilateral latissimus dorsi (LD) muscle is active during the pull phase of maximal kayaking. Further, Brown (2009) found that both external obliques (EO) are recruited during the pull phase, and the opposing EO is responsible for contralateral trunk rotation, that was found to be associated with paddle force generation and boat speed.

We hypothesise that marathon paddlers will use similar muscle recruitment strategies as previously described in the literature for sprint kayakers, including the recruitment of the ipsilateral LD and bilateral EO muscles during the pull phase during maximal kayaking.

Question 4 (Study 3)

What are the muscle activation strategies for the pectoralis major, lower fibres of trapezius, erector spinae and gluteus medius muscles during maximal kayaking?

Currently the contribution of the pectoralis major (PM), lower fibres of trapezius (LT), erector spinae (ES) and gluteus medius (GM) muscles during maximal kayaking remains uncharacterised. During the pull phase, the opposite, aerial arm, adducts at the shoulder, therefore it is hypothesised that the contralateral PM will be activated during the pull phase.

The LT, responsible for upward rotation of the scapula is expected to be active during the pull and push stroke cycles, but activation is expected to peak during the ipsilateral pulling phase, when the load on the shoulder is greatest.

The right and left lumbar spine ES muscles have been found to work in synchrony during resisted rotation eliciting a stabilising relationship of the ES to rotation (Kumar *et al*., 2012). We therefore hypothesise that both ES will be recruited during the pull phase of the stroke when the trunk is rotating towards the pull side.

The GM muscles are responsible for the lateral stability of the pelvis by preventing the dip of the opposite ilium (Gottschalk *et al*., 1989). It is therefore hypothesised that the contralateral GM will be active during the pull phase to provide lateral stability during the loaded, pull phase of the stroke.

Question 5 (Study 3)

What are the muscle recruitment strategies for the ipsilateral latissimus dorsi, contra-lateral pectoralis major, ipsilateral lower trapezius and bilateral external oblique, erector spinae and *gluteus medius muscles during a single arm pull movement? And how do the muscle recruitment strategies vary between a single arm pull movement and the pull phase of kayaking for this group of muscles?*

The muscle recruitment strategies using a single arm pull device, including trunk rotation and hip and knee extension were first investigated by Tokuhara *et al.* (1978). Neuromuscular feedback was found to be a useful training stimulus when force generation during the pull phase was being trained (Tokuhara *et al*., 1987).

We hypothesise that the neuromuscular recruitment strategies during the pull phase of the kayak stroke will be similar to those recruited during a single arm pulling movement.

Chapter 2: Addressing intrinsic risk factors for shoulder injuries in paddlers

Introduction

Structure and neuromuscular interactions of the shoulder girdle

The structure of the glenohumeral (shoulder) joint permits a large range of mobility, allowing for the high functionality of the arm. This relationship of mobility and stability enabling function requires complex interactions. Complex interactions are required in order to facilitate this combination of mobility and stability. Compared to the hip joint, which is also a ball and socket joint, the shoulder has substantially less bone on bone contact, and therefore possess less passive stability (bone and ligaments) and requires greater dynamic stability. The dynamic stabilisers of the shoulder, the rotator cuff, include supraspinatus, infraspinatus, teres minor and subscapularis muscles. These need to work in balanced force-couples for optimal shoulder function (Kibler, 1998; Burkhart *et al.*, 2003; Escamilla, 2009).

The socket of the shoulder joint is the glenoid cavity of the scapula. The position of the scapula is therefore important to the movement and positioning of the glenohumeral joint. The scapula position and movement is governed by the strength and tension of the 18 muscles attaching onto it, therefore also requiring the correct management of these complex interactions for its optimal function (Warner *et al.*, 1992; Smith *et al.*, 2002; Burkhart *et al.*, 2003; Cools *et al.*, 2004; Kibler, 2006).

In non-weight bearing, static positions, the function, strength and activity of the shoulder and scapula stabilising muscles are less important compared to during dynamic situations (arm movements) and weight bearing conditions. Elite sprint paddlers use upward from 100 kg weighted bench press and bench pull training, therefore necessitating correct positioning and use of stabilisers of the shoulder girdle (glenohumeral joint and scapula), in order for these weighted exercises to be safely performed.

The function of the shoulder girdle in kayaking

Flat-water kayaking is a technical power-endurance sport that involves repetitive, shoulder movements, which are predominantly in front of the body (McKean & Burkett, 2009). During the power phase of the kayak stroke: the paddle blade is submerged in the water while shoulder extension, from an outreached position, and trunk rotation toward the same side, are used to draw the boat past the paddle blade (Plagenhoef, 1979; Mann & Kearney, 1980, Kendal & Sanders, 1992). As the paddle blade lines up with the hip it is exited out of the water using a combination of shoulder external rotation, abduction, horizontal extension, trunk rotation and elbow extension (Plagenhoef, 1979; Mann & Kearney, 1980, Kendal & Sanders, 1992).

A delay in elbow flexion during the pull action has since been advised (Sanders, 1998). This encourages the use of the back and abdominal muscles to drive trunk rotation. Sanders, (1998) discusses that a wider stroke, using more arced, lateral movements of the arm, would perhaps allow for conservation of momentum through the paddle moving diagonally away from the boat and therefore have a ‘rounding out’ of the stroke at the end. Whereas pulling backwards with elbow flexion would lose momentum in the sagittal plane. An arced pathway of the paddle through the water would also have hydrodynamic benefits compared to a narrower stroke (Kendal & Sanders, 1992; Jackson, 1995).

The ideal movement of the scapula during kayaking is yet to be described. However, it is often suggested that it would be required to coordinate its movements with the movement of the humerus to ensure that the glenohumeral joint axis of rotation is centred in all positions during all instances of movement (Kibler, 1991; Kibler, 1998; DePalma & Johnson, 2003). This is important for optimal strength-tension relationship of the rotator cuff muscles (Kibler, 1991), ensuring best function and preventing uneven soft tissue loading. The movement of the scapula with the humerus is also important to maintain the sub-acromial space to prevent impingement of the rotator cuff tendons (Kibler, 1991; Kibler, 1998; DePalma & Johnson, 2003).

The magnitude, direction and timing of the previously described biomechanical components, that form the draw phase of a kayak stroke, are highly varied and change according to skill level (Begon *et al*., 2010; Brown *et al*., 2011). Even at the elite level there is variability in the amount and integration of these movements (Begon, 2009).

Subsequently, to achieve optimal scapula kinematics, as previously described, the scapula is required to upwardly rotate (inferior medial angle of the scapula moves laterally upwards) at the beginning of the water phase and posteriorly tilt against the resistance of pulling on the water. Scapula upward rotation is initiated by the fibres of the upper trapezius and performed by activation of the lower fibres of the trapezius (Kibler, 1991). The amount of humeral abduction is determined by the preferred width of the stroke. The scapula upwardly rotates with the abducting humerus (Kibler, 1991), therefore it is inferred that the width of the stroke, may alter the kinematics of the scapula.

During the air phase the arm is elevated requiring upward rotation of the scapula. The arm movements of the kayak stroke occur in front of the body (McKean & Burkett, 2009), without adequate strength of the serratus anterior and flexibility of the pectoralis minor muscle the scapula will be predisposed to anteriorly tilt relative to the ribs (pseudo winging). The serratus anterior muscle, responsible for drawing the scapula against the chest wall (DePalma & Johnson, 2003), is therefore required to be active during all phases of the stroke cycle, to prevent anterior tilting of the scapula, and to preserve the sub acromial space (DePalma & Johnson, 2003).

Shoulder injuries in kayakers and their associated intrinsic risk factors

McKean and Burkett (2009) tested fifteen male and fourteen female kayakers and reported that they had reduced shoulder rotation ranges compared to what is thought as normal range for an optimally functioning shoulder joint (Kobler *et al*., 2009). This study documented greater variance and limitation of the internal rotation compared to external rotation (McKean & Burkett, 2009). Further, they found that these paddlers had weak scapula stabilisers (lower fibres of trapezius) compared to upper body strength (McKean & Burkett, 2009).

The curvature of the thoracic spine has a close relationship with the position of the scapula due to their articulation at the scapula-thoracic joint (Kebaetse *et al*., 1999; Finley &Lee, 2003). Excessive thoracic kyphosis, consistent with a slouched posture, results in ‘winging’ of the scapula and an increase in anterior scapula tilt angle observed posteriorly as ‘pseudo winging’ (Kebaetse *et al*., 1999; Finley & Lee, 2003; Thigpen *et al*., 2010). During the initial 90° of humeral elevation the scapula posteriorly tilts, to further assist the acromion of the scapula to move away for the greater tuberosity of the humerus (Herbert *et al*., 2002; DePalmar & Johnson, 2003). An increased thoracic spine kyphosis, blocks the ability of the scapula to posteriorly tilt sufficiently and thus hinders correct scapulohumeral kinesis (Kebaetse *et al*., 1999; Finley &Lee, 2003).

The strength and tightness of the pectoralis minor is also likely to increase the anterior tilt of the scapula as pectoralis minor attaches on to the coracoid process of the scapula. Anterior tilting will occur if the anterior tightness is not met with adequate strength from thoracic extensors and the serratus anterior muscle (Kibler, 1991). This anterior tilting of the scapula reduces the distance of the acromion from the humerus and therefore increases the risk of rotator cuff injury (Kibler, 1991).

Loaded shoulder flexion is performed better in an erect (straight spine) posture compared to a slouched one as significantly greater forces can be achieved (Kebaetse *et al*., 1999). While the spine is in an erect position, the scapula is able to posteriorly tilt bringing it and its muscle attachments closer to the humerus (Kebaetse *et al*., 1999). This allows the rotator cuff to function in the mid range, as its points of attachments are closer and to maintain the axis of rotation in the centre of the glenoid (Kebaetse *et al*., 1999). The optimal degree of flexion in the hips, and the position of the pelvis, have not yet been described in the literature for kayaking or other anteriorly orientated tasks. We hypothesise that some flexion at the hip, results in a forward lean of the torso, would be beneficial as the portion of the kayak stroke in front of the hip experiences less drag than behind the hip and is therefore more efficient (Mann & Kearney, 1980).

The cervical spine, an extension from the thoracic spine also influences the scapula position (Weon, 2009; Thigpen *et al*., 2010). A posture where the head is anterior to the neck, instead of superior, and when the shoulders are rounded forwards relative to the thoracic spine (forwards head and rounded shoulder posture) has been found to be associated with significantly greater scapula anterior tilting and reduced serratus anterior activation during loaded flexion and reaching tasks, when compared to a control group with ideal head and neck and head and shoulder alignment (Weon, 2009; Thigpen *et al*., 2010). Sitting position in a kayak, on the unstable surface of the water, is however more complicated than simply sitting or standing. Lifting the centre of gravity, when changing from a slouched to an erect posture, will likely reduced the paddler’s stability and therefore make the control of the three dimensional movements of the kayak more difficult. The interaction between the advantages and disadvantages of an erect (straight spine) posture would likely be influenced by core strength, balance and hip flexibility, and further research is required to determine this.

Cox and Nouwen (1989, reported on by Edwards, 1993) found that 53% of elite sprint kayakers reported having a shoulder injury at the time of testing. Twenty percent of these shoulder injuries were attributed to biceps tendonitis, 20 % due to a rotator cuff injury, 14 % from a shoulder bursitis, while 46 % of the shoulder injuries were undiagnosed.

Injury risk factors for the above described shoulder injuries include limited range of pure movement and shoulder function imbalances (Kugler, 1996; Donatelli *et al*., 2000; Kibler, 2006). More specifically scapula malpositioning (Kebaeste *et al*., 1999; Smith *et al*., 2002) and dyskinesis (Warner *et al*., 1992; Smith *et al*., 2002; Burkhart *et al*., 2003; Cools *et al*., 2004; Kibler, 2006), posterior rotator cuff weakness (Kibler, 1998; Burkhart *et al*., 2003; Escamilla, 2009), and decreased glenohumeral internal rotation range (Kibler, 1996; Burkhart *et al*., 2003) may all contribute to injury risk. As previously described, these risk factors are common in elite paddlers.

These risk factors can be exacerbated by extrinsic factors that place more strain on one shoulder than the other while paddling, such as asymmetrical boat kinematics due to cross winds or postural asymmetries in the boat. Exercise selection (Edwards, 1993) and technique during weight training (Kobler *et al*., 2010) and insufficient recovery between training sessions causing fatigue related technique changes (Kobler *et al*., 2010) may also contribute to the development of a shoulder injury. It is therefore important that both intrinsic and extrinsic risk factors to injury are addressed in order to decrease their incidence (Kobler *et al*., 2010).

Prehabilitation and shoulder injury prevention incorporating the whole kinetic chain

A kinetic chain approach to injury prevention in the shoulder is advocated by McMullen and Uhl (2000). This kinetic chain approach to prehabilitation (preventative rehabilitation) educates force transfer from proximal segments towards distal segments and creates the opportunity for efficient transfer of momentum, as the inertia of the entire body contributes to distal segment velocity (Kreighbaum & Barthels, 1996). This is achieved by controlling the proximal segments through deceleration, thus conserving momentum and allowing the greatest force to be transfer to the distal segment, optimising its velocity (Kreighbaum & Barthels, 1996). The kinetic chain approach requires correct motor control, which is the co-ordinated contraction and relaxation of many muscles, not merely the independent contraction of an individual muscle (Zarins *et al*., 1985). Begon *et al.* (2010) also found that paddling efficiency was improved by including the legs, pelvis and trunk during paddling.

For prehabilitation of the shoulder girdle, the trunk, pelvis and legs should be included and involve sequential movement patterns, so that each segment's contribution to a movement is practiced in a functional, sport-specific manner, at the correct time during the movement (McMullen & Uhl, 2000). It is also essential that a prehabilitation programme be individualised, with exercises specific to the paddler's needs and are progressed appropriately (McMullen & Uhl, 2000). This should also incorporate proprioceptive neuromuscular facilitation (PNF) techniques to promote positive neurological over-flow, where weakened structures are stimulated by the movement and force production of adjacent segments (McMullen &Uhl, 2000).

There is a high risk of injury in paddling. This risk is affected by how the shoulder operates, and therefore an intervention to correct this may have merits.

Study aims and objectives

The aim of this study is to provide a prehabilitation programme for a group of healthy kayakers. The programme is targeted at addressing common intrinsic risk factors of shoulder injuries.

We hypothesise that kayakers following the intervention will present with changes tending away from range and strength limitations.

Guided by the findings in the literature for paddlers and shoulder injury prevention described above, the targets or aims set for the intervention were:

1. To train scapular movements with sport-specific glenohumeral and torso activities.
2. To train internal and external shoulder rotation range, in a variety of shoulder flexion and abduction positions whilst ensuring neutral scapular tilt.
3. To attain and maintain normal length of the hamstring muscles.
4. To train the execution of the pulling phase of the kayak stroke by breaking up the segments of the movement.

Measurements and implementations of these aims are descried in the methods section.

Methods

A group of nineteen flat-water marathon kayakers were recruited for this intervention study. All participants were screened before the testing for exclusion on the basis of injury or illness. All participants provided written consent after having the potential risks explained to them. Participants could choose to withdraw from the study at any time. The University of Cape Town Human Research Ethics Committee approved this study.

All nineteen participants were part of the same training group at the same club, trained with the same coach, were of varied abilities and included paddlers who competed internationally for their country (international level, n = 10) and within South Africa for their club (club level, n = 9). The coach set the programme allowing for individual variation in training volume, according to the paddlers' ability. The coach did not offer advice on stroke correction (technical coaching) to the paddlers before or during the intervention period, but rather prescribed the workouts. The participants were randomised into either a control or intervention group by a blinded third party. The control group (CG) included nine paddlers (five international and four club level), while the intervention group (IG) consisted of ten paddlers (four international and six club level). This study did not interrupt the squad's regular training, as it was conducted during their peak-paddling season with the support of the coach, and was additive to training rather than replacing it. The intervention group received two 45 minute supervised supplementary prehabilitation sessions, described subsequently, per week for 10 weeks.

Every participant performed pre- and post-intervention tests. Tests included anthropometric measurements, static and dynamic scapula testing, flexibility assessments and a functional strength trial. The researchers were experienced with the testing battery. The participants were requested to avoid strength and high intensity paddle training in the 48 hours prior to the testing.

Anthropometry measurements and procedures

Anthropometrical testing comprised of standing height (stadiometer, Seca, model 708, Germany), body mass (calibrated scale, Seca, model 708, Germany) and skinfold measurements. The sum of seven skin folds was calculated using measurements taken from the triceps, biceps, subscapular, suprailiac, abdominal, thigh and calf using skin fold (Durnin & Womersly, 1974). Body fat was also calculated using the Durnin and Womersly equation (Durnin & Womersly, 1974). Limb girths of forearm and calf were measured using a standardised tape measure.

Procedure for measurement of the position of the scapula at rest

Each participant was asked to take their shirt off to expose their trunk for scapula position measurements. The females wore a crop-top under their t-shirt. Bilateral body markers were placed onto bony landmarks of the inferior medial and superior medial angles of the scapulae. The participants were requested to stand in a natural posture with arms at their side.

The first phase of the lateral scapula slide test (LSST) (Kibler, 1998) was performed and is described subsequently. The test has been validated by comparing the results of the LSST to x-ray positioning (Kibler, 1999). The test has also been found to be reliable (Curtis & Roush, 2006). The first phase of the LSST had correlation coefficients of 0.91-0.92, coefficients of determination of 0.83-0.85 and interclass correlations of 0.94-0.95 when comparing results of three experienced clinicians measuring the scapula positions of 18 uninjured males (Curtis & Roush, 2006).

The horizontal distance was measured with a tape measure from the transverse processes of the spine (at the same height as the scapula marker) to the superior and inferior medial angles of the scapulae. The horizontal distance between the superior medial angle of the scapula and the transverse process of spine was measured (d*s*), along with the horizontal distance between the inferior medial angle of the scapula and the transverse process of spine (d*i*). These were measured for both the left and the right scapulae. The difference in height between the where d*s* right and d*s* left intersect the spine was determined (h). The measurements were reported using a co-ordinate system, where the various distances, d*s*, d*i* and h are reported for left and right. For convention, measurements to the left of the spine were reported as negative values and to the right were positive (Figure 2.1). A negative h indicates that the right scapula was lower than the left, whereas a positive h indicates that the left scapula was lower than the right. For figure 2.1 the right scapula is lower than the left; therefore the h will be negative.

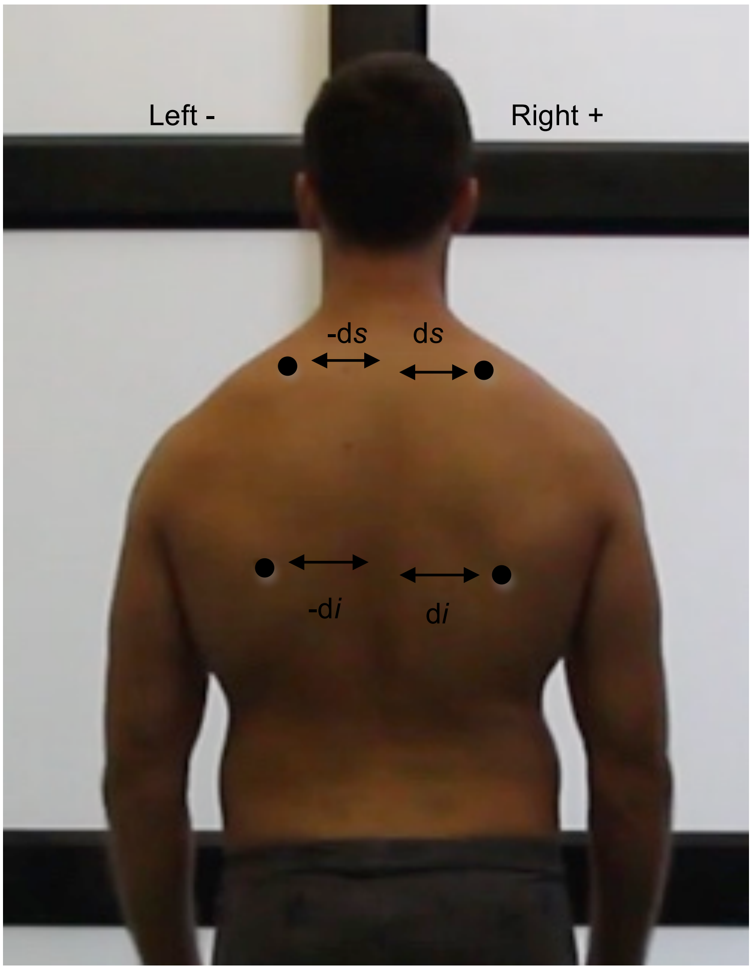

Figure 2. 1: Position used for measurement of the scapula position at rest.
Displaying the marker placements and showing the measurement of the distance between the superior medial angle of the scapula ant the spine (ds), the distance between the inferior medial angle of the scapula and the spine (di), for left and right scapulae.

Procedure for measurement of the sagittal position of the shoulder

The position of the acromion in supine, as described by Host (1995) and Nijis *et al*. (2006) was measured as an indication of the position of the shoulder girdle in the sagittal plane (Figure 2.2). The height of the posterior acromion from the bed was measured with the participant lying supine with their arms by their sides. The distance of the acromion from the bed, as well as the left vs. right differences are important components to this measurement. A higher acromion is suggestive of a tighter pectoralis minor and anterior tilted scapula (Kibler, 1991).

This test is performed in a supine position, as the bed standardised the position. The support that the bed provides the scapula, in this passive position, isolates the passive effect of the anterior structures. When interpreting the results, there are no ‘normal values’ to use, as comparisons for a test of this nature are influenced by chest girth and posterior shoulder musculature. A reduction of the measured distance would indicate less shoulder protraction (Host, 1995).

Figure 2. 2: Position used for the measurement of the sagittal position of the shoulder.

Displaying the position where the height of the posterior acromion was measured from the bed.

Procedure for the measurement of the active range of rotational movement of the shoulder

Active shoulder rotation range was measured with the participant lying in the supine position with the arm to be tested abducted at the shoulder to 90° and the elbow flexed to 90° with the forearm vertical in neutral rotation (Figure 2.3a). The participant was instructed to retract their shoulder so that their scapular was stabilised onto the bed for the duration of each test. The participant was then asked to take their hand backwards (externally rotate) as far as they were able to without any forward lifting of the shoulder (Figure 2.3b). The rotation range was measured using a goniometer. The axis of rotation was over the olecranon; the stationary arm held perpendicular to the bed, while the moving arm of the goniometer was lined up with the ulnar styloid process. The angle between the goniometer arms represents the active shoulder rotation range. This was repeated for internal rotation when the participant was instructed to take their hand forwards as far as possible without the shoulder lifting off the bed (Figure 2.3c). Both directions were tested on both sides. If the shoulder being tested showed any visible anterior translation or began to lift off the bed this marked the end of the range, thus the test measured pure and controlled active shoulder rotation. Normal ranges for these rotation ranges for optimal function are described to be 60° and 104-105° for internal and external rotation respectively (Kobler *et al*., 2009).

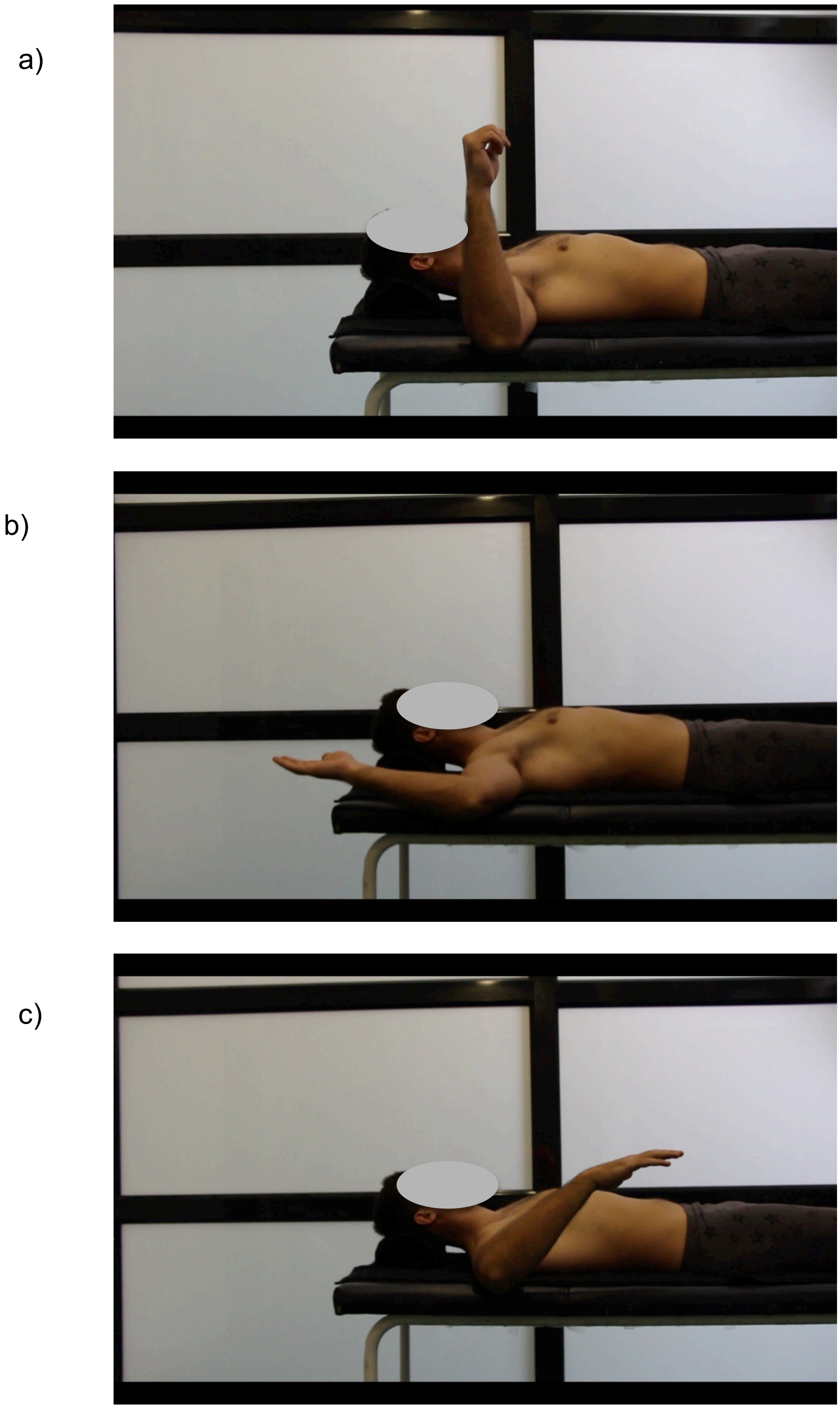

Figure 2. 3: Positions used for the measurement of active shoulder rotation range of movement.

Displaying the (a) start position, (b) external rotation and (c) internal rotation.

Procedure for the measurement of the kinematics of the scapulae

Scapula kinematics were recorded from a posterior view using high-speed video camera set at 210 frames per second (Exilim Casio, EX-FH20). The participants were instructed to slowly lift their arms up at their sides, as high as they could above their head, and to slowly lower them back down (Figure 2.4). This movement was performed twice. The video was later analysed, and described subsequently, for the presence of scapula dyskinesis by an experienced physiotherapist (five years of sports-related clinical practice and four years of clinical training) using commercially available video analysis software (Dartfish TeamPro 4.0). The same researcher analysed all of the video data. This observational assessment of scapular kinematics is well described in the literature (Kibler, 1991; Kibler, 1998; DePalma & Johnson, 2003), has been shown found to be reliable (McClure *et al*, 2009).

Normal scapulohumeral kinesis on both sides was defined as smooth and continual upward rotation of the scapula during shoulder abduction, so that that the upward rotation of the scapula was no less than 0° at 30° of humeral abduction and no less than 10° of upward rotation at 60° of humeral abduction (Tate *et al*., 2009). Followed by continuous downward rotation on humeral lowering with no evidence of winging (McClure *et al*., 2009). Winging was identified by an increase in the shadow of the medial border of the scapula, indicating that the distance between the medial border of the scapula lifted posteriorly off the chest wall (Kibler, 1998).

Obvious scapula dyskinesis was classified as downward rotation of the scapula in the first 30° of humeral abduction, scapular elevation and less than 10° of scapula upward rotation at 60° of humeral abduction with non-smooth or stuttering motion through range of glenohumeral abduction. During arm lowering rapid downward rotation and winging of the scapula was classified as dyskinesis. (McClure *et al*., 2009).

Each participant was coded with a “0” if they exhibited normal scapula kinematics, as described previously, if one or both of their scapulae had obvious dyskinesia, as defined above, a score of “1” was awarded.

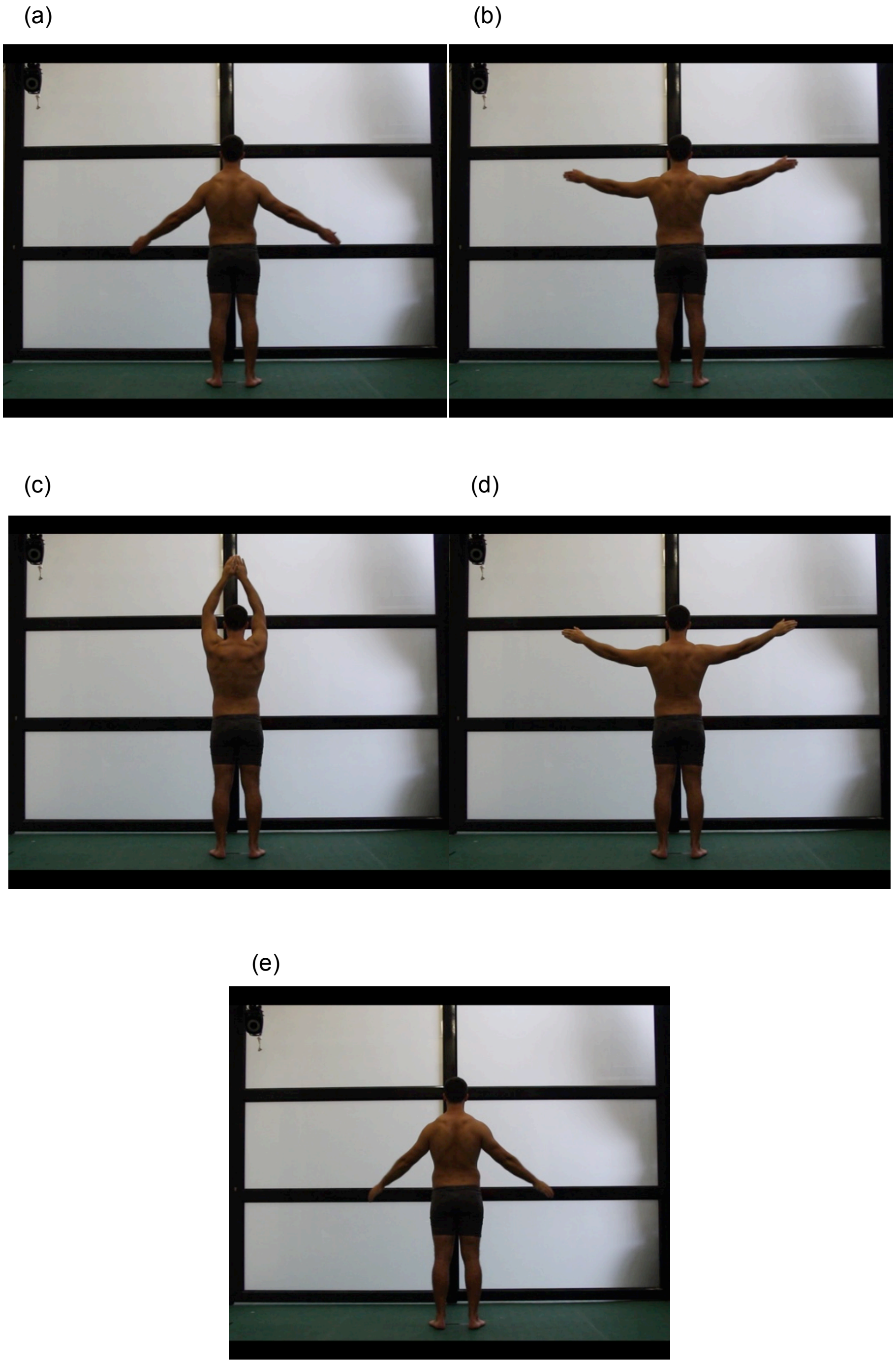

Figure 2. 4: A series of snapshots from the video analysis used to determine scapular kinematics.

Photographs desplaying the scapular kinematics during bilateral shoulder abduction (a & b), full range of shoulder abduction (c) and the eccentric lowering phase (d & e).

Procedure for the measurement of hamstring flexibility

A straight leg raise (SLR) test was used to assess hamstring flexibility (Witvrouw, 2003). The participant lay supine with their back flat on the bed, while the investigator passively lifted their leg, maintaining knee extension with the ankle in neutral, while ensuring the other leg did not lift off the bed. The participants were instructed to keep the back and opposite leg flat on the bed in order to stabilise the tilt of the pelvis. The test was stopped either when the participant reported a limiting discomfort or when there was a block to the movement. Hip angle was then measured using a goniometer with the axis of rotation on the greater trochanter of the tested leg. The stationary arm of the goniometer was lined up with the body and the moving arm was lined up with the lateral femoral epicondyle of the same leg. This was performed on both legs. The normal value for this test is considered to be 90° of hip flexion with a straight knee and ankle in neutral. This method has been shown to have inter-session reliability of 0.88 (Hsieh *et al*., 1983).

Figure 2. 5: Position used for measurement of hamstring flexibility.

Procedure for assessing flexibility of thoracic extension and shoulder flexion

The range and strength of thoracic spine extension was tested using the combined elevation test (Dennis *et al*., 2008). The participant was asked to lie on their stomach on the floor with arms extending out in front of them. With palms facing down, to ensure forearm pronation, thumbs were crossed over and elbows maintained in extension and the participant was asked to lift their hands as high as possible while keeping the chin, hips and legs on the floor (Figure 2.6). The height of the base of the right thumb from the floor was measured to the closest 0.1 cm. A higher score indicated greater thoracic extension and general shoulder flexibility.

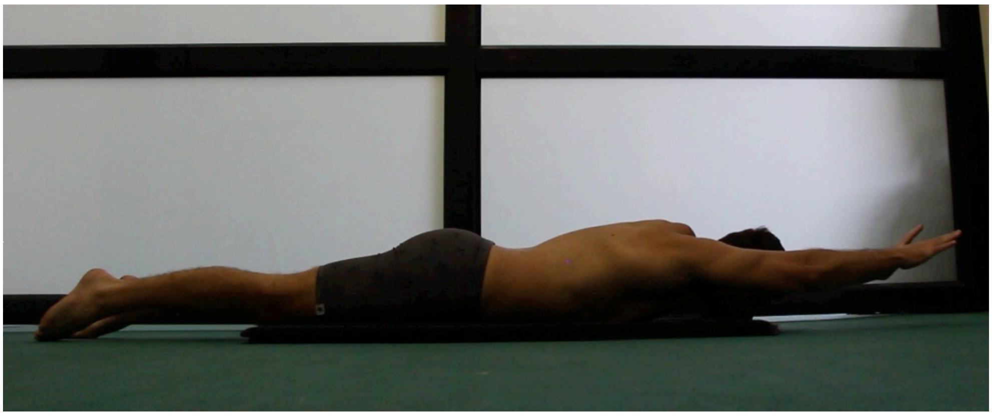

Figure 2. 6: Position used for the measurement of thoracic extension and shoulder flexibility.

Procedure of assessing kayak-specific pulling strength

Each participant's pull ability was tested on a single arm pull device. The single arm pull machine is a kayak-specific unilateral trainer that is used internationally by paddlers to develop pulling strength and co-ordination (Figure 2.7). The participant sits on a kayak seat with their feet strapped onto the footrest, in a similar set-up to sitting in a kayak or on a kayak ergometer (Figure 2.7). There is a paddle shaft, which is pulled to result in the forward displacement of the seat complex. The sliding mechanism of the seat has been designed to replicate the sensation of the boat moving past the submerged paddle whilst paddling on the water. Ergometers with a sliding seat have been validated to closely represent the paddling action (Begon, 2009), with elastics attach onto the back of the seat to provide resistance. The participant was familiarised with the movement, the footrest distance was self-selected to reproduce individual boat configuration and the number of elastics giving resistance to the seat's movement was selected according to body weight. These calculations were based on ergometer resistance settings and presented in Table 2. 1.

Table 2. 1: Single arm pull resistance settings for various body weights.

Athlete Weight (kg)	<60	60 - 70	70 - 80	80 - 90	90 – 100
Elastics	Body weight	Body weight plus one elastic	Body weight plus two elastics	Body weight plus three elastics	Body weight plus four elastics

A FitroDyne (FitroDyne, Fitronic, Bratislava, Slovakia) was attached to the seat. The device is used to determine the speed of the seat's forward displacement, while the participant performed ten repetitions at maximal effort. The maximum and average speeds were recorded.

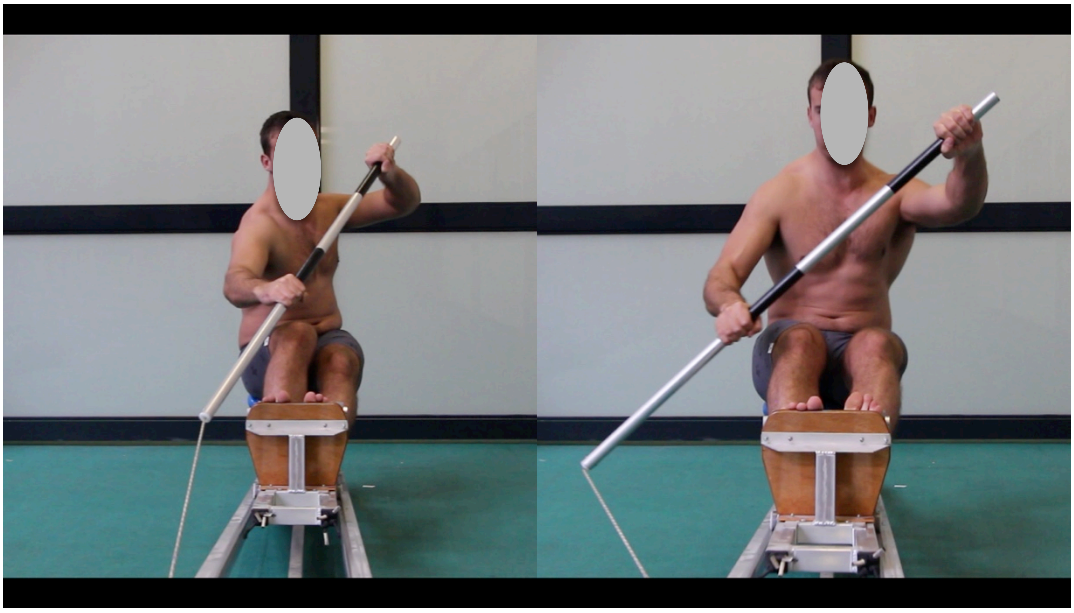

Figure 2. 7: Single arm pull device.

Depicts the position at the beginning (left) and during (right) the single arm pull test.

A major reported difference between land and water padding is the stable versus unstable sitting positions provided by land and water respectively. An effort to reduce the lateral stability in the tested seated position, participants sat on an inflatable disc (Figure 2.8). The inflatable disc necessitated the participant to counter stabilise as they would in the boat. The use of such devices are novel and future research with regards to their validation in mimicking on-water paddling is suggested.

Figure 2. 8: Photograph of the inflatable disc used on the seat of the single arm pull device.

Displaying the disc used to better represent the instability experienced during on-water paddling.

10-week prehabilitation intervention

The IG attended the 10-week intervention, which included two supervised prehabilitation sessions a week lasting 45 minutes each. The sessions were conducted by the author of this thesis (who at the time of intervention had four years of experience in paddling injuries and biomechanics). The exercises performed during the intervention were planned to progress in increasing complexity, resistance, range, repetitions and speed, while decreasing verbal and tactile feedback (Table 2.2 & 2.3, Appendix 1). The prehabilitation followed a kinetic chain approach that was not limited to the shoulder girdle (McMullen & Uhl, 2000).

In the first week, the sessions were individual one-on-one sessions to ensure the fundamental principles were thoroughly explained and taught to each participant (Table 2.4, Appendix 1). The following nine weeks involved two group sessions a week prior to paddle training (Table 2.4, Appendix 1).

The prehabilitation programme was divided into three core aspects; flexibility, strength and motor control training, which will be subsequently explained. Detailed descriptions of each exercise, their progressions and technical pointers can be found in Appendix 1.

Flexibility training for kayakers

Flexibility was targeted at three areas; the upper spine, shoulders and hips. Dynamic exercises that encouraged full range of motion as well as dynamic PNF stretches (Sharman *et al*., 2006) were used throughout the intervention programme. Each prescribed exercise for flexibility is listed along with its objectives and references for previous successful use for the defined objectives. This is repeated for motor control and strength in Table 2.3.

Table 2. 2: Intervention programme exercises included for flexibility training.

Displaying the exercises, the exercise objective and the references where these objectives have been successfully met with the associated exercise.

Exercise name	Exercise objectives	References
Sleepers stretch with PNF “hold and relax” technique.	Flexibility: train the flexibility of the external rotators and the posterior shoulder joint capsule.	Kibler, 1998; Burkhart *et al*., 2003; Cools *et al*., 2008; McClure *et al*., 2007; Laudner *et al*., 2008.
Pectorals stretching with PNF “hold and relax” technique.	Flexibility: train the flexibility of all the fibers of the pectoralis major and minor muscles.	Paine & Voight, 2013.
Biceps stretching	Flexibility: train the flexibility of the biceps brachii	Kibler, 1998.
Hamstring stretching	Flexibility: train the hamstrings and hip extensors flexibility.	Decoster *et al*., 2005.

Strength training for the supportive muscles in the shoulders of kayakers

Strengthening exercises of the shoulder girdle targeted serratus anterior, the middle and lower fibres of trapezius and the rotator cuff muscles. Sitting in the same position as when in the boat and using the correct, erect posture was incorporated for sport-specific relevance.

Training the control of movement

Participants were taught to activate and deactivate different muscles during upper body movements.

During the execution of all the prehabilitation exercises (Appendix 1), spinal posture and scapula position were constantly monitored, to achieve a neutral spine and a correctly set scapula (described previously). Ensuring activation and integration of the scapula and spinal stabilising muscle groups were reinforced.

Table 2. 3 Intervention programme exercises included for strength and motor control training.

Displaying the exercises, the exercise objective and the references where these objectives have been sucessfully met with the assocoated exercise.

Exercise name	Exercise objectives	References
Subscapularis activation	*Motor control and strength training* for subscapularis.	Richardson and Jull, 1995; Magarey and Jones, 2003.
Shoulder external rotation in neutral	*Strength training* for shoulder external rotators (infraspinatus, teres minor) and scapula stabilisers (lower fibres of trapezius, serratus anterior).	Escamilla *et al*., 2009; van de Velde *et al*., 2011.
Shoulder external and internal rotation, in 90 ° scaption (humeral elevation 30° anterior to the frontal plane)	*Strength training* for shoulder external (infraspinatus, teres minor, supraspinatus) and internal rotators (subscapulais) as well as scapula stabilisers (lower fibers of trapezius, serratus anterior). *Motor control training for* maintaining a centered humerus in the glenoid cavity during dynamic movements using the above mentioned muscles.	Escamilla *et al*., 2009; Hellwig & Perrin, 1991.
Scapula clock	*Motor control:* Teaching kinesthesia of the scapula.	Kibler, 1998; Burkhart *et al*., 2003; Burmitt, 2006.
Scapula hug	*Strength:* Serratus anterior strengthening *Motor control:* the co ordination of maintaining shoulder depression with active shoulder protraction is practiced.	Burmitt, 2006; van de Velde *et al*., 2011.
Wall press ups	*Motor control:* Scapula kinesthesis is practiced as well as co ordination of the scapula and glenohumeral stabilisers *Strength:* strengthening of the scapula stabilisers.	Laudner *et al*., 2008.
Window washers	*Motor control:* Scapula kinesthesis is practiced as well as co ordination of the scapula and glenohumeral stabilisers *Strength:* strengthening of the scapula and glenohumeral stabilisers.	McMullen, 2000; Burkhart *et al*., 2003.
4 point kneeling	*Strength:* Strengthens shoulder and pelvis stabilisers.	Magarey & Jones, 2003; Escamilla *et al*., 2009.

Front, side and backwards planks	*Strength:* Shoulder pelvis and trunk stabiliser strengthening. *Flexibility*: Increasing anterior shoulder and chest musculature flexibility.	van de Velde *et al*., 2011.
Prone elevation and retraction	*Strength:* Strengthening for scapulae upward rotators, shoulder retractors, external rotators and depressors. *Motor control:* Co ordination training of the above muscle groups. *Flexibility*: Increase thoracic spine extension and shoulder retraction mobility and upper cervical spine flexibility.	Burkhart *et al*., 2003; Ekstrom *et al*., 2003; Burmitt, 2006; Cools *et al*, 2007; Escamilla *et al*., 2009; van de Velde *et al*., 2011.
PNF upper limb diagonal 2 flexion pattern	*Motor control:* Increase the co-ordination of synergistic muscles *Strengthen:* posterior shoulder muscles. *Flexibility*: increase flexibility in anterior shoulder and chest muscles.	Voigt & Thomson, 2000; Escamilla, 2009.
Segmental kinetic chain training for the pull phase of the kayak stroke.	*Motor control:* Corrected movements and co-ordination of the pull phase of the kayak stroke.	Movements based on technical description by Plagenhoef, 1979; Mann & Kearney, 1980, Kendal & Sanders, 1992.

Table 2. 4: Summary table of the intervention programme.

Displaying exercises' aims, objectives and periodisation.

Aims	Periodisation	
	Week 1 (Individualised sessions)	Week 2-10 (Group sessions)
To train scapular movements with sport specific glenohumeral movements.		Pectoralis and biceps stretching. Wall flies Prone elevation and retraction exercises. Resisted ER.
	Scapula clock. Window washers.	Wall flies Prone elevation and retraction exercises. Resisted ER. PNF upper limb diagonals.
	Subscapularis activation. Scapula clock. Window washers.	4-point kneeling, plank and side planks. Wall flies Prone elevation and retraction exercises. Resisted ER. PNF upper limb diagonals.
To train active shoulder rotation bilaterally.	Subscapularis activation. Active shoulder rotation range in supine.	Active shoulder rotation in neutral and 90° scaption. Sleepers stretch (Lauder *et al*., 2008).
To train the execution of the pulling motion of the kayak stroke.		Dynamic and static stretching of the hamstrings. Exercises performed in long sitting.
To train length in the hamstrings muscles.		Movement sequencing including the legs, trunk, shoulder and arm during the kayak motion.

Statistical analysis

The data were analysed using repeat-measures ANOVA factoring for group by time interaction (Hopkins, 2003). Group differences between the change in the mean (pre- vs. post-intervention) were performed according to Hopkins (2003). All data are presented as mean ± SD. Statistical significance is expressed as $p < 0.05$.

Effect sizes were also calculated to determine magnitude-based inferences between the groups (Cohen, 1988). Conservative thresholds and descriptors were used for interpreting the effect sizes were: 0.00 = trivial, 0.01 - 0.10 = small, 0.11 - 0.30 = moderate, 0.31- 0.50 = high, 0.51 - 0.70 = very high, 0.71 - 0.90 = near perfect and 0.91- 1.00 = perfect (Hopkins, 2002).

Results

Anthropometry

No differences in the pre-test anthropometric measurements between groups or mean pre-post-intervention between groups were found (all p-values were above 0.41) (Table 2.5).

Table 2.5: The results for anthropometric tests for control and intervention groups.

Displaying anthropometrical measurements for males and females from pre and post tests. There were no statistical differences.

Anthropometry measurements	Males				Females			
	Control group (n = 5)		Intervention group (n = 6)		Control group (n = 4)		Intervention group (n = 4)	
	PRE Mean ± SD	POST Mean ± SD	PRE Mean ± SD	POST Mean ± SD	PRE Mean ± SD	POST Mean ± SD	PRE Mean ± SD	POST Mean ± SD
Weight (kg)	77.28 ± 11.48	78.23 ± 12.66	80 ± 7.68	79.48 ± 6.30	67.08 ± 11.48	66.56 ± 11.29	62.58 ± 1.23	62.49 ± 1.58
Sum of seven skin folds (mm)	54 ± 11.69	58.76 ± 19.54	77.88 ± 38.48	77.9 ± 27.4	134.45 ± 47.81	125.4 ± 44.26	99.25 ± 19.46	100.58 ± 27.02
Body fat %	14.65 ± 3.34	17.1 ± 5.61	16.25 ± 4.23	16.99 ± 3.26	31.42 ± 7.25	29.98 ± 6.23	26.03 ± 1.86	25.36 ± 3.92

Scapula position

In Figure 2.9, the position of the scapulae are represented for the control (a) and intervention (b) groups. Circular and triangular symbols represent the control and intervention groups respectively. Similar results between pre (solid symbols) and post (outlined symbols) testing will result in the symbols being close or overlapping each other, as seen for the control group (Figure 2.9a). For the intervention group however, the scapulae are closer to the y-axis (representing the spine) and their scapulae are therefore more retracted during the post-test compared to the pre-test.

The measurements used to define the scapula position at rest, as depicted in Figure 2.9 and Table 2.6, included; the distance (cm) of the superior (d*s*) and inferior (d*i*) medial angles from the spine, and the relative height difference (h) between left and right scapulae. At the pre-test, there were no significant differences in these measurements between groups.

There was a significant difference in the change of means between the IG and the CG for the measurement of the distance of the inferior angle of the scapulae from the spine for left (-1.54 ± 1.40 cm vs. -0.22 ± 1.23 cm respectively, p = 0.04, Table 2.6, Figure 2.9) and right (-1.76 ± 1.35 vs. -0.17 ± 0.41 respectively, p = 0.00, Table 2.6, Figure 2.9) shoulder girdles.

The difference in the pre- and post-intervention measurements of the distance measured of the superior angle of the scapula from the spine was also found to change significantly different between the IG and CG for the left (-2.21 ± 1.17 cm vs. -0.43 ± 1.57 cm respectively, p = 0.01, Table 2.6, Figure 2.9) and right (-2.33 ± 1.78 cm vs. -0.73 ±1.08 cm respectively, p = 0.03, Table 2.6, Figure 2.9) scapulae.

In both groups, the right scapula was lower than the left at the pre-test (-0.9 ± 0.5 cm and -0.7 ± 1.2 cm for the CG and IG respectively, Table 2.6, Figure 2.9). After the ten weeks there was no significant difference in change of scapula height between groups (0.2 ± 1.2 cm vs. -0.3 ± 2.3 cm for change in height, for CG and IG respectively, p = 0.95, d = 0.04, Table 2.6, Figure 2.9)

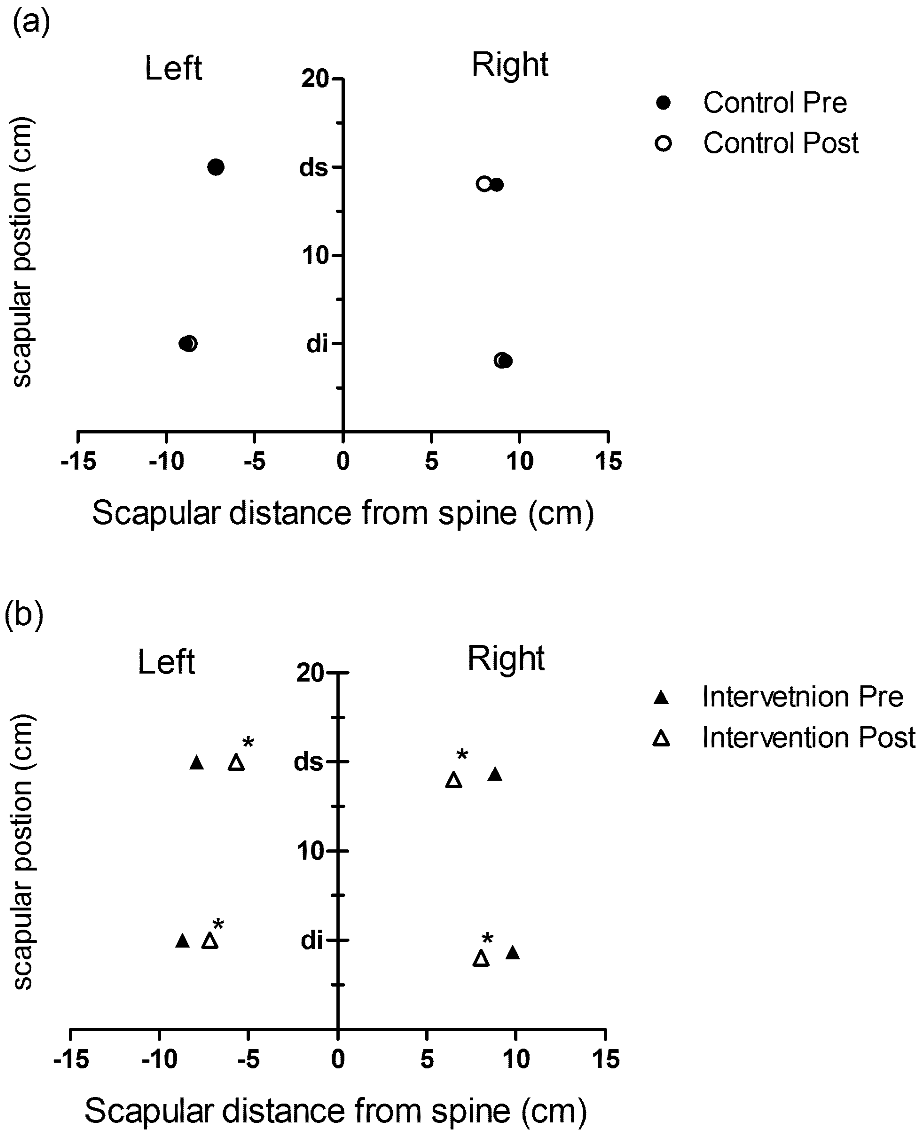

Figure 2. 9: Schematics representing the left and right scapula positions for pre and post testing.

*In each schematic the four higher symbols represent the superior medial boarders of the left and right scapulae and the four lower symbols represent the inferior medial angle of the left and right scapulae. With the left scapula on the left of the y-axis (negative) and the right scapulae on the right of y-axis (positive). Solid symbols represent the pre test measurements and the outlined symbols represent the post test measurements, for (a) control group (circles) and (b) the Intervention group (triangles) * $p < 0.05$ for pre vs. post measurements.*

Table 2.6: The results for scapula position measurements at rest.

Depicts pre- and post-intervention measurements for the control and intervention groups. Values indicate distance from the spine, negative values were used for the left scapula and positive values were used for right scapula. The difference represents the change in scapula position between pre and post measurements.
** p < 0.05 for between group difference in pre vs. post measurements.*

	Position (cm) (Mean ± SD)					
Measure-ments	**Control Group**			**Intervention group**		
	PRE	POST	Difference	PRE	POST	Difference
d*s* left	-7.7 ± 1.3	-7.2 ± 1.0	0.3 ± 1.6	-8.0 ± 1.4	-5.7 ± 0.8*	2.2 ± 1.2
d*i* left	-8.9 ± 1.7	-8.7 ± 1.4	0.2 ± 1.2	-8.7 ± 1.7	-7.2 ± 0.6*	1.5 ± 1.4
d*s* right	8.8 ± 1.1	8.0 ± 0.8	-0.7 ± 1.0	8.8 ± 1.5	6.5 ± 1.1*	-2.3 ± 1.8
d*i* right	9.2 ± 1.4	9.0 ± 1.5	-0.2 ± 0.4	9.8 ± 1.5	8.1 ± 0.1 *	-1.8 ± 1.4
h	-1.2 ± 0.9	-0.9 ± 0.5	0.2 ± 1.2	-0.74 ± 1.2	-1.0 ± 1.6	-0.3 ± 2.3

Sagittal position of the shoulder

In supine, the distance of the posterior acromion from the bed for the CG during the pre-test was 5.67 ± 1.87 cm and 5.63 ± 1.36 cm for the left and right respectively (Figure 2.10). The IG had similar baseline test results, 5.44 ± 1.01 cm and 5.86 ± 0.95 for the left and right respectively (Figure 2.10). The CG's distance increased on both shoulders by 0.16 ± 1.08 cm and 0.46 ± 0.77 cm, on the left and the right shoulders respectively (Figure 2.10). In the IC the acromion distance from the bed decreased by - 0.62 ± 1.82 cm and - 0.67 ± 1.4, on the left and right shoulders respectively Figure 2.10). There was only a difference found on the right shoulder (p = 0.04 and p = 0.27 for right and left respectively) for a inter group comparison for difference in change of means (Figure 2.10).

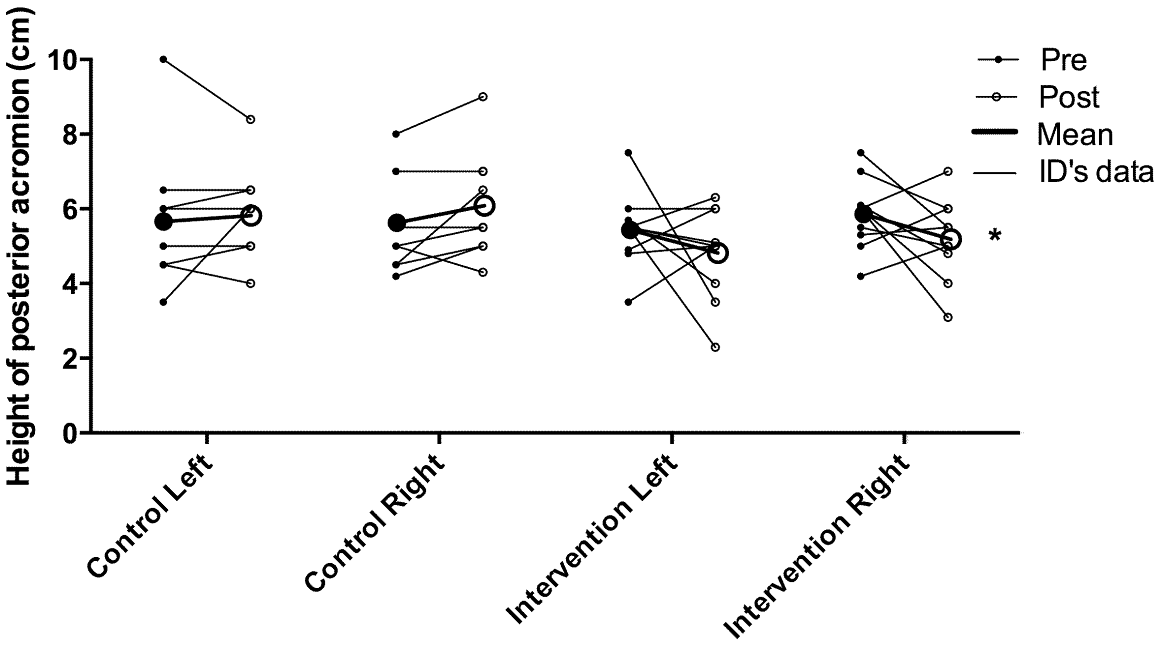

Figure 2.0-10: Results of measurement for the sagittal position of the shoulder.

*Depicts the values of the height of posterior acromion from the bed for the control and intervention groups' right and left shoulders mean values (bold) and the individual results (fine lines) for pre (solid symbol) and post (outlined symbol) measurements. * p < 0.05 for between group difference in means of pre vs. post measurements.*

The difference in the change of means between groups was 0.8 cm (17.3 %) and 1.1 cm (19 %) (left and right respectively), resulting in a moderate effect size difference (d = - 0.79, d = - 1.08).

Active shoulder rotation range of movement

Figures 2.11 and 2.12 show the mean and individual variation of the active shoulder rotation range of movement and how these ranges changed between pre and post testing for the two groups.

There was a significant difference in the change of means for the left shoulder internal rotation range of motion (p = 0.04, Figure 2.11c). The intervention group increased their IR ROM by 8.00 ± 6.32° while the control group lost 2.11 ± 11.54° of IR ROM. On the right, there was no significant difference between groups (p = 0.87, Figure 2.11c) as both groups improved in internal rotation range (4.20 ±10.52° vs. 3.44 ± 9.67° for difference in means for the intervention and control groups respectively).

For external rotation range, both groups decreased similarly on the left (-2.70 ± 5.50° vs. -0.67 ± 11.18°, p = 0.63, for difference in means for the intervention vs. control group) while increasing slightly on the right (4.30 ± 7.17° vs. 1.00 ± 5.24°, p = 0.27, for difference in means for the intervention vs. control group).

Two participants in the control group had a history of a severe injury on their left shoulders. Their internal shoulder rotation range decreased by 19° (Figure 2.11c) on the injured side after the ten weeks of training.

Table 2.7 shows that in both groups, the co-efficient of variation for internal rotation range was nearly twice that of external rotation (CV of 25.99% vs. 11.42% and 22.85% vs. 8.22% for IR vs. ER the left shoulder, control and intervention groups, respectively, and 18.73% vs. 9.03% and 24.98% vs. 9.44% for the right shoulder, control and intervention, respectively).

Table 2. 5: Co-efficient of variance for shoulder rotation ranges.

Displays the internal (IR) and external (ER) shoulder rotation ranges for the left and right shoulders of the control and intervention groups.

Groups	**CV (%)**			
	Left		**Right**	
	IR	ER	IR	ER
Control group	25.99	11.42	18.73	9.03
Intervention group	22.85	8.22	24.98	9.44

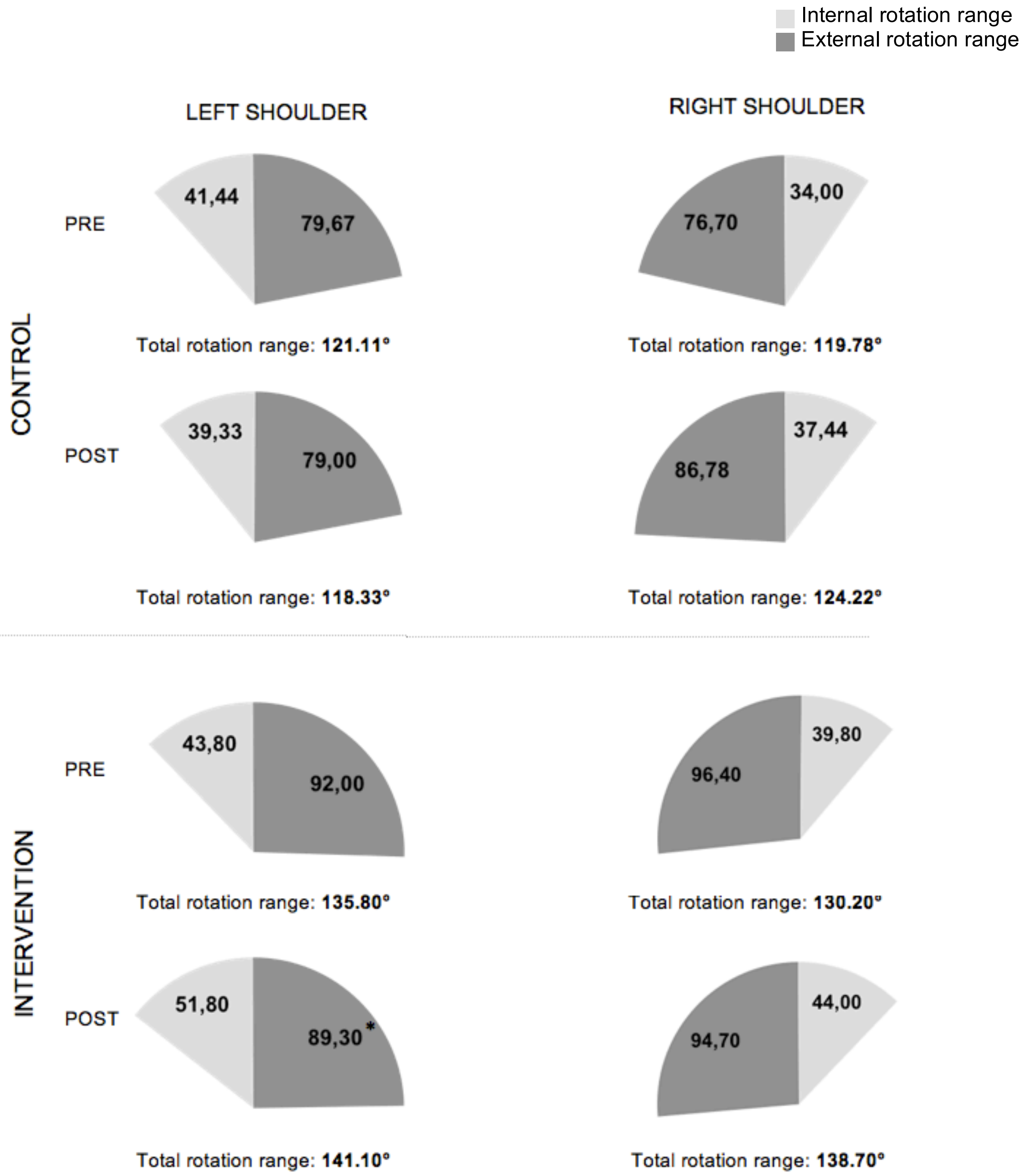

Figure 2. 0-11: Mean active shoulder rotation ranges

*Displaying mean external (dark grey) and mean internal (light grey) rotation ranges as well as the total range of motion values for pre and post-test measurements for control (above) and intervention (below) groups. * $p < 0.05$ for between group difference in means of pre vs. post measurements.*

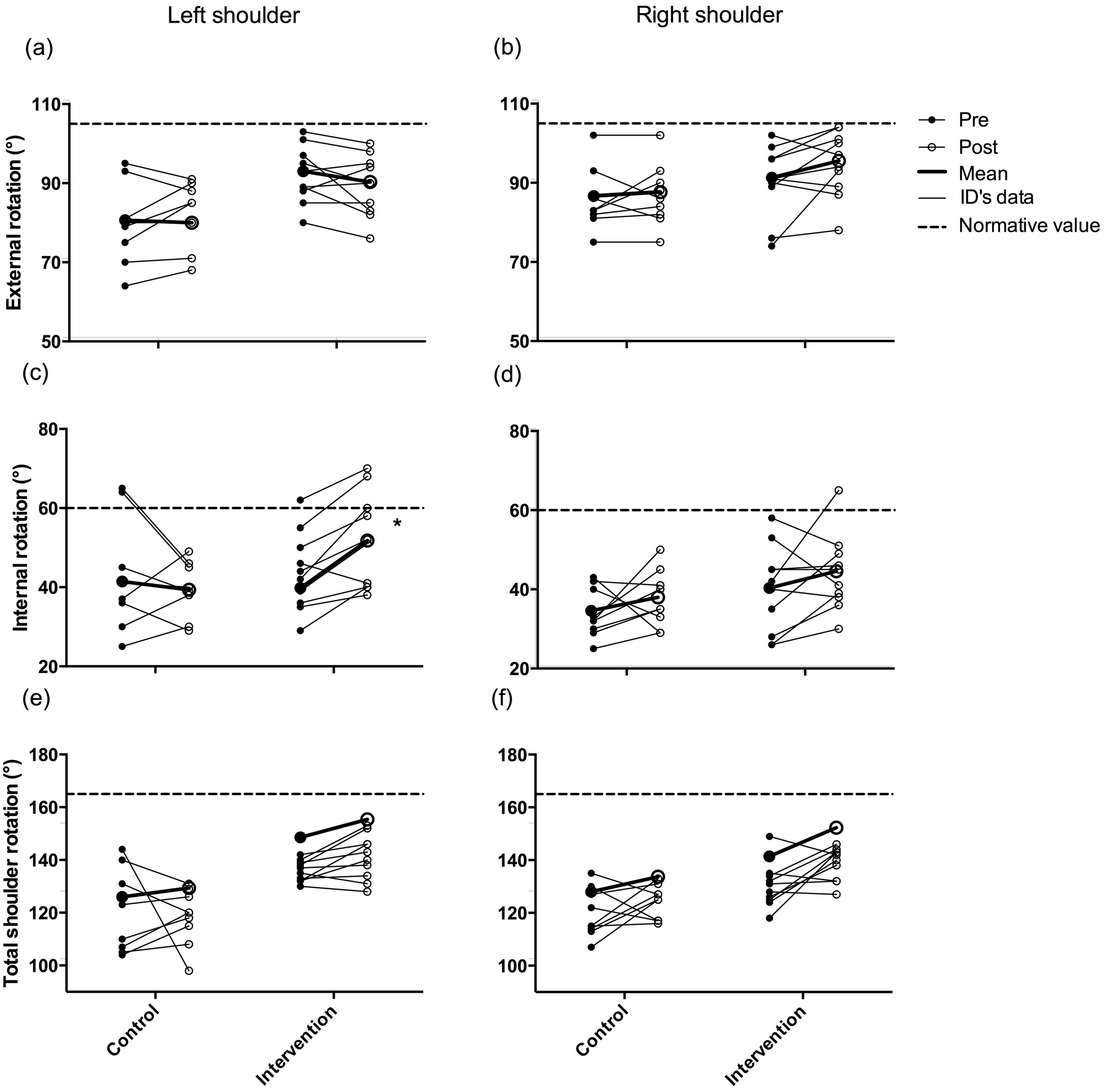

Figure 2. 0-12: Mean and individual active shoulder rotation ranges.

*Displaying mean (bold lines and symbols) and individual (fine lines and symbols) vales for (a) left shoulder external rotation, (b) right shoulder external rotation, (c) left shoulder internal rotation, (d) right shoulder internal rotation, (e) left shoulder total rotation range and (f) right shoulder total rotation range. Including results from the pre (solid symbols) and post (outlined symbols) test shoulder rotation ranges for the control and intervention groups. Also indicating normative values (Kobler et al., 2009) (bold dashed lines). * p < 0.05 for between group difference in means of pre vs. post measurements.*

Scapula kinematics

In the pre-test all ten in the CG and nine in the IG participants had scapula dyskinesis, classified during humeral abduction as either downward rotation of the scapula in the first 30°, scapular elevation or less than 10° of scapula upward rotation at 60° with a non-smooth or stuttering motion through range. Scapula dyskinesis was also classified as a rapid downward rotation and winging of the scapulae (McClure *et al*., 2009).

In the CG there was no change in the presence of scapula dyskinesis between the pre and post-test. In the IG six of the nine participants had normal scapulohumeral kinesis in the post-test. Normal scapula rhythm was defined during humeral abduction as smooth and continual upward rotation of the scapula during shoulder abduction, so that that the upward rotation of the scapula was no less than 0° at 30° and no less than 10° of upward rotation at 60° (Tate *et al*., 2009). This was followed by continuous downward rotation on humeral lowering with no evidence of winging (McClure *et al*., 2009).

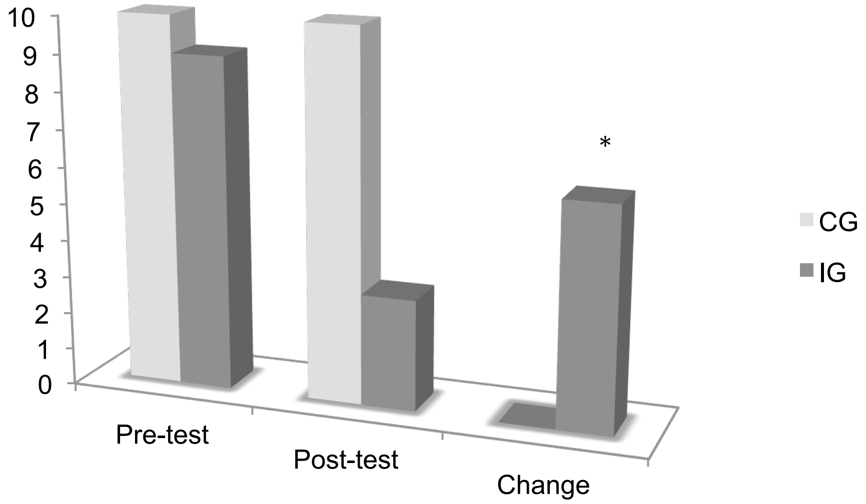

Figure 2. 13: The presence for scapula dyskinesis during bilateral shoulder abduction.

Depicts scapula dyskinesis results for pre and post testing for the control (light grey) and intervention groups (dark grey). * $p < 0.05$ for between group difference in means of pre vs. post results.

Hamstring flexibility

There was a significant difference in means between groups for hamstring flexibility. On the left leg during the SLR test the hip angle increased 15.90 ± 11.34° for the IG and 3.78 ±

7.81° for the CG (p = 0.02, Figure 2.14). On the right side there was also a significant difference in means between groups for pre vs. post-intervention change (18.30 ± 10.00° vs. 5.44 ± 10.06° for IG vs. CG, P = 0.01, Figure 2.14).

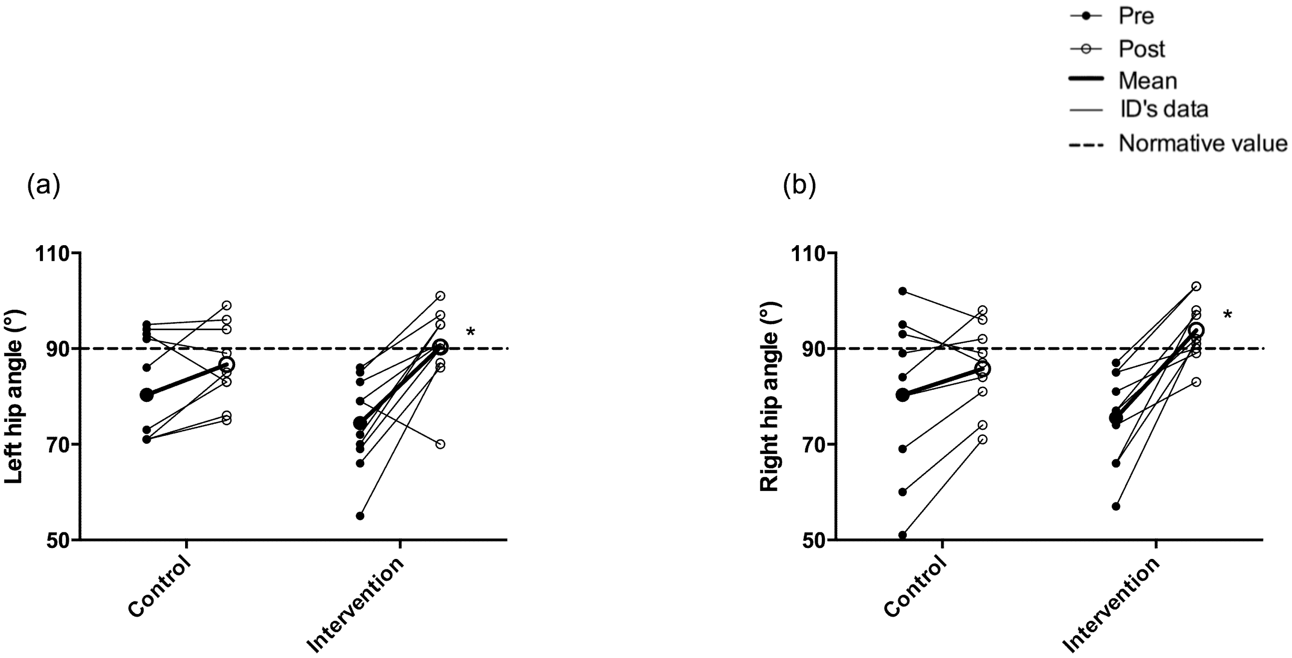

Figure 2. 0-14: Hamstring flexibility indicated by hip flexion angle during the straight leg raise test

*Displaying the pre (solid symbol) and post (outlined symbol) test results for the control and intervention groups for (a) left and (b) right legs. Compared against normative values (bold dashed line) (Witvrouw, 2003), including mean (bold lines and symbols) and individual (fine lines and symbols) values. *p < 0.05 for between group difference in means of pre vs. post measurements.*

Thoracic extension and shoulder flexibility

A difference in the change in means for the intervention versus the control group was found in the combined elevation test (-0.7 ± 3.19 cm vs. 7.7 ± 6.37 cm, CG vs. IG for differences in change in means, p = 0.00, Figure 2.15).

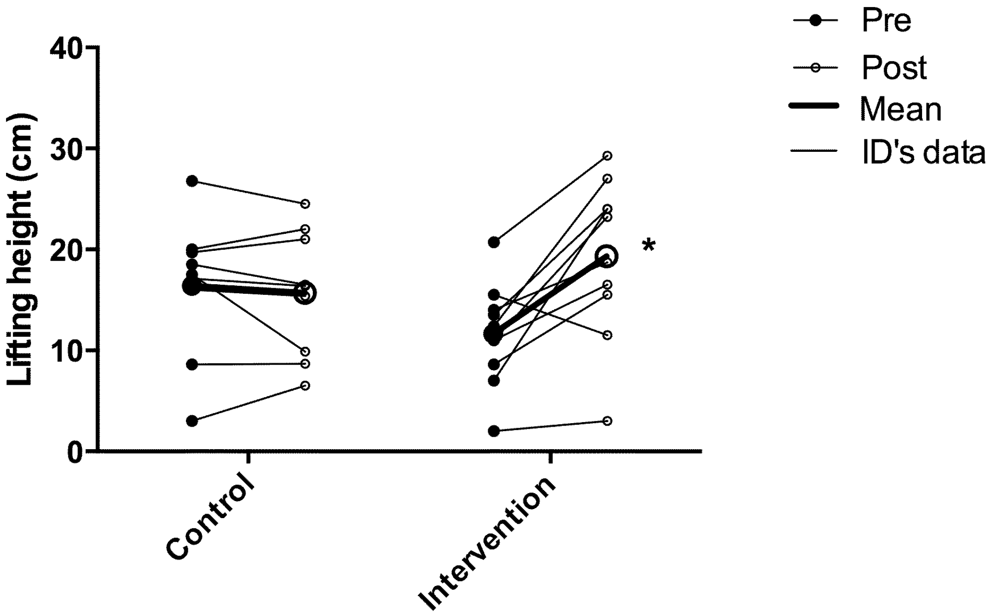

Figure 2. 0-15: Thoracic extension and shoulder flexibility measured using the combined elevation test.

*Displaying results for the pre (solid symbols) and post (outlined symbols) measurements for the control and intervention groups including mean (bold lines and symbols) and individual (fine lines and symbols) values. *p < 0.05 for between group difference in means of pre vs. post measurements.*

Functional pulling strength

A significant improvement in the intervention group's average trolley speed compared the control group, after the 10-week intervention (0.11 ± 0.12 m/s vs. -0.03 ± 0.12 m/s for IG vs. CG difference in change of means, p = 0.02, *d* = 1.39, Figure 2.16a). The maximal trolley speed also improved in the intervention group and had a moderate effect size difference compared to the pre-score (0.07 ± 0.08 m/s vs. -0.04 ± 0.16 m/s for IG vs. CG difference in change of means p=0.08, *d* = 1.03, Figure 2.16b).

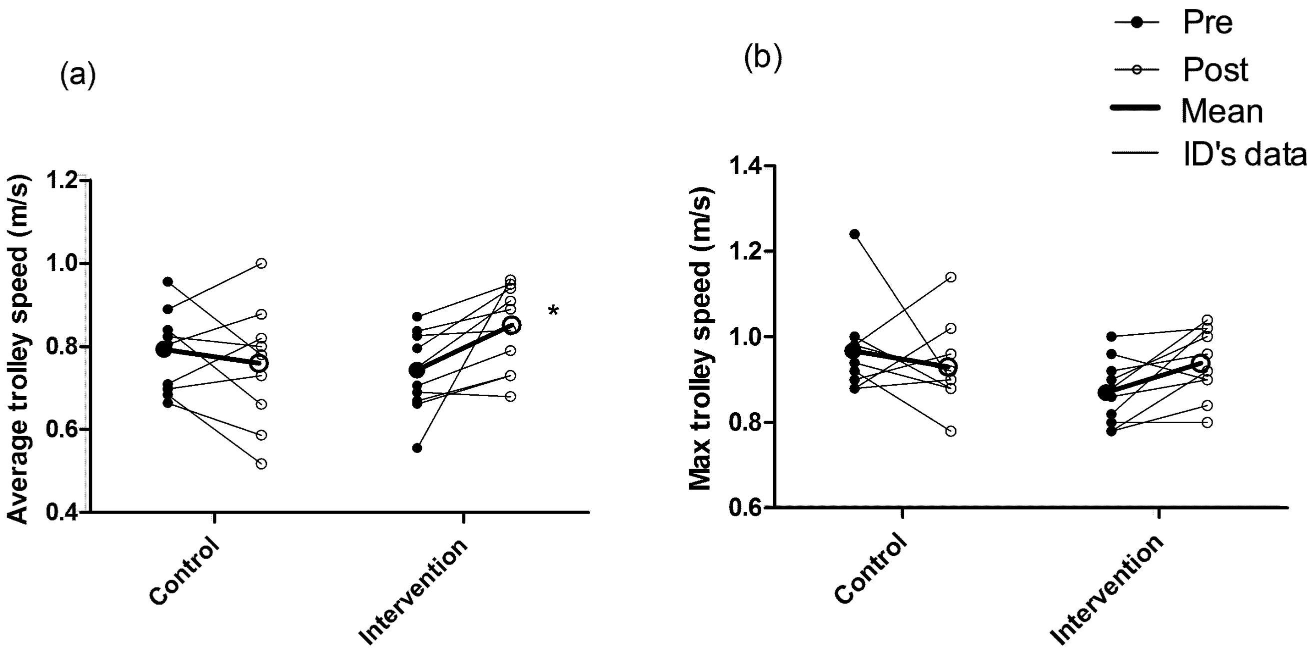

Figure 2. 0-16: Single arm pull ability using the single arm pull device.

*Displaying average (a) and maximum (b) speed of the sliding trolley, including mean (bold lines and symbols) and individual (fine lines and symbols) values.*p < 0.05 for pre vs. post measurements*

Discussion

Overview of the discussion

The differences between how the IG changed compared to the CG during the 10-week intervention programme and their potential implications for shoulder injury risk and optimal shoulder girdle biomechanics and therefore kayak biomechanics are discussed subsequently.

Clinical implications of the changes measured in scapula position and kinematics

Scapula dyskinesia defined as an imbalance in the recruitment and flexibility of muscles attaching onto the scapula is a recognised risk factor for shoulder injury (Kibler, 1998; McClure *et al.*, 2008). Competitive paddlers who want to stay injury free and use their bodies optimally would therefore find it desirable to overcome this risk factor for shoulder injury.

Seven of the 10 participants in the IG changed their scapular movement during bilateral glenohumeral abduction over the 10-week intervention programme. Scapula dyskinesis was not evident in the post-test and they exhibited scapula kinematics similar to those described as normal by Tate *et al.* (2009) and McClure *et al.* (2009) (Figure 2.13).

There was no measured change in scapula kinematics in the CG. All participants in this group had obvious scapula dyskinesis in one or both shoulders during the pre- and post-test (Figure 2.13).

Changes in measurements of the position of the scapula at rest (Figure 2.9, Table 2.6) before and after the 10-week intervention programme showed a significant difference in the intervention compared to the control group for distance of both the superior (0.3 ± 1.6 cm vs. 2.2 ± 1.2 cm and -0.7 ± 1.0 cm vs. -2.3 ± 1.8 cm for CG and IG for left and right respectively) and inferior (0.2 ± 1.2 cm vs. 1.5 ± 1.4 cm and -0.2 ± 0.4 cm vs. -1.8 ± 1.4 cm for CG and IG for left and right respectively) medial borders of the scapula from the spine.

The reduction in the distance of the superior border was greater than the inferior border, thus resulting in upward rotation of the scapula, which is associated with retaining the subacromial space, which has been proposed to reduce the risk of the painful condition of shoulder impingement (De Palmer & Johnson, 2003).

These noted changes in scapula position and movement of the IG is attributed to a number of contributing factors. Education and awareness contribute to improved kinaesthesia, which was a focus in the early stages of the intervention programme (Appendix 1, Table 2.4). A retracted, posteriorly tilted and upwardly rotated scapula position, instructed throughout all the intervention exercises would facilitate greater awareness of the co-ordination of the scapula and glenohumeral movements. It is likely that the exercises targeted at improving the strength and recruitment of scapula stabilisers (lower trapezius and serratus anterior) also contributed to change in position and movement of the scapula measured in the IG (Figures 2.9 & 2.13).

The position of the acromion in supine is a reference to the anterior or posterior tilt and protraction or retraction of the scapula. A greater distance of the acromion from horizontal indicates an anterior tilted, protracted scapula. Both left and right shoulders in the intervention group had reduced acromial height in supine in the post-test compared to the pre-test (- 0.62 ± 1.82 cm and - 0.67 ± 1.4 cm, on the left and right respectively, p = 0.27, p = 0.04, for difference in change of means, for the left and right respectively, Figure 2.10) whereas the control group showed no significant change in distance (0.16 ± 1.08 cm and 0.46 ± 0.77 cm, on the left and the right respectively, for change in means Figure 2.10). It is likely that the stretching of anterior structures (pectoralis major and biceps brachii,

Table 2. 2, Appendix 1), the strengthening exercises for the posterior structures (infraspinatus, supraspinatus, teres minor, lower fibres of trapezius, Table 2. 3, Appendix 1), as well as improved kinaesthesia are responsible for these changes in the intervention group. After ten weeks of paddling training, the shoulder position of the CG group elevated, this change in the opposite direction to the intervention group is undesirable for injury prevention and maintaining optimal scapulohumeral biomechanics (Burkhart *et al*., 2003).

Active shoulder rotation range results

A reduction in glenohumeral flexibility is a well established injury risk factor (Kibler, 1996; Burkhart *et al*., 2003) as the reduced range, specifically internal rotation, is associated with posterior capsule thickening and an anteriorly inferiorly translated humerus in the glenoid fossa (Kibler, 1996 & 2006). These positional and capsular changes de-centre that axis of rotation, and therefore the stress on the soft tissue structures surrounding this ball and socket joint are not evenly distributed (Kibler, 1998).

In the pre vs. post measurement of active shoulder rotation, the left shoulder in the IG was the only range found to increase significantly (41° vs. 39° and 34° vs. 37° for the CG and 43° vs. 51° and 40° vs. 44° for the IG, internal rotation pre vs. post for left and right shoulders respectively, Figure 2.12). There was no change in the external rotation ranges either group (80° vs. 79° and 77° vs. 87° for the CG and 92° vs. 89° and 96° vs. 94° for the IG pre vs. post for left and right shoulders respectively, Figure 2.12). All active shoulder rotation in these paddlers is less than what is considered normal (60° and 105° for IR and ER ranges respectively, Kobler *et al*., 2009).

McKean and Burkett (2009) tested a group of paddlers (males n = 15, females n = 14) and found active shoulder rotation restrictions for both internal rotation (42.9° and 51.5° for males and females respectively) and to a lesser extent for external rotation 87.2° and 88.5° (males and females respectively). The findings of this study therefore agree with previous studies, that paddlers have reduced shoulder rotation range compared to normal population.

There was greater variability of the internal rotation in both groups (CV 19 - 26%, Table 2. 5) compared to external rotation (CV 8 - 11%, Table 2. 5). The larger inter individual variability of internal rotation suggests that there is a complicated scenario that gives rise to this limitation, and that each paddler should be assessed and treated individually.

Although the sleepers stretch and active shoulder range exercises were included in the intervention programme to help and increase internal shoulder rotation, these may not have been sufficiently aggressive (length of time, depth of range, number of repetitions). It is also possible that other contributing factors were not addressed. Both groups continued with normal paddle and strength training, some of these practices could prevent an increase in shoulder rotation range. High tone in the muscles responsible for internal shoulder rotation (latissimus dorsi, subscapularis, sternal fibres of pectoralis major) could reduce the effectiveness of the shoulder training.

Hamstring flexibility results

Hamstring muscle length in normal population is measured as 90° of hip flexion during SLR test (Witvrouw, 2003). Time spent with legs in a flexed position is expected to reduce hamstring flexibility. Paddlers in this study and in McKean and Burkett's (2009) including 29 paddlers presented with reduced hamstring flexibility. Poor hamstring flexibility is associated with a posteriorly tilted pelvis (Kendal *et al*., 1993). The position of the pelvis in the sagittal plane (anterior, neutral or posterior tilt) affects the position of the spine and therefore it s ability to move. Pelvic rotation is required to initiate trunk rotation (Begon *et al*., 2010) and trunk rotation is associated with greater mechanical efficiency while paddling (Begon *et al*., 2010). It is therefore hypothesised that hamstrings with greater flexibility are advantageous for kayakers in order to attain a neutral pelvic tilt and therefore the forward lean, which is a favourable kayaking posture (Brown *et al*., 2001).

There was a significant time by group interaction in hamstring length (P = 0.01, Figure 2.14). Supervised hamstring stretching and long-sitting activities are likely to have caused the improvement in the IG's hamstrings flexibility (74 ± 10° vs. 90 ± 8°, p = 0.01 and 76 ± 10° vs. 94 ± 6°, p = 0.01 for left and right respectively pre vs. post) which is regarded as a positive effect.

Thoracic spine extension ability results

Thoracic spine extension is important for the capacity of the scapula to be able to tilt posteriorly in order to maintain the acromiohumeral interval (Kebaetse *et al*., 1999; Finley & Lee, 2003) and therefore important for correct shoulder girdle biomechanics and injury prevention. A straight thoracic spine, as apposed to a flexed or rounded one when sitting, shifts the centre of gravity forwards. The portion of the kayak stroke in front of the hip experiences less drag than behind the hip and is therefore more efficient (Mann & Kearney, 1980). Strategies that encourage forward displacement are therefore more advantageous compared to those that train a backward displacement of the body.

The ability to attain increased thoracic extension with full shoulder flexion improved significantly more in the IG compared to the CG (8.4 cm for difference in the change in means, p = 0.00, Figure 2.15). This significant improvement in the IG is likely due to the numerous extension-based exercises performed in prone and against the wall during the intervention (Table 2.3, Appendix 1).

Co-ordination training of stroke technique

Begon *et al*. (2010) found that the work done by sprint kayakers was reduced by 4% and their performance was improved by 6% with the inclusion of leg movements and pelvic rotation. They suggest the use of the legs in a pedalling motion increases paddling efficacy and that specific motor control tasks should be practiced by paddlers to improve kayaking performance. The intervention therefore included segmental training of the kayak stroke where co-ordinatino rather than strength was the focus (Appendix 1).

The IG, who practiced segmental control of the whole kinetic chain during the pull phase, improved average speed of the trolley propulsion compared to the control group (0.11 ± 0.12 m/s vs. -0.03 ± 0.12 m/s for IG vs. CG difference in change of means, p = 0.02, *d* = 1.39, Figure 2.16a). The mechanisms responsible for the significant increase in power, would be better explained by including objective kinematics.

Brown *et al*. (2010) describe internationally competitive paddlers to use more leg drive and trunk rotation, and to have greater forward reach than national and club level paddlers. Further assessment of the co-ordination and biomechanics of the movement would shed better light on the mechanism by which trolley speed changed differently in the two groups and if this was associated with different movements.

It is recognised that the inclusion of the inflatable disc on this device has not gone through a validation study. Future studies are suggested to include this in seated positions and compare it to sitting on a hard seat in a boat on water. Only once this relationship has been established will the true value of this accessory for land training and testing be known.

Acknowledgement of other influencing factors beyond the scope of this study

The tipping point from a healthy state to one of pain and breakdown is complex and multifactorial and therefore can be difficult to judge. In this study therefore, some of the established mechanisms to injury predisposition have been measured and addressed through an intervention in a group of healthy kayakers. The benefit of overcoming intrinsic risk factors to injury would be negated if extrinsic factors are not managed. Therefore, coaches, trainers and athletes are encouraged to also be mindful of other factors that could contribute to advancing towards the tipping point of injury. Some of these include using correct technique and volume of resistance training (Kobler *et al*., 2010), symmetrical boat biomechanics and not to paddling in one direction in strong side winds.

Conclusion

A supervised prehabilitation programme, following a kinetic chain approach, was successful in adjusting paddlers' scapula position at rest (greater abduction and upward rotation) and kinematics (normal scapula kinematics) and increasing their thoracic spine extension ability. These features have been previously described to cooperate as factors that decrease the risk of repetitive strain injuries in the shoulder.

The intervention group that received, among other training, specific co-ordination practice of the pull action in paddling resulted in improved ability of this task, supporting the suggestion that co-ordination practice; not just strengthening should be included in kayaking performance training.

The individual variation seen in the measured variables in this population of healthy paddlers, suggests that there is uniqueness in each paddler and specific assessment and training is suggested for optimising physique and minimising characteristics that could contribute to injury predisposition or vulnerability.

Chapter 3: Analysis of boat and paddle kinetics and kinematics during on-water paddling of sprint and marathon paddlers

Introduction

Overview of kayaking biomechanics

In kayaking, the paddler and boat are propelled across the water by alternately submerging each paddle blade in the water and pulling it with more force than the combination of aero- and hydrodynamic drag (Plagenhoef, 1979; Mann and Kearny, 1980; Aitken & Neal, 1992; Timofeev *et al*. 1996; Sperlich & Baker, 2002; Begon *et al*., 2009; Michael *et al*. 2009; Rottenbacher *et al*., 2011; Brown *et al*., 2011). The contact between the paddler and the kayak seat and footrest also contributes to the forward movement of the system (Mann and Kearny, 1980; Begon *et al*., 2009; Michael *et al*. 2009) while gravitational pull and buoyancy affect the vertical position of the kayak (Mann and Kearny, 1980; Begon *et al*., 2009; Michael *et al*. 2009). The magnitude, direction and timing of the previously mentioned forces, relative to the direction of the kayak, play a role in the resultant movement of the boat (Begon *et al*., 2009). In order to improve kayaking performance, kayakers needs to maximise their mean velocity, either by increasing acceleration in the direction of the kayak's movement or by decreasing the deceleration of the kayak.

The force applied by the paddle to the water fluctuates throughout the pull phase of the paddle stroke (Plagenhoef, 1979; Mann and Kearny, 1980; Michael *et al*., 2009). These changes in paddle force are the primary drivers of the boat's acceleration during a stroke (Plagenhoef, 1979; Mann and Kearny, 1980; Michael *et al*., 2009). Profiles of paddle force per stoke have previously been documented in the literature (Aitken & Neal, 1992; Timofeev *et al*., 1996; Sperlich & Baker, 2002; Rottenbacher *et al*., 2011; Brown *et al*., 2011) and efficiency calculations have been used to optimise paddle shape (Summer *et al*., 2003) and size (Sprigings *et al*., 2006). Paddle force has also been compared with stroke rate and boat acceleration to optimise racing strategies (Brown *et al*., 2011).

The unilateral application of force not only results in forward movement of the boat but also in three-dimensional accessory deviations described as pitch, rolls and yaw (Begon *et al*., 2009; Michael *et al*. 2009, described subsequently) of the boat. These three dimensional kinematics have been described for rowing and have been found to be associated with performance and efficiency outcomes (Baudouin & Hawkins, 2002).

On-water kayaking kinematics has yet to be described in literature. A kayak ergometer with a fixed seat prevents measurement of the three dimensional kinematics of the kayak, as well as the paddle, footrest and seat forces. McKean and Burkett (2009) previously acknowledged this limitation where measures of strength were not associated with kayak ergometer performance. It is therefore important to conduct specific and accurate performance testing on the water, where instability and efficiencies can be considered as affecting overall performance.

Jackson (1995) describes the increase in frictional and wave drag associated with an increase in the wetted surface area of the hull. Additional energy is required from the paddle to overcome the drag caused by the increased wetted hull surface (Pendergast, 2005). It was therefore hypothesised that minimising the three dimensional kinematics of the boat would increase the boat's efficiency through the water (Mann & Kearny, 1980; Jackson, 1995; Begon *et al*., 2010; Brown *et al*., 2010).

The performance of the boat is the result of the acceleration and deceleration produced by the pull-phase and the water resistance, respectively. In order to assess the balance between these factors and how they change over distance, this study investigated paddle torque, forward acceleration, pitch, roll and yaw during water kayak performance and how they each changed over a 180 meter time trial and its hypothesised optimal presentation is described below.

Three-dimensional properties of paddle torque

The paddler's force application on the water is three-dimensional with components in the axis of movement, laterally and vertically (Michael, 2009; Brown, 2009). As the paddle position changes and moves through the water, the direction of the resultant force changes. The consequence of the resultant force is a change to boat kinematics. Therefore the differences in the direction and magnitude of the paddle force through the water cause direction and magnitude reactions of the boat's kinematics in all directions. It is expected that greater paddle force will result in greater forward acceleration of the boat per stroke and that large paddle forces applied at initial water contact (catch) will cause vertical disturbance in the position of the boat.

Boat forward acceleration during a paddle stroke

Fluctuations occur in the boat's velocity with each stroke due to the alternating paddle force (Plagenhoef, 1979; Mann and Kearny, 1980; Michael *et al*., 2009). With the primary performance outcome in kayaking being the average velocity of the boat, large fluctuations in velocity are considered inefficient use of energy (Mann and Kearny, 1980). The properties of hydrodynamics suggest that the drag experienced by the boat can be approximated as a squared relationship with velocity (Horner, 1965). The true relationship is highly complex and can only be calculated with the aid of advanced computer simulations. It is fair to say that the energy used to increase velocity is greater than the energy saved by an equivalent decrease in velocity, thus making fluctuations an inefficient use of energy to obtain maximum average velocity (Mann & Kearny, 1980). It is under speculation whether large accelerations, being energy-costly, are practically detrimental to performance.

Boat 'see-saw' oscillations: pitch

Pitch is defined as the angle of the boat around a horizontal axis across the width of the boat (0°). Raising the bow (nose of the boat) and dipping the stern increases the angle (positive) and *vice versa.* The weight of the athlete and boat (Jackson, 1995), the position of the athlete's seat and the shape of the hull contribute to the pitch of the boat in the water. A heavy paddler, sitting far back, will sit deeper in the water with the nose of the boat in a lifted position.

Intra-stroke changes in pitch are also expected due to the changes of the paddle position and fluctuations in velocity and acceleration. From the moment the paddle enters the water and the pull-phase is initiated, the initial strong downward component of the paddle force is hypothesised to produce a drop in the nose of the boat, such that the pitch decreases. Similarly, as the paddle exits the water, the nose is hypothesised to lift up, causing pitch to increase.

The effect of pitch on efficiency is unclear. We hypothesise that the greatest inefficiency may occur when the nose drops too far into the water, since this increases both the wetted surface area and drag forces. However, the magnitude of the pitch change over the course of the paddle stroke may not influence performance significantly unless the nose drops too far into the water.

Boat side dips: roll

Boat roll defined as the side-to-side (lateral) dipping of the boat, and is caused by asymmetrical force application and body kinematics of the paddler during the unilateral paddle stroke. It is measured as the angle of the boat, around the horizontal axis along the length of the boat (left and right dips are positive and negative respectively).

Mann and Kearny (1980) explain that at the beginning of the stroke, an upward reactive thrust is experienced at the wrist and elbow on the pull side due to the initial water contact. They describe that in order to maintain a grip on the water and not to lose efficiency through paddle slip, the kayakers must shift their weight towards the pulling side to counteract this upward thrust.

Towards the end of the stoke, the vertical force is reversed and the paddlers are now is advised to shift their centre of mass away from the pulling side. If the paddlers have the necessary skill and strength to execute these changes in their centre of mass, these optimal changes would result in the boat rolling either towards the pull side at the beginning of the stroke and away from the pull side at the end of the stroke or *vice-versa*.

Measurement of intra-stroke roll of a kayak has not yet been described in the literature and is expected to be varied as many inter-related factors contribute to the roll of the boat, rendering it a complex task.

Technical differences between paddlers are expected to cause differing interactions with the boat between paddlers. These varying technical attributes include acceleration of body segments, including amount of trunk rotation, levelness of trunk rotation (shoulder dipping or hip hitching), amount of leg drive and body position. Further, strength of pelvic and torso stabilisers, proprioception, static and dynamic weight distribution, width of the stroke and neruomuscluar strategies are hypothesised to be inter-related during maximal paddling and are expected to affect the lateral position of the boat on an unstable surface.

Boat transverse 'snaking' movements: yaw

Yaw is defined as the snaking movement of the boat, and is influenced by the pulling of the water on alternate sides of the boat and by the position of the rudder. It is measured as the angle of deviation around the vertical axis.

In canoeing (as opposed to kayaking), the athlete kneels in the canoe and only paddles on one side of the boat. In order to direct the boat in a straight line, a ‘J’ shaped stroke is used. The combination of the narrow beginning and the wide posterior portion of the stroke keep the nose of the boat straight. Therefore the pathway of the paddle through the water in kayaking is likely to influence the intra-stoke deviations of the boat’s yaw. Previous observations between groups of paddlers report international level sprint paddlers to have wider strokes than national and club level paddlers (Brown *et al*., 2011). It is likely that the stroke width of international level sprint kayakers will be different to marathon paddlers and therefore these two groups could have differing deviations in the yaw of the stroke with each stroke.

Study aims and hypotheses

Although three-dimensional kinematics have been mentioned in the kayaking literature (Mann & Kearny, 1980; Begon *et al*., 2010; Michael *et al*. 2009), currently no intra-stroke data describes these variables during flat-water kayaking for sprint or marathon kayakers. Therefore, the purpose of this study is to describe and provide statistical and notational analysis of the three-dimensional boat kinematics of a group of elite flat-water kayakers relative to forward acceleration and paddle torque. The study specifically investigated the kinematic factors known to influence efficiency, with specific hypotheses outlined previously for each of acceleration, pitch, roll and yaw.

In summary, the hypotheses of this study are:

1. The nose of the boat will dip at the beginning of the water phase and lift again during the air phase.
2. The boat will dip towards the stroke side during the water phase and be level during the air phase.
3. The nose of the boat will deviate to the opposite side to the stroke side at the beginning of the water phase and return again during the opposite water phase.

4. Large amplitude intra-stroke fluctuations of the pitch, roll and yaw of the boat will be negatively associated with the forward acceleration of the boat.
5. The paddle torque and forward acceleration of the boat will be less at the end compared to the beginning of the time trial, for all groups.

Methods

Twenty-three paddlers performed maximal time trials on the same 180 meter stretch of water, in similar environmental conditions. Four of the paddlers were international level male sprint kayakers, 11 were male marathon paddlers (6 international level and 5 club level), and 8 were female marathon paddlers (4 international level and 4 club level). No female sprint paddlers were available to participate in this study.

The marathon paddlers who trained on the water for 10 sessions a week were from the same training squad. They frequently performed high intensity intervals and repeat sprints as a part of their on-water training and therefore were familiar with paddling for 180 meters maximally.

Ethical approval was obtained for this study from the Human Research Ethics Committee of the University of Cape Town.

The environmental conditions were recorded to ensure uniformity in conditions. The tail-wind speed was always less than 3m/s, air temperature was between 15 and 21 °C, humidity was between 50 and 60% and the depth of the water did not change.

Participants were permitted to use a boat that they were familiar with, to ensure natural paddling technique was measured. The marathon paddlers tended to use wider and thus more stable boats, whereas the sprint kayakers used narrower, less laterally stable boats. Fourteen of the marathon paddlers used a bucket seat, five used a flat seat and all the sprint paddlers used a flat seat.

Anthropometry measurement and procedures

Each paddler’s body weight was recorded in the same week as the on-water testing, using a calibrated scale (Seca, model 708, Germany).

Procedure for measurement of paddle torque

Instrumented paddles with a strain gauge were fitted onto the end of each paddle shaft, positioned 15 mm from the end of the shaft using specialised strain gauge cement epoxy. They were further water proofed with silicone. The wires were wrapped onto the paddle shaft and connected to the data-logger in the boat, which was positioned between the paddler's legs. The standard error of measurement for the strain gauges was 0.02 and 0.04 for right and left respectively. Two different paddles were used so that each group (the sprint paddlers and marathon paddlers) used a paddle they were familiar with to reduce changes to paddle technique. The strain gauges were calibrated using known weights (Appendix 2). Data was recorded at 200 Hz. The generated paddle force is reported as units of torque (Nm). The strain gauges attached to the paddles were of negligible weight and size. Tape was placed over the strain gauges to ensure a smooth paddle shaft surface.

Guidelines for on-water paddle instrumentation, stipulated by Stothart *et al*. (1986) and Aitken and Neal (1992), recommend that the system is waterproof, lightweight, portable, stable in changing environments and able to maintain paddle dimensions so there is no alteration in kayaking technique. It also needs to collect data reliably at a high frequency for up to 5 minutes with the ability to collect more than one kayaker's paddle force data simultaneously. In this study only one paddler's paddle force data was collected at a time, although the data-logger had ports for a maximum of four paddlers. Our system met all of the above listed criteria.

Procedure for measurement of the kinematics of the boat

The accelerometer and gyroscope unit (Minimax B4, Catapult, Australia), measured the forward acceleration, pitch, roll and yaw at 1000 Hz. Each of these was measured and reported for left and right stroke cycles at different time points within the time trials. The data obtained for the accelerometer was not GPS-based. The use of a GPS to determine boat speed has been found to be inaccurate between morning and afternoon recordings, likely due to the change in location of satellites (Janssen & Sachlikidis, 2010). The GPS device was attached to the back deck of the boat in a standardised, horizontally level position along the longitudinal axis of the boat.

A level one model of stroke analysis was performed, following the guidelines by McDonnell *et al.* (2012). Each stroke on the right and left was divided into two phases, water or pull phase and an aerial or air phase. A full stroke cycle (100%) was identified by the forward acceleration, such that the beginning of positive acceleration marked the beginning and end of a stroke (Figure 3.1a) (Michael *et al*., 2009). Each stroke cycle includes both positive (pull phase) and negative (air phase) acceleration, caused by the force applied by the submerged paddle and the drag forces once the paddle is exited from the water, respectively. The pull phase of the stroke, within the stroke cycle, includes only the positive acceleration. The data was temporally normalised, so that each stroke cycle had 100 data units. Results from five strokes were averaged to represent each portion of the time trial (start and end).

The first five strokes on the left and right (second to eleventh strokes) were averaged to represent the start of the time trial (Figure 3.1b). Five strokes from the middle of the time trial were averaged to reflect boat kinematics at high speeds in the relative absence of fatigue-effects. The last five strokes on the left and right (eleventh last to second last stroke) were averaged to represent the end of the time trial. The average of every stroke from the time trial was calculated and reported on as the mean for the right and left strokes. The initial and the last strokes were omitted due to high variance.

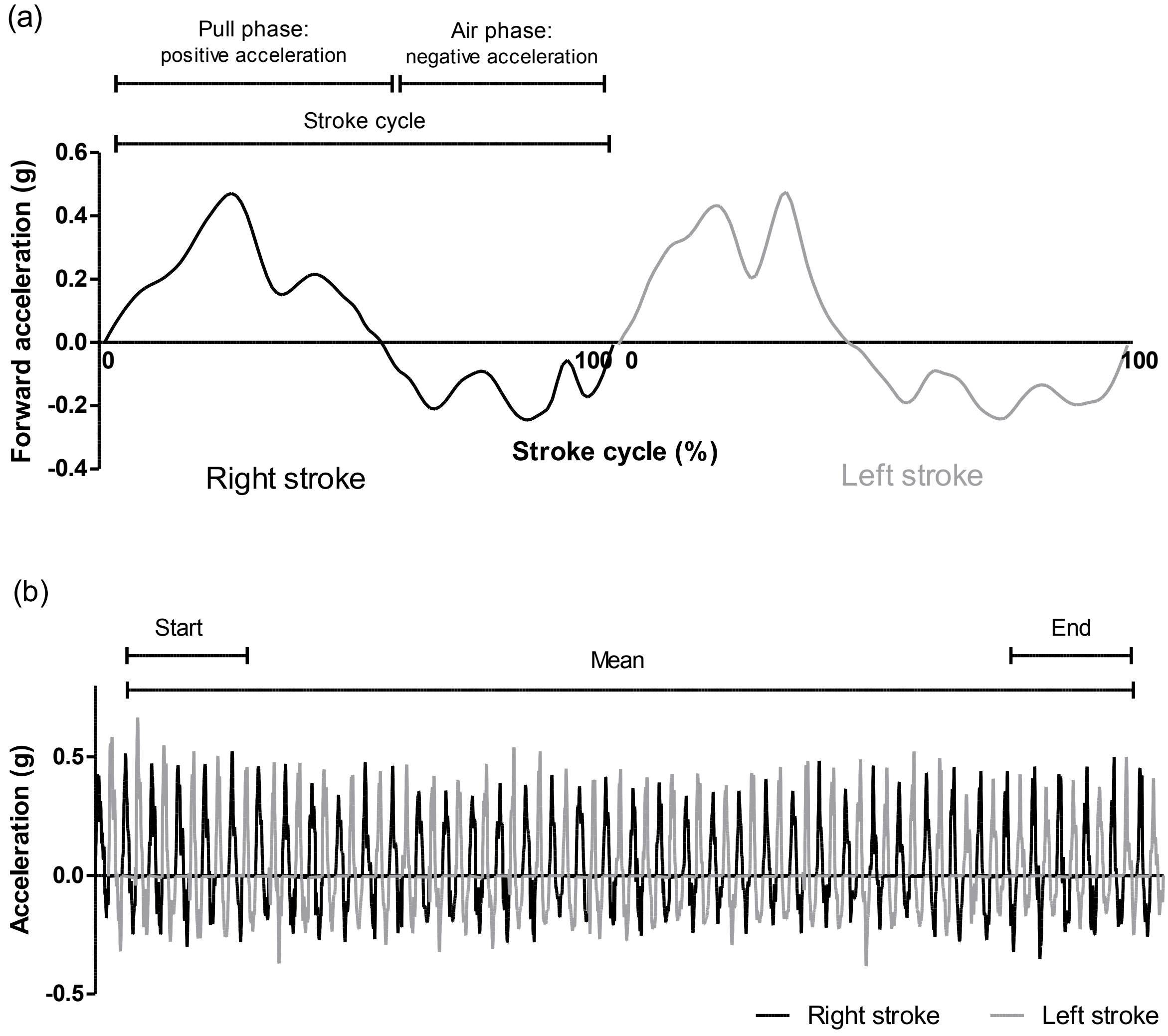

Figure 3. 1: Typical forward acceleration during a maximal on-water time trial.

Displaying (a) two consecutive strokes and (b) a full time trial. Right strokes are shown in black and left strokes are in grey

Statistical analysis

The data was analysed using Statistica Version 11 (StatSoft Inc. Tulsa, OK, USA). All data is represented as mean ± standard deviation (SD). Significance for all statistical analysis was determined by a p value of less than 0.05.

The groups of paddlers were categorised as male sprint paddlers, male marathon paddlers and female marathon paddlers. No female sprint paddlers were available for this study. Each variable was reported for the mean, start, middle and end values where the start comprises of the first five strokes, the middle; the middle five strokes and the end; the last five strokes of the time trial. The mean left and right strokes were also reported.

Each variable was analysed for distribution using the Shapiro Wilk test for normality. General linear models were performed for investigation of the time course changes (mid vs. end) and the side differences (left vs. right) for all variables between the three groups. A Tukeys honestly significant difference (HSD) test was performed to determine within group effects of the time course changes (mid vs. end) and the side differences (left vs. right). For pitch and yaw variables ranges of motion were used for statistical analysis.

Correlation coefficients within each sub-group were then calculated using a Pearson's correlation, to investigate relationships between variables. The used descriptors for the magnitude of correlations were: 0.00 = trivial, 0.01 - 0.10 = small, 0.11 - 0.30 = moderate, 0.31- 0.50 = high, 0.51 - 0.70 = very high, 0.71 - 0.90 = near perfect and 0.91- 1.00 = perfect (Hopkins, 2002).

Results

Data from the water testing is presented below. Time-related data for left and right strokes are shown, followed by individual variability of the mean data for the time trial. This is repeated for each variable with figure legends remaining consistent throughout. Green is used for the sprinters, blue for the male marathon paddlers and red for the female marathon paddlers. Darker variations depict the right stroke and lighter variations are used for the left stroke. The solid lines show the data for the middle five strokes (mid) of the time trial, while the dashed lines represent the data from the first five strokes of the time trial (start), and the dotted lines represent the last five strokes of the time trial (end). Statistical significance is indicated on the figures and tables where appropriate. All variables within the sub-groups were normally distributed.

The average stroke rate during the time trials was greatest for the sprint paddlers (131.21 ± 2.67 spm), followed by the male marathon (116.90 ± 8.20 spm) and the female marathon paddlers (102.39 ± 10.45 spm).

Anthropometry

The mean body weight was 81.25 ± 5.32 kg, 78.77 ± 9.93 kg and 64.85 ± 7.93 kg for the male sprint, male marathon and female marathon paddlers respectively.

Paddle torque

Figure 3.2 shows paddle torque during the water phase of the stroke during different phases of the time trial for right (in a darker colour) and then left strokes (in a lighter colour) for the three sub-groups (3.2 a: male sprinters, b: male marathon paddlers and c: female marathon paddlers). All participants were right hand dominant. One sprint and two male marathon paddler paddle torque data sets were lost due to technical faults during data capturing and processing.

A significant time by group interaction effect was evident for the change in paddle torque over time ($p < 0.01$) for middle vs. end, for both groups of male paddlers (49.88 ± 5.16 Nm vs. 42.70 ± 5.09 Nm and 56.60 ± 9.75 Nm vs. 52.81 ± 8.91 Nm for middle vs. end for sprint and male marathon paddlers respectively, Figure 3.2, Table 3.1). In the group of female marathon paddlers, there was no significant time-related change between the middle of the TT and the end of the TT (35.76 ± 3.61 Nm vs. 33.02 ± 4.09 Nm for middle vs. end, Figure 3.2, Table 3.1).

A significant right vs. left effect was present in all three subgroups (male sprint paddlers, male marathon paddlers and female marathon paddlers), with the right paddle stroke producing significantly more torque through the water compared to the left (52. 59 ± 5.00 Nm vs. 45.55 ± 2.28 Nm, 58.79 ± 6.25 Nm vs. 53.87 ± 9.04 Nm and 38.42 ± 3.69 Nm vs. 33.67 ± 4.17 Nm for right vs. left for sprint, male marathon and female marathon paddlers respectively, Figure 3.3, Table 3.1). Significant side differences were also present in the max paddle torque applied (77.35 ± 4.94 Nm vs. 67.07 ± 4.79 Nm, 83.39 ± 13.38 Nm vs. 75.47 ± 13.38 Nm and 54.33 ± 4.20 Nm vs. 47.14 ± 3.32 Nm for right vs. left for sprint, male marathon and female marathon paddlers respectively Table 3.1).

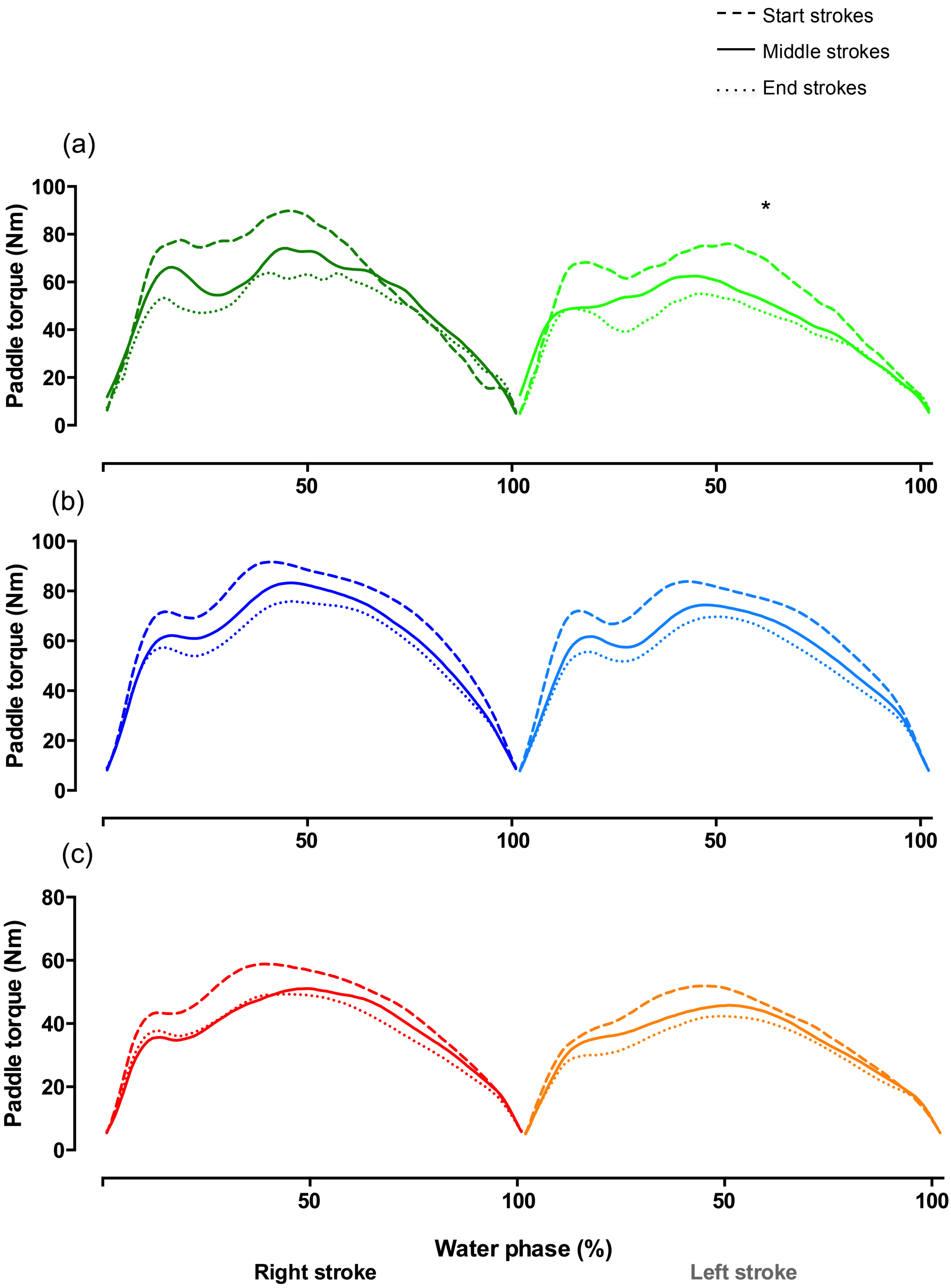

Figure 3. 2: Paddle torque for right and left strokes during different phases of the time trial for the three sub-groups.

*Depicts the first five strokes (dashed lines), middle five strokes (solid lines) and last five strokes (dotted lines) for a) sprint paddlers (top panel in greens), b) male marathon paddlers (middle panel in blues) and c) female marathon paddlers (bottom panel in red and orange). The darker colour represents the right strokes and the lighter colours represent the left strokes. * p < 0.05 for within group time differences (middle vs. end).*

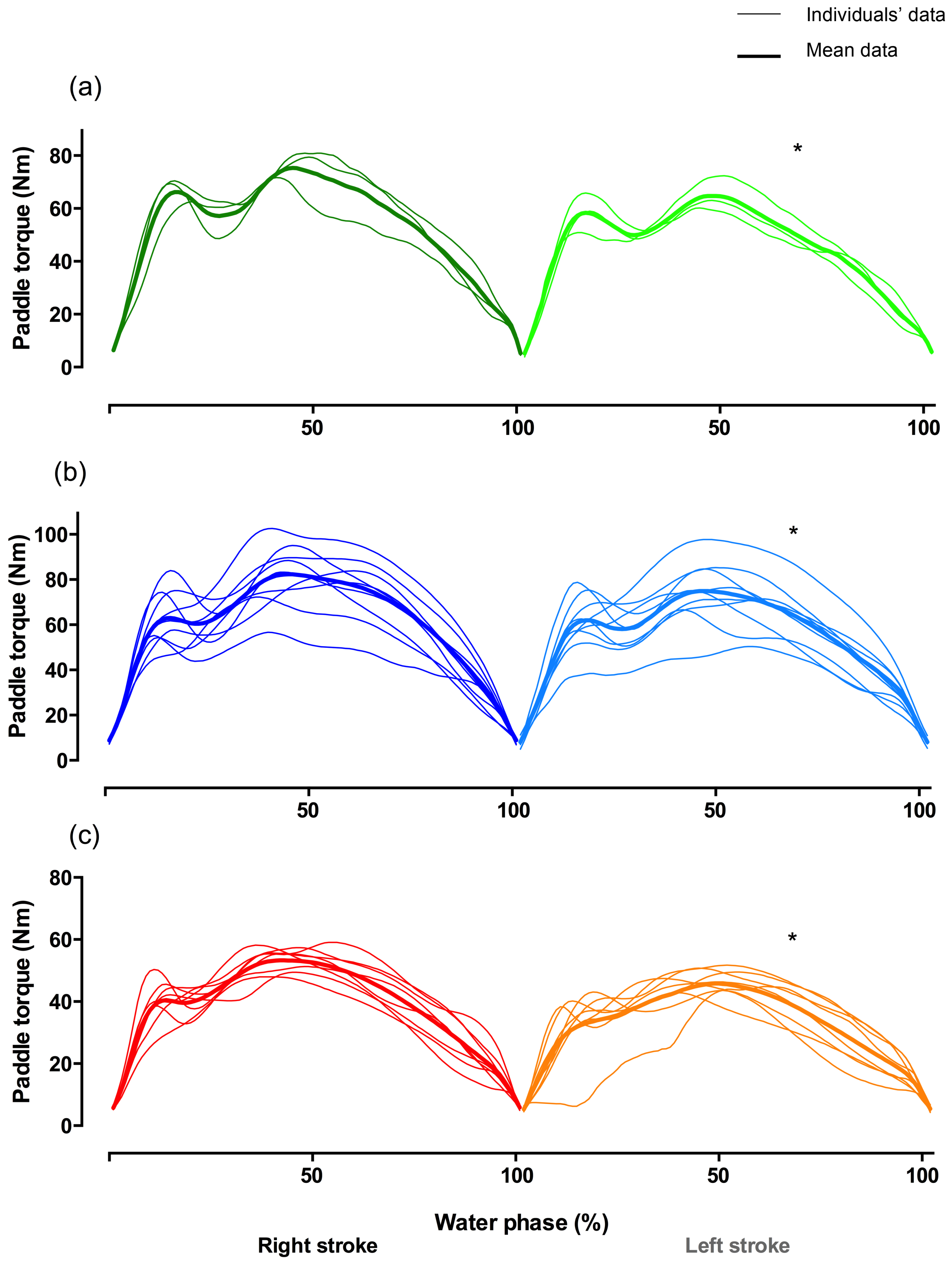

Figure 3. 3: The individual data for paddle torque for the right and left strokes for the three sub-groups. *Depicts the mean (bold line), and individual's data (thin lines) for a) sprint paddlers (top panel in greens), b) male marathon paddlers (middle panel in blues) and c) female marathon paddlers (bottom panel in red and orange). The darker colour represents the right strokes and the lighter colours represent the left strokes. * $p < 0.05$ for within group side differences (right vs. left).*

The shape of the paddle torque data represented in Figure 3.3a-c indicates how the force is applied to the water.

Table 3. 1: The paddle torque generated during the maximal time trial.

*Displays the mean, start (first five strokes), middle (middle five strokes) and end (last five strokes) values as well as the right and left mean vales for male sprint, male marathon and female marathon paddlers. * p < 0.05 Within group time differences, (mid vs. end),* † *p < 0.05 Within group side differences (right vs. left).*

	Paddle torque (Nm) (mean ± SD)					
	Mean paddle torque			**Maximum paddle torque**		
	Male sprint paddlers	**Male marathon paddlers**	**Female marathon paddlers**	**Male sprint paddlers**	**Male marathon paddlers**	**Female marathon paddlers**
Mean	49.25 ± 3.09	56.40 ± 9.42	35.54 ± 3.75	72.21 ± 4.04	79.66 ± 14.09	50.73 ± 3.58
Start	56.24 ± 3.67	63.47 ± 8.73	39.40 ± 4.30	85.33 ± 5.40	87.55 ± 12.14	56.45 ± 4.09
Middle	49.88 ± 5.16*	56.6 ± 9.75	35.76 ± 3.61	72.05 ± 7.94*	78.85 ± 14.85	48.97 ± 3.57
End	42.70 ± 5.09	51.81 ± 8.91	33.02 ± 4.09	62.62 ± 6.86	74.61 ± 13.00	47.32 ± 4.39
Rt. stroke (mean)	52.59 ± 5.00†	58.79 ± 6.25†	38.42 ± 3.69†	77.35 ± 4.94†	83.39 ± 13.38†	54.33 ± 4.20†
Lf. stroke (mean)	45.55 ± 2.28	53.87 ± 9.04	33.67 ± 4.17	67.07 ± 4.79	75.47 ± 13.33	47.14 ± 3.32

Forward acceleration

Figure 3.4a-c depicts the forward acceleration of the boat during the first, middle and last phases of the time trial for the sprint, male marathon and female marathon paddlers. The acceleration was characterised by positive acceleration (water phase) followed by negative acceleration (air phase).

The mean boat forward acceleration of the sprint paddlers during the water phase was 0.23 ± 0.09 g and full stroke cycle 0.05 ± 0.01 g. The male marathon paddlers boat acceleration was 0.18 ± 0.06 g and 0.00 ± 0.04 g (water phase and stroke cycle respectively) and 0.17 ± 0.07 g and 0.03 ± 0.03 g for female marathon paddlers (water phase and stroke cycle respectively) (Figure 3.4, Table 3.2).

The mean maximum acceleration over the TT for sprint paddlers was 0.39 ± 0.09 g and the mean minimum acceleration was -0.21 ± 0.06 g (Table 3.4). The male marathon paddlers mean maximum acceleration and minimum acceleration were 0.31 ± 0.13 g and -0.25 ± 0.06 g respectively. The maximum and minimum acceleration for the female marathon paddlers were 0.29 ± 0.13 g and -0.16 ± 0.06 g respectively (Table 3.4).

There was no significant drop-off in mean acceleration per stroke for all three groups from the middle to the end of the time trial (0.04 ± 0.01 g vs. 0.05 ± 0.00 g, -0.04 ± 0.05 g vs. -0.01 ± 0.04 g and 0.02 ± 0.03 g vs. 0.02 ± 0.03 g for sprint, male marathon and female marathon paddlers respectively, Figure 3.4, Table 3.2). There was, however a significant group by time interaction (p = 0.00), with the female paddlers dropping-off less than their male counterparts between the middle and last five strokes of the time trial.

The individual data depicted in Figure 3.5 shows uniqueness in the shape of the acceleration profiles of participants within the same group and between groups.

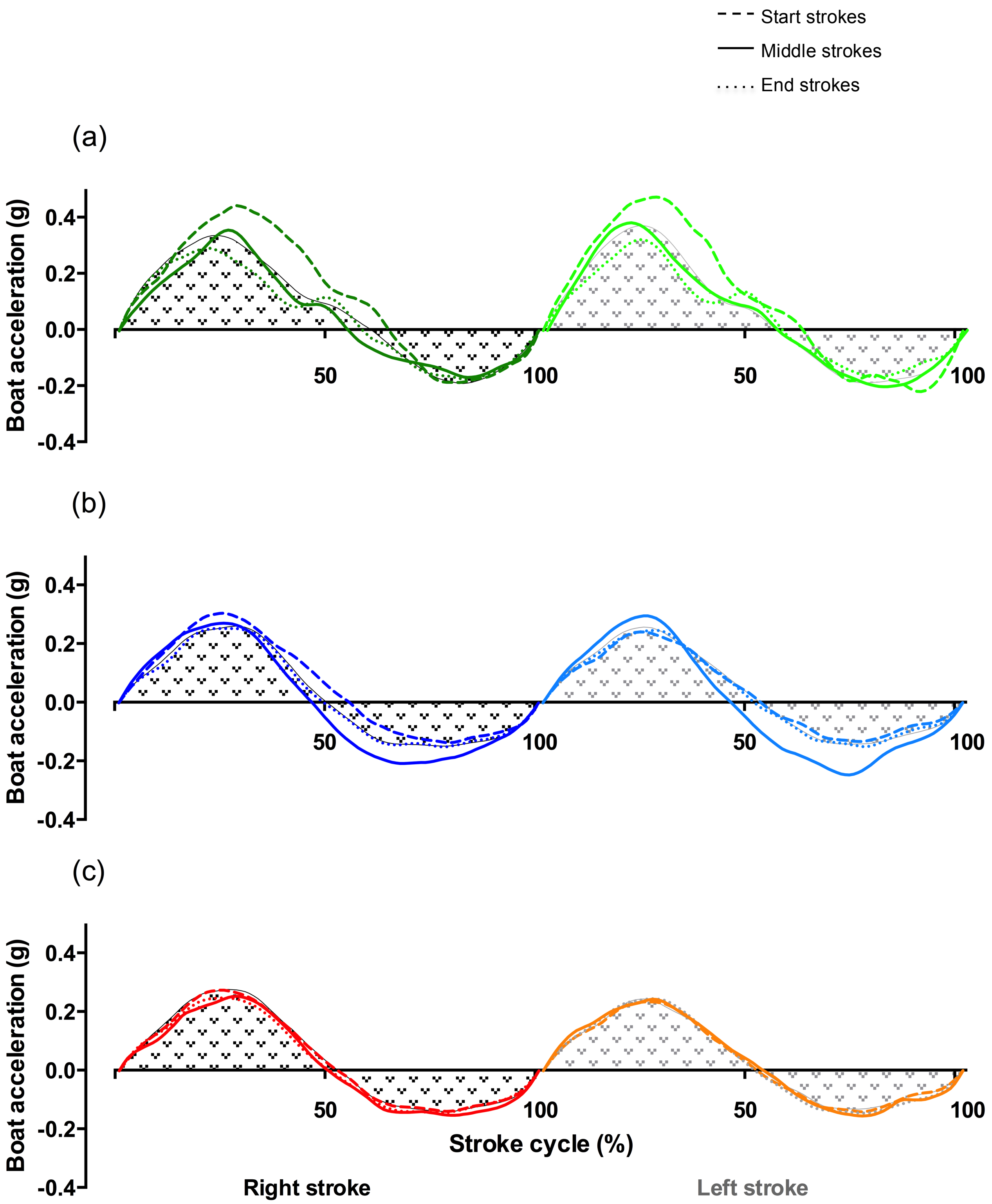

Figure 3. 4: Boat forward acceleration for right and left strokes during different phases of the time trial for the three sub-groups.

Depicts the first five strokes (dashed lines), middle five strokes (solid lines) and last five strokes (dotted lines) for a) sprint paddlers (top panel in greens), b) male marathon paddlers (middle panel in blues) and c) female marathon paddlers (bottom panel in red and orange). The darker colour represents the right strokes and the lighter colours represent the left strokes. The shaded area depicts the forward acceleration.

Table 3. 2: The forward acceleration of the boat per water phase and stroke cycle during the maximal time trial for the three sub-groups.

Displays the mean, start (first five strokes), middle (middle five strokes) and end (last five strokes) values as well as the right and left mean vales for male sprint, male marathon and female marathon paddlers. No within-group time-effect significance was found.

	Boat forward acceleration (g) (Mean ± SD)					
	Water phase			**Stroke cycle (water and air phase)**		
	Male sprint paddlers	**Male marathon paddlers**	**Female marathon paddlers**	**Male sprint paddlers**	**Male marathon paddlers**	**Female marathon paddlers**
Mean	0.23 ± 0.09	0.18 ± 0.06	0.17 ± 0.07	0.05 ± 0.01	0.00 ± 0.04	0.03 ± 0.03
Start	0.24 ± 0.09	0.22 ± 0.06	0.17 ± 0.06	0.11 ± 0.01	0.04 ± 0.04	0.04 ± 0.02
Middle	0.19 ± 0.05	0.15 ± 0.06	0.17 ± 0.07	0.04 ± 0.01	-0.04 ± 0.05	0.02 ± 0.03
End	0.17 ± 0.04	0.15 ± 0.05	0.16 ± 0.07	0.05 ± 0.00	-0.01 ± 0.04	0.02 ± 0.03
Rt. stroke (mean)	0.23 ± 0.09	0.18 ± 0.06	0.17 ± 0.07	0.05 ± 0.02	0.00 ± 0.04	0.02 ± 0.03
Lf. stroke (mean)	0.23 ± 0.09	0.17 ± 0.07	0.16 ± 0.07	0.05 ± 0.01	0.00 ± 0.05	0.03 ± 0.03

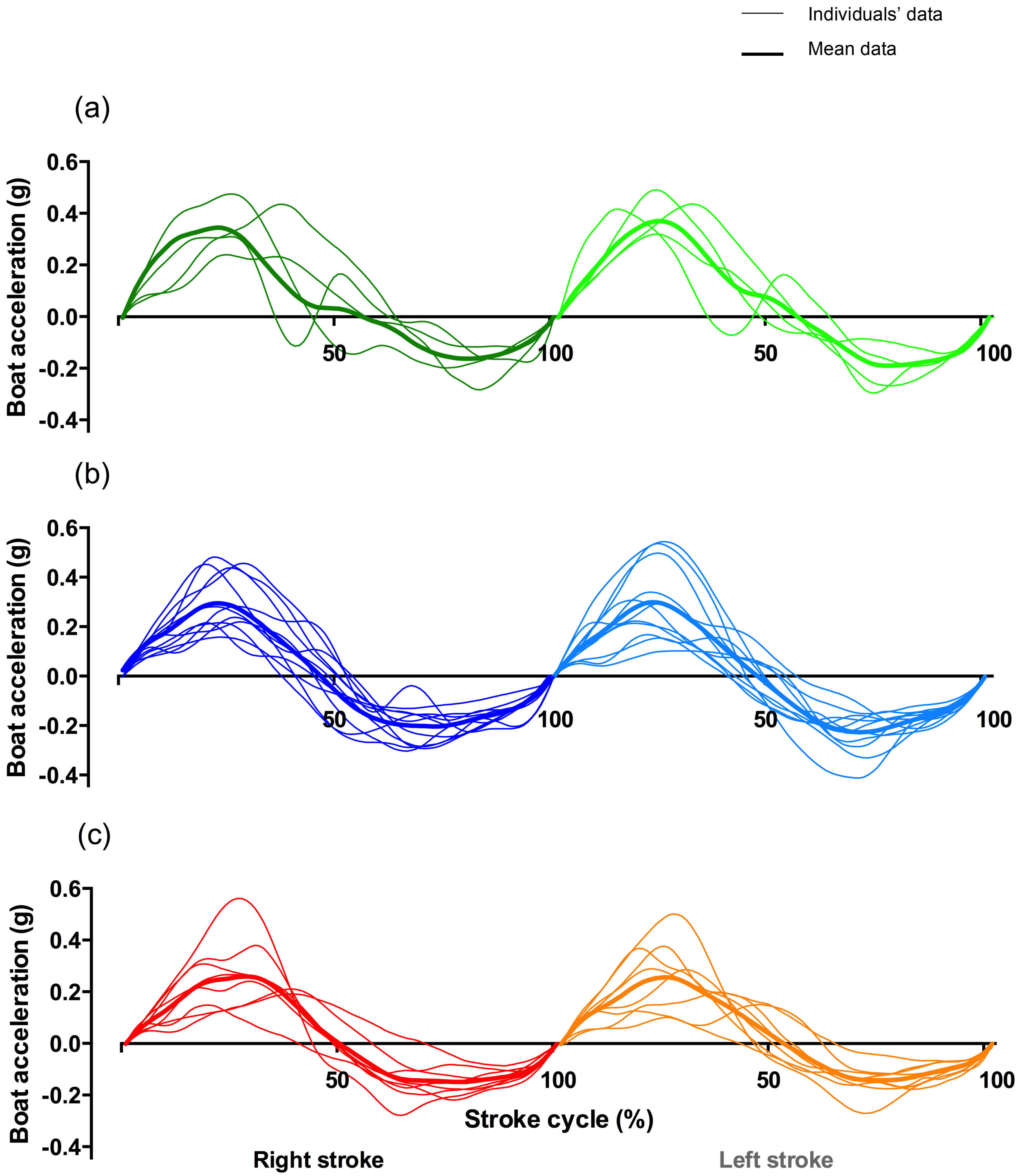

Figure 3. 5: The individual data for boat forward acceleration for the right and left strokes for the three sub-groups.

Depicts the mean (bold line), and individual's data (thin lines) for a) sprint paddlers (top panel in greens), b) male marathon paddlers (middle panel in blues) and c) female marathon paddlers (bottom panel in red and orange). The darker colour represents the right strokes and the lighter colours represent the left strokes.

Table 3. 3: The maximum and minimum forward acceleration of the boat during a stroke cycle for the three sub-groups.

Displays the mean, start (first five strokes), middle (middle five strokes) and end (last five strokes) values as well as the right and left mean vales for male sprint, male marathon and female marathon paddlers. No within-group time-effect significance was found.

	Boat forward acceleration and deceleration per stroke cycle (g) (Mean ± SD)					
	Maximum acceleration per stroke cycle			**Minimum acceleration per stroke cycle**		
	Male sprint paddlers	**Male marathon paddlers**	**Female marathon paddlers**	**Male sprint paddlers**	**Male marathon paddlers**	**Female marathon paddlers**
Mean	0.39 ± 0.09	0.31 ± 0.13	0.29 ± 0.13	-0.21 ± 0.06	-0.25 ± 0.06	-0.16 ± 0.06
Start	0.52 ± 0.08	0.39 ± 0.12	0.31 ± 0.11	-0.26 ± 0.10	-0.29 ± 0.06	-0.17 ± 0.06
Middle	0.35 ± 0.11	0.28 ± 0.12	0.25 ± 0.14	-0.19 ± 0.06	-0.22 ± 0.06	-0.16 ± 0.06
End	0.36 ± 0.06	0.29 ± 0.12	0.28 ± 0.13	-0.20 ± 0.04	-0.25 ± 0.06	-0.16 ± 0.06
Rt. stroke (mean)	0.38 ± 0.12	0.31 ± 0.12	0.29 ± 0.13	-0.17 ± 0.04	-0.25 ± 0.05	-0.17 ± 0.06
Lf. stroke (mean)	0.39 ± 0.09	0.30 ± 0.15	0.29 ± 0.23	-0.22 ± 0.07	-0.26 ± 0.08	-0.16 ± 0.06

Pitch

The mean boat acceleration from Figure 3.4 has been reproduced and presented as a shaded background to all figures for group mean roll, pitch and yaw (Figures 3.6, 3.8 & 3.10), to serve as a biomechanical reference.

Uniform intra-stroke deviations were found for pitch (Figure 3.7a-c). The pitch of all boats decreased (nose of boat dipped into the water) during the water phase of the stroke (indicated by the background shading showing positive boat acceleration) and increased (nosed lifted) during the air phase during boat deceleration (shaded negative acceleration) when no paddle force was applied.

Differences in the magnitudes and ranges of the pitch are depicted in Figure 3.6a – c and presented in Table 3.4. The average pitch for the sprint paddlers was 3.54 ± 0.60° and the intra-stroke range of pitch was 0.92 ± 0.46° (Figure 3.6a, Table 3.4). The male marathon paddlers average and range of pitch was 0.54 ± 1.29° 0.92 ± 0.46° respectively (Figure 3.6b, Table 3.4). The female marathon paddlers had 0.27 ± 0.82° and 0.59 ± 0.27° as their mean and range of pitch respectively (Figure 3.6c, Table 3.4).

Figure 3.7 shows that the individual variation for the position of the boat on the water and the intra-stroke deviations of the pitch are less within the group of sprinters compared to the marathon paddlers.

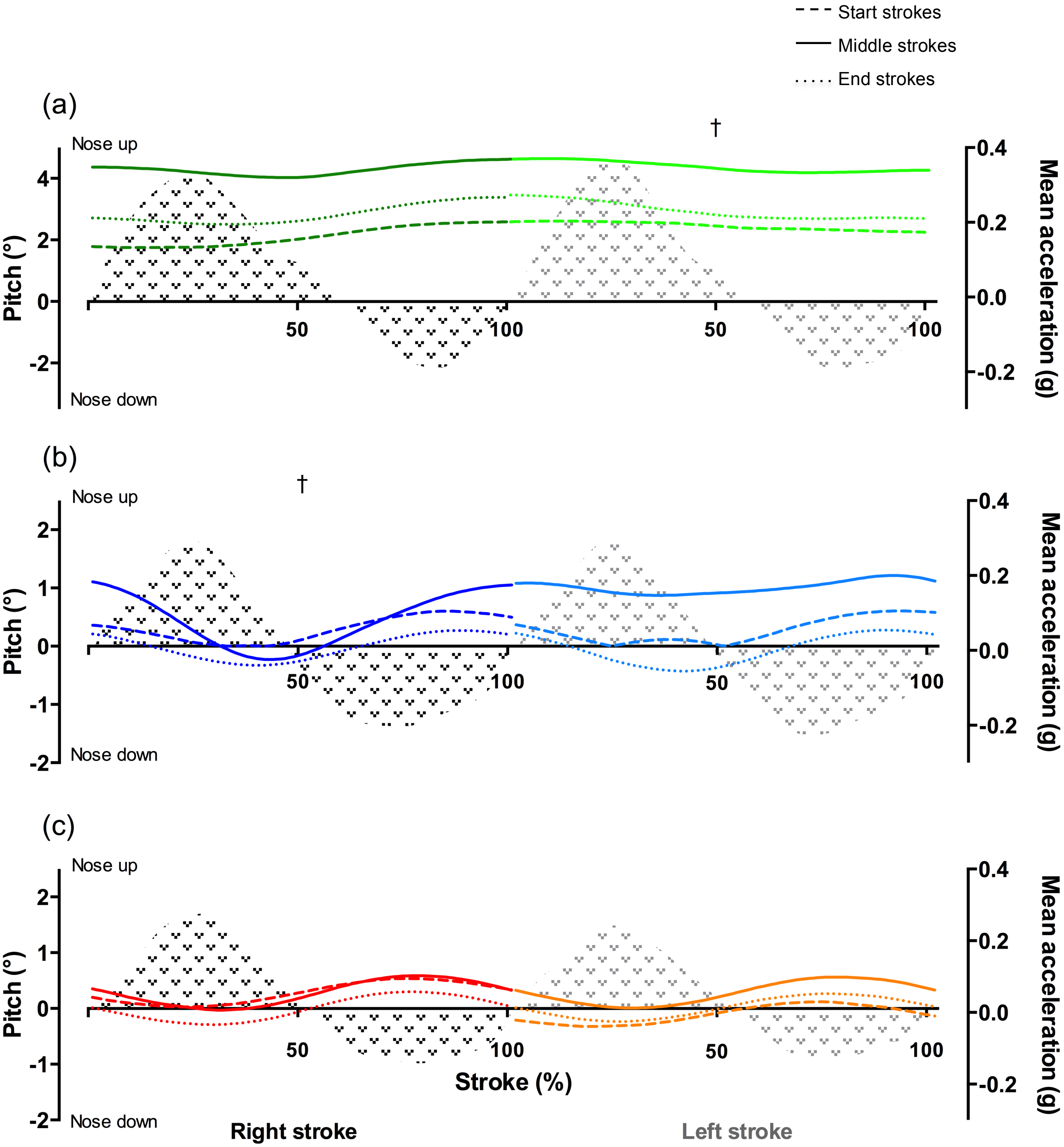

Figure 3. 6: Boat pitch for the right and left strokes during different phases of the time trial for the three sub-groups.

Depicts the first five strokes (dashed lines), middle five strokes (solid lines) and last five strokes (dotted lines) for a) sprint paddlers (top panel in greens), b) male marathon paddlers (middle panel in blues) and c) female marathon paddlers (bottom panel in red and orange). The darker colour represents the right strokes and the lighter colours represent the left strokes. [†] *$p < 0.05$ for within group time differences (middle vs. end). The shaded area depicts the forward acceleration.*

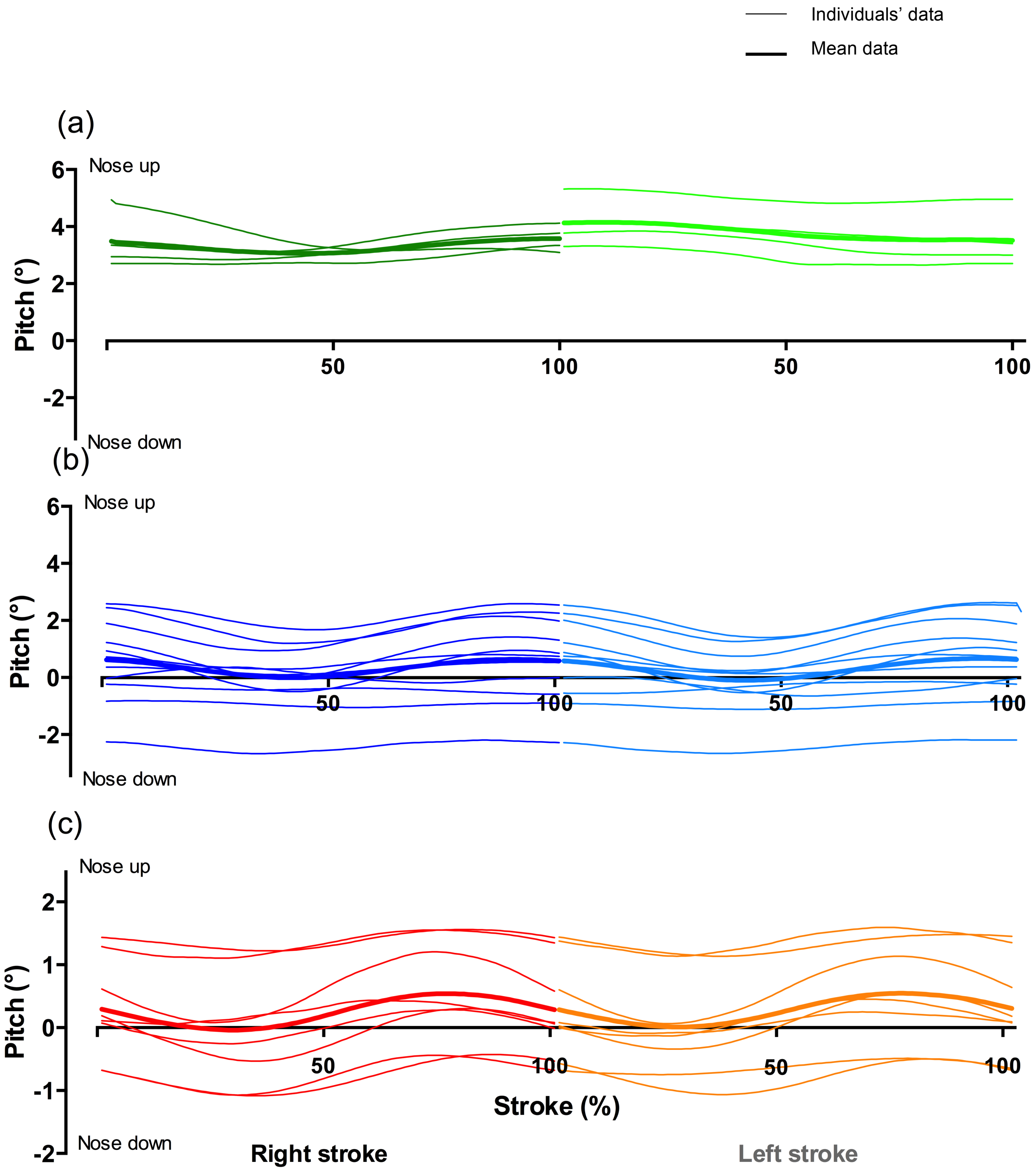

Figure 3. 7: The individual data for boat pitch for the right and left strokes for the three sub-groups. *Depicts the mean (bold line), and individual's data (thin lines) for a) sprint paddlers (top panel in greens), b) male marathon paddlers (middle panel in blues) and c) female marathon paddlers (bottom panel in red and orange). The darker colour represents the right strokes and the lighter colours represent the left strokes.*

Table 3. 4: The mean and range of boat pitch during a stroke cycle for the three sub-groups.

Displays the mean, start (first five strokes), middle (middle five strokes) and end (last five strokes) values as well as the right and left mean vales for male sprint, male marathon and female marathon paddlers. $p < 0.05$ for within group time differences (mid vs. end). † $p < 0.05$ within group side differences (right vs. left).*

	Boat pitch per stroke cycle (°) (mean ± SD)					
	Mean pitch per stroke cycle			**Range of pitch per stroke cycle**		
	Male sprint paddlers	**Male marathon paddlers**	**Female marathon paddlers**	**Male sprint paddlers**	**Male marathon paddlers**	**Female marathon paddlers**
Mean	3.54 ± 0.60	0.34 ± 1.29	0.27 ± 0.82	0.87 ± 0.11	0.92 ± 0.46	0.59 ± 0.27
Start	2.28 ± 0.39	0.21 ± 1.75	0.39 ± 1.20	0.69 ± 0.08	0.85 ± 0.46	0.58 ± 0.28
Middle	4.33 ± 1.51*	0.73 ± 1.32*	0.28 ± 0.70	0.36 ± 0.19	0.77 ± 0.41	0.58 ± 0.28
End	2.90 ± 0.61	0.11 ± 1.16	-0.18 ± 0.61	0.91 ± 0.04	0.91 ± 0.44	0.58 ± 0.25
Rt. stroke (mean)	3.29 ± 0.34	0.36 ± 1.28†	0.25 ± 0.83	1.12 ± 0.52	0.91 ± 0.46	0.62 ± 0.26
Lf. stroke (mean)	3.79 ± 0.90†	0.32 ± 1.31	0.28 ± 0.79†	0.69 ± 0.14	0.94 ± 0.46	0.57 ± 0.29

Roll

The three groups rolled their boats differently during the stroke cycle (Figure 3.8). The sprint paddlers were found to roll their boats towards the stroke side so that their boats rolled towards the right side while the right paddle blade was submerged in the water (Figure 3.8a). When the paddle exited the water and the air phase commenced, the boat was rolled towards the other side so that the boat pasted through being horizontally level (roll = 0) during the air phase. The four sprint kayakers executed this roll strategy very similarly (Figure 3.9a).

The female marathon paddlers rolled in the opposite direction to the stroke side. During the water phase of the right stroke the boat was rolled left and during the air phase, transitioning to the left water phase, the boat was brought level again, so that at the beginning of each water phase the boat was approximately level. Although all female paddlers adopted this paradoxical roll of the boat compared to the sprint paddlers, the timing of when the boat was rolled towards the other side varied (Figure 3.9c).

The male marathon paddlers had more variability in the co-ordination of the roll of the boat (Figure 3.9b). One paddler from this group rolled similarly to the sprinters, rolling towards the stroke side, while the remaining male marathon paddlers presented with a variety of rolling strategies, with most of them dipping the boat away from the submerged paddle. The timing of when the boat was brought to dip towards the opposite direction was also highly varied within this group.

There were no within or between group differences for right vs. left (12.22 ± 2.50° vs. 12.57 ± 3.17°, 11.29 ± 5.42° vs. 9.33 ± 4.62° and 9.28 ± 2.40° vs. 8.62 ± 2.90° for right vs. left roll for sprint, male marathon and female marathon paddlers respectively, Figure 3.9, Table 3.5) differences for the range of the roll. There were also no time-course differences for middle strokes compared to end strokes (13.31 ± 3.76° vs. 13.71 ± 3.17°, 9.82 ± 5.27° vs. 10.50 ± 6.20° and 10.10 ± 2.65° vs. 9.95 ± 2.19° for mid vs. end range of roll for sprint, male marathon and female marathon paddlers respectively, Figure 3.8, Table 3.5).

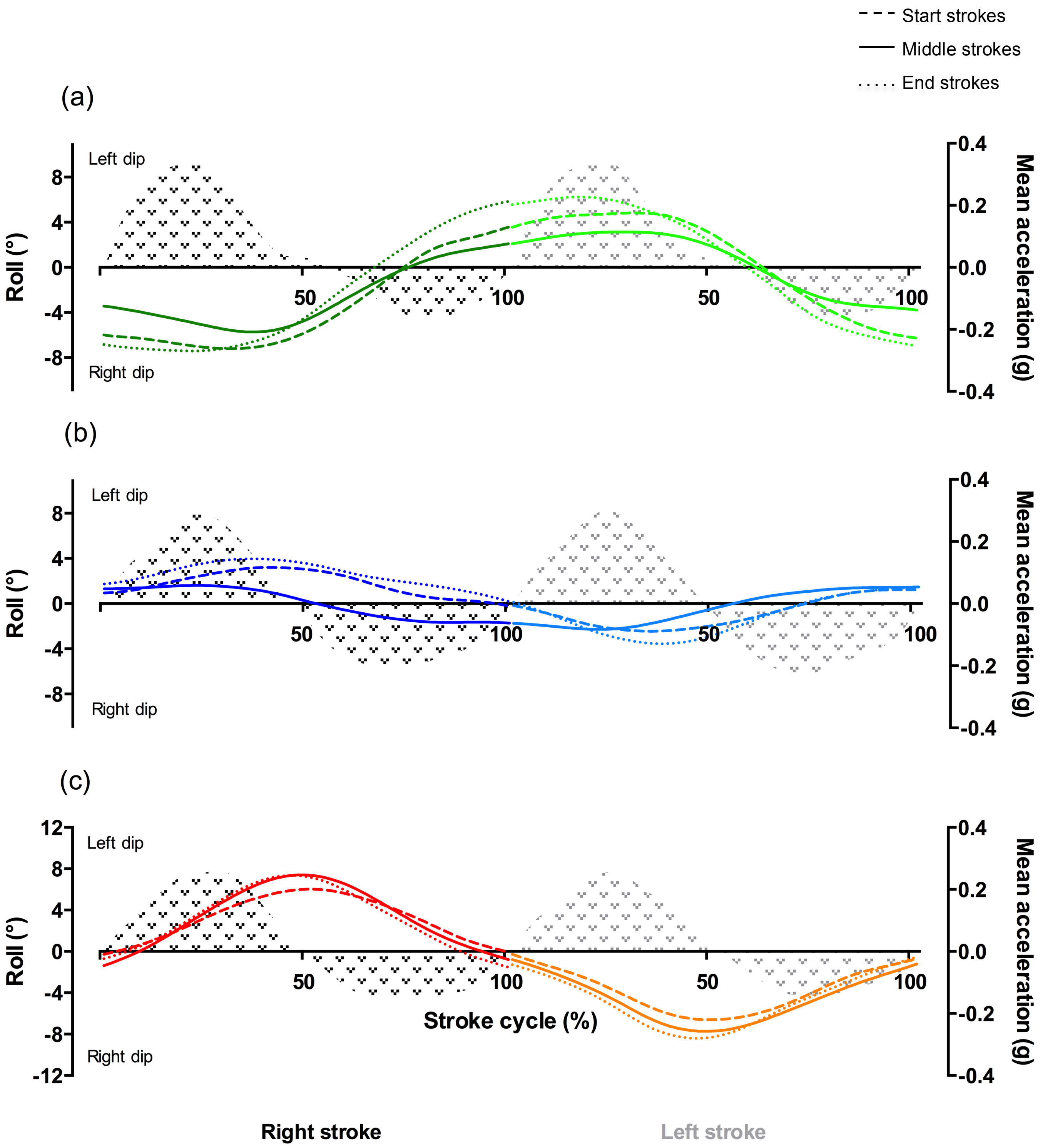

Figure 3. 8: Boat roll for right and left strokes during different phases of the time trial for the three sub-groups.

Depicts the first five strokes (dashed lines), middle five strokes (solid lines) and last five strokes (dotted lines) for a) sprint paddlers (top panel in greens), b) male marathon paddlers (middle panel in blues) and c) female marathon paddlers (bottom panel in red and orange). The darker colour represents the right strokes and the lighter colours represent the left strokes. The shaded area depicts the forward acceleration.

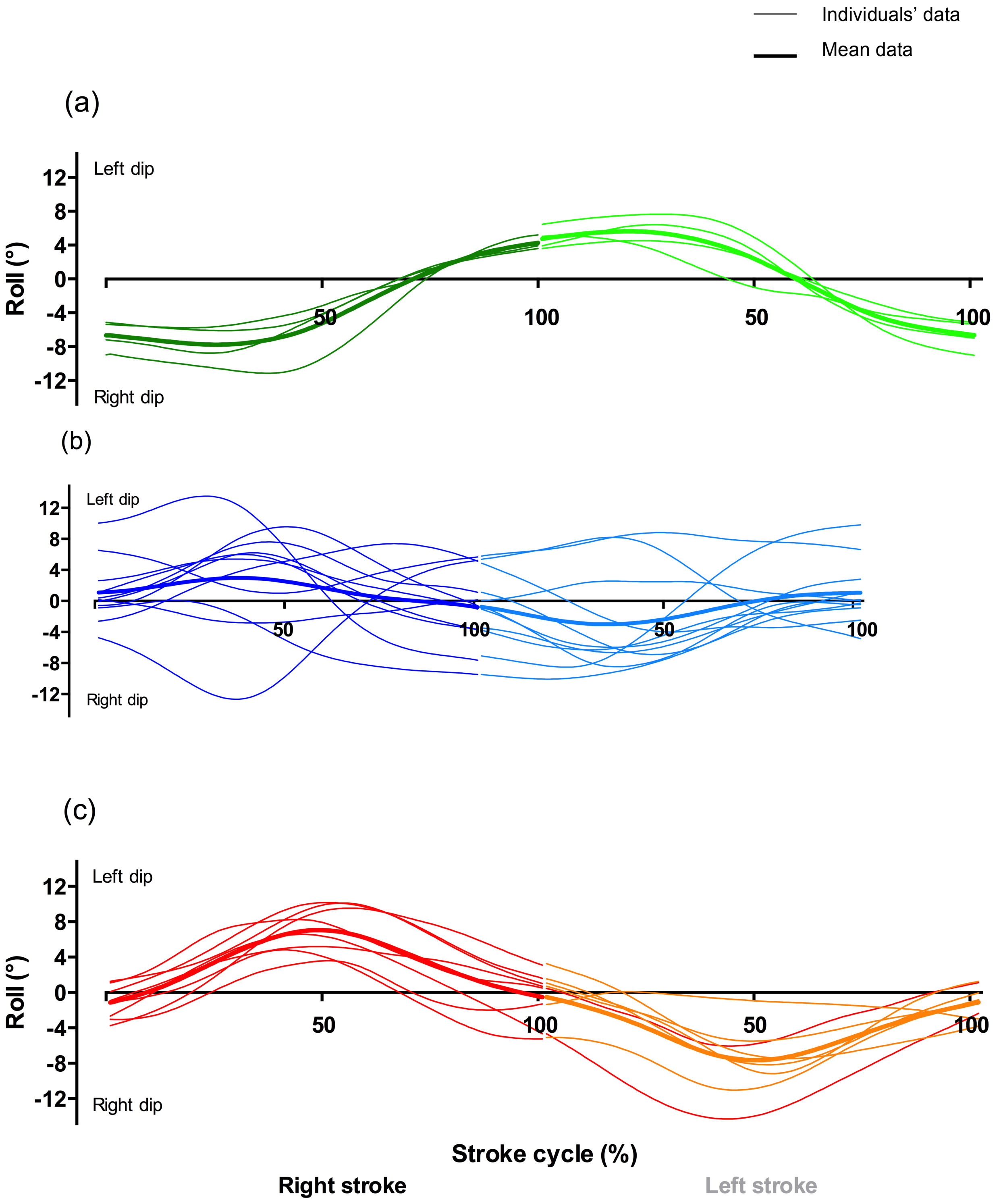

Figure 3. 9: The individual data for boat roll for the right and left strokes for the three sub-groups. *Depicts the mean (bold line), and individual's data (thin lines) for a) sprint paddlers (top panel in greens), b) male marathon paddlers (middle panel in blues) and c) female marathon paddlers (bottom panel in red and orange). The darker colour represents the right strokes and the lighter colours represent the left strokes.*

Yaw

All three sub-groups had similar intra-stroke yaw deviations, such that the nose of the boat was laterally steady during the initial water phase and as the stroke progressed it was found to change during the positive acceleration phase (Figure 3.10). During the air phase, the boats' change in yaw reduced. The individual data sets, displayed in Figure 3.11, show a common finding for the nose of the sprinters' boats to deviate towards the stroke side (Figure 3.11a), whereas the female marathon paddlers' (Figure 3.11c) boats were deviated away from the stroke side during the pull phase. There was directional variation within the group of male marathon paddlers, with the boat yaw going in different directions during the stroke cycle (Figure 3.11b). There were no significant within-group time related changes (1.69 ± 0.37° vs. 1.48 ± 0.25°, 1.15 ± 0.46° vs. 1.15 ± 0.38° and 1.21 ± 0.26° vs. 1.20 ± 0.34° for middle vs. end for male sprint, male marathon and female marathon paddlers respectively, Table 3.5).

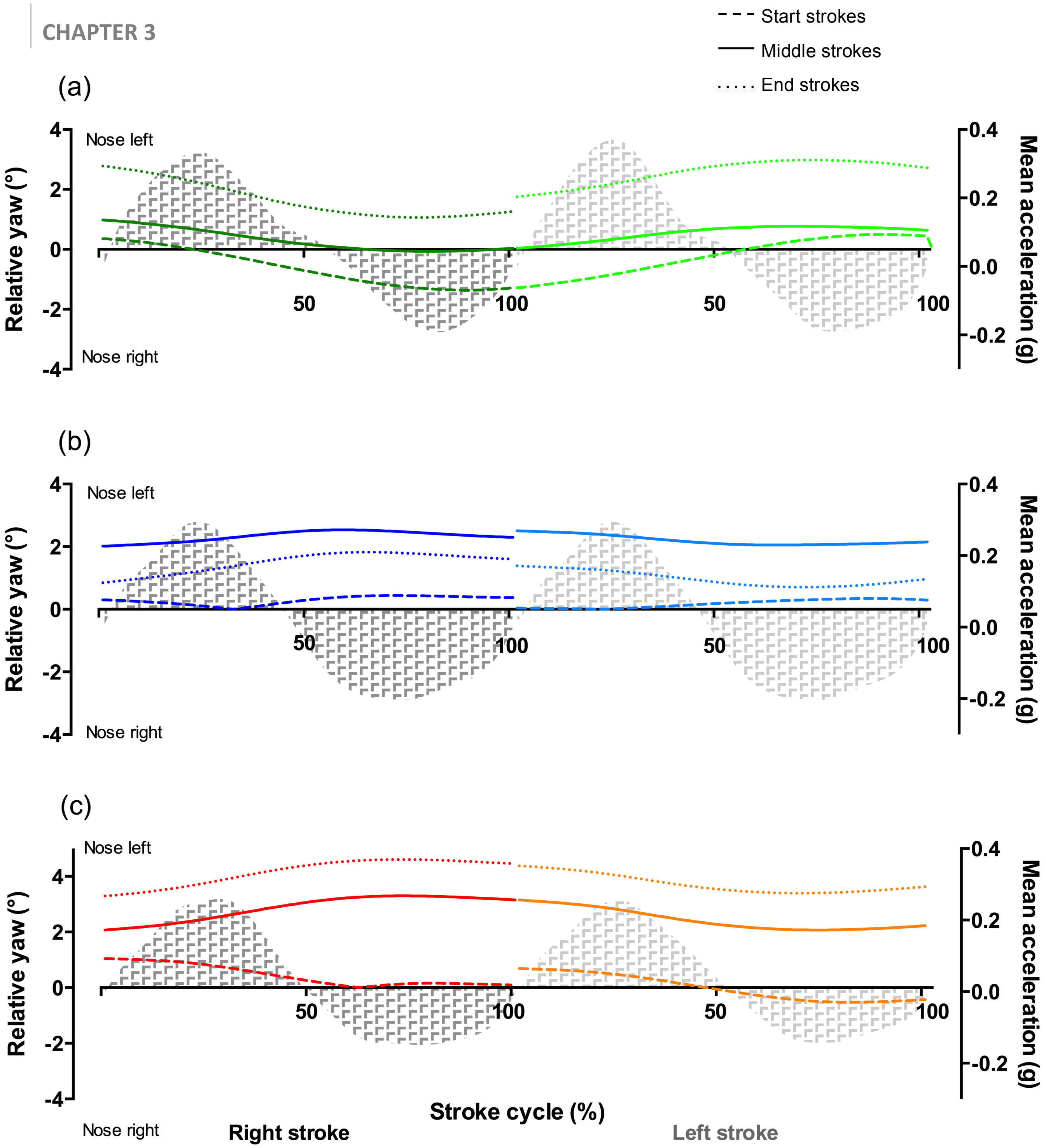

Figure 3. 10: Boat yaw for right and left strokes during different phases of the time trial for the three sub-groups.

*Depicts the first five strokes (dashed lines), middle five strokes (solid lines) and last five strokes (dotted lines) for a) sprint paddlers (top panel in greens), b) male marathon paddlers (middle panel in blues) and c) female marathon paddlers (bottom panel in red and orange). The darker colour represents the right strokes and the lighter colours represent the left strokes. * p < 0.05 for within group time differences (middle vs. end). The shaded area depicts the forward acceleration.*

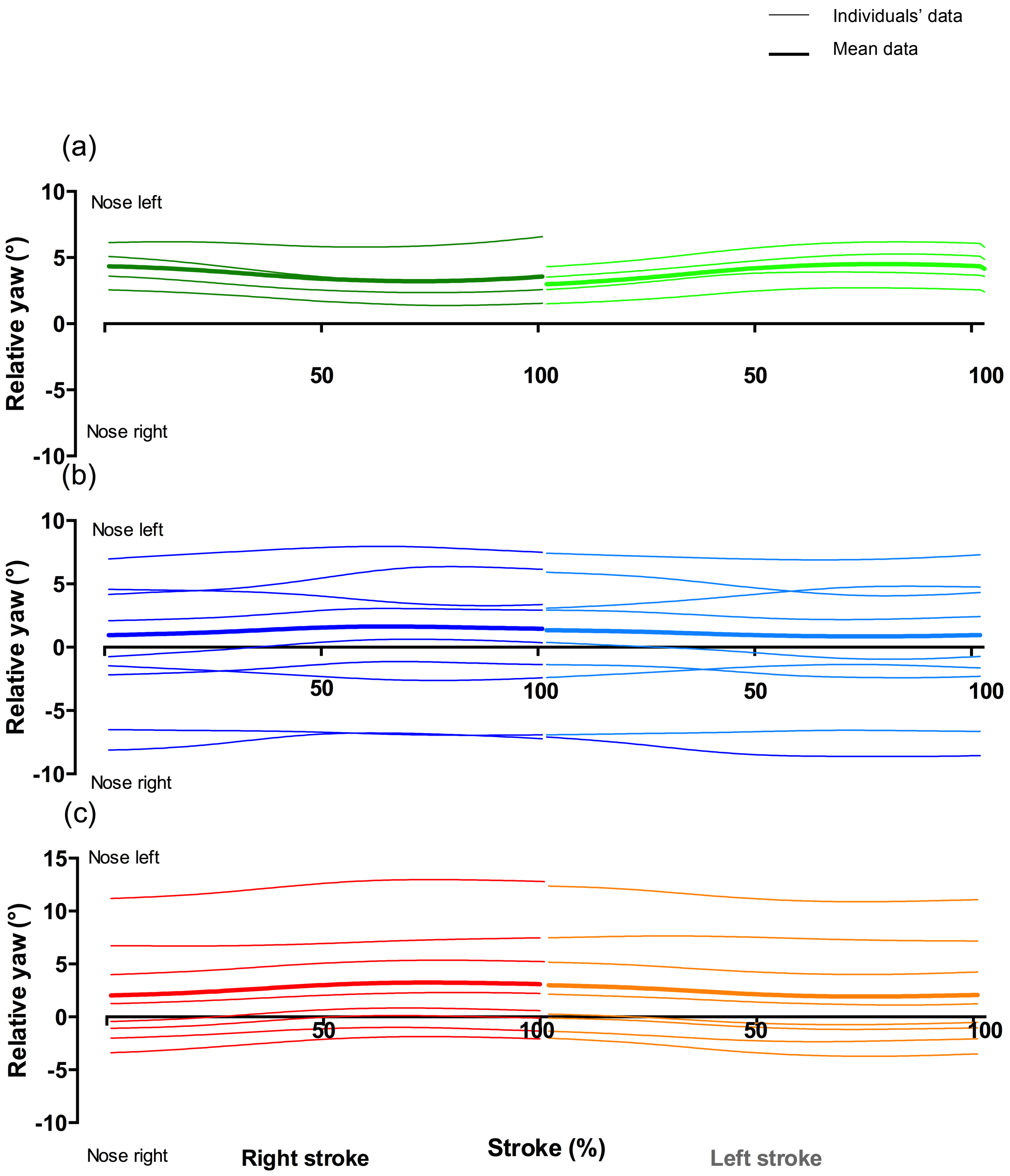

Figure 3. 11: The individual data for boat yaw for the right and left strokes for the three sub-groups. *Depicts the mean (bold line), and individual's data (thin lines) for a) sprint paddlers (top panel in greens), b) male marathon paddlers (middle panel in blues) and c) female marathon paddlers (bottom panel in red and orange). The darker colour represents the right strokes and the lighter colours represent the left strokes. * p < 0.05 for within group side differences (right vs. left).*

Table 3. 5: The range of the boat roll and yaw values per stroke cycle for the three sub-groups. *Displays the mean, start (first five strokes), middle (middle five strokes) and end (last five strokes) values as well as the right and left mean vales for male sprint, male marathon and female marathon paddlers. No within-group time-effect significance was found.*

	Range of boat roll and yaw per stroke cycle (°) (mean ± SD)					
	Range of roll			**Range of yaw**		
	Male sprint paddlers	**Male marathon paddlers**	**Female marathon paddlers**	**Male sprint paddlers**	**Male marathon paddlers**	**Female marathon paddlers**
Mean	12.40 ± 2.83	10.31 ±4.91	8.95 ± 2.55	1.40 ± 0.27	1.18 ± 0.43	1.18 ± 0.33
Start	11.50 ± 3.13	9.72 ± 3.60	7.80 ± 3.14	1.77 ± 0.34	1.42 ± 0.43	1.36 ± 0.61
Middle	13.31 ± 3.76	9.82 ± 5.27	10.10 ± 2.65	1.69 ± 0.37	1.15 ± 0.46	1.21 ± 0.26
End	13.71 ± 2.69	10.60 ± 6.20	9.95 ± 2.19	1.48 ± 0.25	1.15 ± 0.38	1.20 ± 0.34
Rt. stroke (mean)	12.22 ± 2.50	11.29 ± 5.42	9.28 ± 2.40	1.27 ± 0.44	1.25 ± 0.46	1.25 ± 0.31
Lf. stroke (mean)	12.57 ± 3.17	9.33 ± 4,62	8.62 ± 2.93	1.54 ± 0.32	1.12 ± 0.50	1.12 ± 0.37

Relationships between variables

Within group correlations for relationships between the biomechanical variables of paddle torque, boat forward acceleration (per stroke cycle and per water phase) and the range of pitch, roll and yaw were performed.

There were no significant relationships found between paddle torque and any of the boat kinematic variables. The range of the roll had a near perfect positive correlation to maximum acceleration for both groups of male paddlers (sprint paddlers $p = 0.16$, $r = 0.99$ and male marathon paddlers $p < 0.01$, $r = 0.96$). The range of the pitch of the boat during a stroke cycle was significantly related to maximum acceleration for the female paddlers only ($p = 0.02$, $r = 0.76$). Similarly, the range that the boat yawed during a stroke cycle was only found to be significant to the mean acceleration per stroke in the group of female marathon paddlers ($p < 0.01$, $r = -0.93$) so that the less the boat yawed, the greater the forward acceleration per stroke.

Discussion

Overview of the discussion

This study aimed to provide novel data on the three-dimensional, intra-stroke biomechanics of the boat during maximal flat-water kayaking. Paddle torque and boat kinematic factors (forward acceleration, pitch, roll and yaw) were measured in order to describe these factors, and explore their inter-individual variability.

Paddle torque results

All three groups produced significantly greater mean paddle torque for the right stroke compared to the left (52.59 ± 5.00 Nm vs. 45.55 ± 2.28 Nm, 58.79 ± 6.25 Nm vs. 53.87 ± 9.04 Nm and 38.42 ± 3.69 Nm vs. 33.67 ± 4.17 Nm for the right vs. left paddle torque for sprint, male marathon and female marathon paddlers respectively, Table 3.2). This unilateral strength bias has been documented previously for paddle forces of elite sprint paddlers (Begon *et al*., 2010); it is also typical in the general population. It may be postulated that in paddlers, part of the side difference can be accounted for by the fact that the paddle stroke kinematics are not symmetrical because the left hand momentarily releases its grip so that the paddle shaft can be rotated prior to the right catch. It may also be that strength differences between sides contribute to the differences in paddle torque. Unilateral strength training of the weaker side may be beneficial for paddlers to prevent the development of asymmetrical force production, and future research may investigate this.

Interactions of paddle torque and boat acceleration

Significant discrepancies between right and left paddle torque generation were not translated to discrepancies between acceleration of the boat during the water phase of the stroke (0.23 ± 0.09 g vs. 0.23 ± 0.09 g, 0.18 ± 0.06 g vs. 0.17 ± 0.07 g and 0.17 ± 0.07 g vs. 0.16 ± 0.07 g, comparing right vs. left acceleration per stroke for the sprint, male marathon and female marathon paddlers respectively, Table 3.2). The relationship between paddle force and the forward acceleration of the boat was not significant. Biomechanical factors that have previously been identified to influence kayak technique, and thus performance, include the angle of the paddle force relative to the water (Kendal & Sanders, 1992) and the timing of the application of the force during the water phase (Mann & Kearny, 1980; Kendal

& Sanders, 1992). Future investigations including analysis of paddle pathway through the water (stroke length, depth and width) would help expand the understanding of the relationship between paddle biomechanics and the forward acceleration of the boat. These measurements would also assist in understanding the mechanism behind the individual variation of paddle force application.

Considering differences in equipment and anthropometry between groups - paddle and boat biomechanics

The sprint paddlers used the same paddle and had a similar timing of force application to the water which is displayed in the similarity of the shape of the paddle torque graphs in Figure 3.3a. The common characteristic in the group of sprint paddlers was an early peak followed by a second peak later in the stroke phase. Some of the marathon paddlers' force curves displayed the same shape as the sprint paddlers, and some displayed a single peak, without the initial peak. (Figure 3.3b,c).

Male marathon paddlers generated the greatest mean and maximum paddle torque (Table 3.1) but not the greatest acceleration per water phase or stroke cycle (Table 3.2). The male sprint paddlers accelerated their boats more than the male marathon paddlers (Table 3.2). This is likely, in part, due to the differences in the shape of the hull of the boats. The narrower hull of the sprint kayaks are expected to undergo less hydrodynamic drag through the water as these narrower boats have a smaller wetted surface area and therefore should experience less deceleration (Jackson, 1995) during the stroke cycle. The stroke rate was lower for the male marathon paddlers (116.90 ± 8.20 spm) compared to the sprint paddlers (131.21 ± 2.67 spm) creating longer impulse times and thus contributing to the marathon paddlers' increased torque per stroke.

The female marathon paddlers generated less force than the male marathon paddlers but accelerated the boat more using similar equipment to their male counterparts. This is likely due to their lighter body mass. The females' stroke rate was also less than the males.

The stroke rate of the sprint paddlers (131.21 ± 2.67 spm) was higher than both groups of marathon paddlers (116.90 ± 8.20 spm and 102.39 ± 10.45 spm for male and female marathon paddlers respectively); this further reduces the opportunity for deceleration to occur during the shorter air phase and contributes to greater acceleration per stroke achieved by the sprint paddlers (Table 3.2).

The both groups of male paddlers displayed a similar time-related change in acceleration kinematics, where the relative duration of the pull phase decreased over the course of the time trial (Figure 3.4).

Complexity of the three dimensional kinematics of the boat

The complexity of kayaking technique is further explored as the three dimensional kinematics are discussed.

The boats of the sprint paddlers sat in the water with greater pitch (nose up position) compared to the boats of the marathon paddlers (3.54 ± 0.60° vs. 0.34 ± 1.29° vs. 0.27 ± 0.82° for the sprinters, male marathon and female marathon paddlers respectively, Figure 3.6, Table 3.4). This may again be attributed to differences in the shape of the boats used in these events, the boat configuration or set-up (distance of the seat from the nose of the boat and height of the seat) or paddlers' biomechanics (footrest and seat forces).

The more level the boat sits in the water, as found in the two groups of marathon paddlers, the greater the wetted surface area and therefore the greater the water resistance and drag experienced (Jackson, 1995). On the other hand, a pitched boat, as used by the sprint paddlers, also increases the area resistance to flow. An interaction must exist when optimising these two forms of drag.

A novel finding of the present study is that some paddlers displayed a direction of roll that is contrary to what has previously been suggested as typical and optimal in the literature (Mann & Kearny, 1980), though this has never been directly measured during on-water kayaking performance. The sprint paddlers and three of the male marathon paddlers rolled their boat towards the stroke side, as suggested is optimal by Mann and Kearny (1980). However, the female marathon paddlers, and the majority of the male marathon paddlers contradicted this hypothesis and rolled their boats in the opposite direction, away from the stroke side during the water phase of the stroke cycle (Figure 3.9).

By rolling towards the opposite side, a theoretical performance disadvantage is created as the buoyancy of the water upwards causes a reduced grip on the water and the paddle slips through the water (Mann and Kearny, 1980). The energy lost from the paddle slipping through the water does not translate to forward acceleration of the boat and is therefore technically inefficient (Mann and Kearny, 1980). The backward movement of the paddle compared to a lateral or diagonal movement does not benefit from lift (Kendal & Sanders, 1992)

Rolling towards the stroke side may increase the requirement for superior balance, co-ordination, proprioception, and core strength because the paddle force and body weight are applied on the same side. The ability to counter-balance without using body weight (by shifting to the contralateral side) may be developed in sprint paddlers who receive supervised and more specific training than marathon paddlers. Sprint paddlers also use a bar or strap over their feet and are therefore able to counter balance their power and weight shift to the stroke side by pulling with the opposite foot on the foot bar, serving as point of counterbalance for lateral stability during the unilateral force generation. Pulling on the foot strap has been found to reduce the forces in the seat (Begon *et al.*, 2010; Loi Lok, 2013) and therefore is expected to reduce the roll.

Marathon boats typically do not have a foot bar and paddlers may have to shift their weight away from the stroke side to counter balance the transfer of power to the water in order to maintain lateral stability. Therefore, the seat becomes the point of counterbalance for lateral stability during the unilateral force generation rather than the foot bar. Future research, specifically designed to investigate how differences in boat set-up affect boat biomechanics is indicated to better understand how the boat configuration interacts with the paddler and paddle for optimal propulsion through the water.

Rough, unpredictable water conditions and longer distances may make rolling onto the paddle a more difficult task for marathon paddlers compared to sprint paddlers. These groups of marathon paddlers received no technical training (involving individual attention to kayaking technique from a coach during on-water paddling sessions and supervised strength training), whereas the sprint paddlers received daily supervision with feedback on their technique often involving video analysis.

While investigating the biomechanics of paddling in a group of elite sprint kayakers, Begon *et al*. (2010) noted the biggest technical difference within the group was the movement of their pelvises. As paddling is a seated sport on an unstable surface, the roll of the boat is guided by the movement and weight distribution of the trunk and pelvis.

In the female marathon paddlers, there was less disparity in the roll compared to their male counterparts. All participants rolled their boat in the opposite direction of the submerged paddle blade during the water phase of that stoke, before rolling back towards horizontal during the air phase (Figure 3.9c). The symmetrical oscillation of the roll of their boats, with little time-course changes over the trial, is consistent with their paddle torque and boat acceleration. In contrast all male paddlers changed the direction of the roll during one stroke cycle (Figure 3.9a).

The water pushing against the submerged paddle (drag) during the unilateral propulsion phase pushes the nose of the boat away from the stroke side. The marathon paddlers boats followed this principle; however, the nose of the boat of the sprint paddlers (and three male marathon paddlers) deviated slightly towards the stroke side (Figure 3.11) and therefore is suspected of using a wider stroke as found by Brown *et al.* (2011). The interactions of lift with the wider stroke would bring the nose back towards the stroke side, similarly to the method used in canoeing, but on a smaller scale (less width).

Once the paddle has exited the water (no unilateral forces experienced) the boats did not show changes in yaw (Figure 3.10). At the beginning of the time trial, when the boat was accelerating from a stationary start, the range of the yaw was greater than at the end of the time trial when the boat speed would have been higher (Table 3.5). This suggests that the speed of the boat, rate of acceleration, paddle torque and pathway of the paddle through the water influence the longitudinal stability of the boat.

The intra-stroke deviations of the pitch and yaw values were considerably less than the deviations of the roll of the boat (Tables 3.4 vs. 3.5). This is expected due to the comparison of the length to the breadth of the boat. The deviations of the pitch and yaw data are stabilised by the length of the boat, whereas the slimness of the boat does not offer the same stability to the roll of the boat.

It is therefore suggested that the less stable roll of the boat should be prioritised when trying to achieve optimal boat efficiency through reducing wetted surfaces area as suggested by previous discussions on reducing the three-dimensional movements of the kayak of greater efficiency (Mann & Kearny, 1980; Jackson, 1995; Begon *et al*., 2010; Brown *et al*., 2010).

Attaining improved lateral stability is not a simple task, as suggested by the large variation of the roll of the boat and the numerous contributing factors, which means potential trade-offs of ability to deliver unilateral paddle force to the water need to be investigated together with the pursuit of increased lateral stability (reduced wetted surface area).

The large variability of boat kinematics between and within groups with reference to performance and clinical implications

The individual data graphed in this chapter allows for clinical interpretation of the boat kinematics, with right vs. left stroke comparisons on an individual level. This approach can be useful for coaches, trainers, scientists and rehabilitation professionals working with an athlete on kayaking technique or technique related injuries. For example, the individually graphed data for the roll of the boat, of the male marathon paddlers (Figure 3.9b) shows that one paddler does not roll his boat right at all (the roll is always positive). Several participants in this group also had magnitude and timing differences in their roll so that they roll more during one side compared to the other or with slightly different timing according to the water and air phases of the stroke.

The implications of unique technical features between athletes possibly becomes more important when two or four paddlers are in a team boat together. It is common for a crew to report that they are ‘leaning’. It is also common for team members to feel that they are leaning towards opposite sides when sitting in the same boat. In this case, both static and dynamic boat position should be assessed and addressed.

When a K2 or K4 boat is sitting stationary in the water, it is orientated according the crewmembers and not to an absolute levelness. Therefore, the roll of the boat becomes relative to what each individual perceives level to be; ‘right-down’ for one paddler could feel ‘level’ for another.

The use of a gyroscope to provide objective measurement of the three-dimensional movements of the kayak could assist the support-staff of team boats in training each individual on symmetrical technique. Additionally, this data may assist selectors with team boat selection.

Individual analysis of the three-dimensional boat kinematics can also be useful in optimising each individual’s boat set up. Alterations in the position and height of the seat would interact with the boats orientation around the three axes of movement.

Limitations of the study and suggested future research

The small sample sizes, in particular of the male sprint paddlers, weakened the strength of the statistical analysis conducted in this study. Further research of on-water paddle and boat biomechanics is therefore suggested to include larger sample sizes and an accurate method of measuring kayak performance, so that the discussed performance implications and interactions for three-dimensional biomechanics can be understood more clearly.

Overview of findings and leading onto the next study

The collective findings are that paddle force production and boat kinematic differences exist between groups who perform different events (sprint vs. marathon paddlers) and thus different types of training, use of different equipment, and of different genders. These differences may have performance implications, which would potentially be of interest to coaches and support staff wishing to optimise kayaking performance and manage injury risk.

The direction and the timing of the boat kinematics are ultimately controlled by muscle activity. Chapter 4 of this thesis explores muscle activity timing of marathon paddlers and compares it to that of sprinters previously described in literature using similar methods.

Conclusion

The biomechanical variables measured in this study are novel and show individual technical differences between paddlers within disciplines using similar equipment.

Sprint paddlers rolled their boats towards the stroke side during the water phase of the stroke, while some of the male marathon paddlers and all of the female marathon paddlers rolled their boats in the opposite direction. This was similar for the findings of the intra-stroke change in yaw, such that the direction of the nose of the boat was not consistent between paddlers. The angle of the pitch of the boat was also not consistent between paddlers. There were no significant and common within-group relationships between biomechanical variables.

It has been a trend in biomechanical analysis of kayaking to measure the paddlers' upper body movements (forward reach and trunk rotation), and we strongly suggest that athletes and coaches also consider the movement of the boat when analysing kayak technique, as this has was highly individualised and has potential performance implications.

This study has explored aspects of the complex arrangement of relationships among biomechanical variables' magnitude, distribution and direction during on-water maximal kayaking and we encourage athletes and coaches to consider these discussed interactions during technical training and when selecting the appropriate boat, boat set-up and for optimisation of team-boat synergy.

Chapter 4: The neuromusclular co-ordination of muscles of the torso and pelvis in marathon flat-water kayakers during a time trail and a shorter, simpler pull action

Introduction

Electromyography included in the biomechanical analysis of kayaking

Electromyography has been described as an important contributor to biomechanical analysis (De Luca, 1997), as it provides information that cannot be deduced from visual kinematics. The previous chapter in this thesis (Chapter 3) reported large individual variability and atypical boat kinematics by marathon paddlers, as measured with a gyroscope and accelerometer (Minimax B4, Catapult, Australia). This invites the question of what neuromuscular manifestations are associated with these particular kinematics.

The paradoxical roll of the boat was the most interesting finding, (marathon paddlers rolled their boat away from the stroke side during the water phase of paddling); therefore the stabilising muscles of the torso and pelvis, believed to interact with lateral weight lifts, are included in this study.

Previously measured muscle group activations during kayaking

The motor control of the shoulder and stomach muscles while paddling have previously been investigated for elite sprint paddlers (Brown, 2009; Fleming *et al*.; 2012). The function of the latissimus dorsi (LD), as described in Greys Atlas of Anatomy, is to pull the torso toward an outstretched arm (Agur & Lee, 1999) and has been described as the prime mover during the ipsilateral pull phase of the stroke (Trevithick *et al*., 2007; Brown, 2009; Fleming *et al*., 2012). This is unsurprising, as this phase starts with the arm outstretched and the boat and body are pulled towards the submerged paddle (Mann & Kearney, 1980). Further, the LD is recruited during ipsilateral trunk rotation (McGill, 1991), therefore increasing its contribution to the ipsilateral pull phase during kayaking.

On-water electromyography has been found to be similar to ergometer electromyography for phase of stroke activation (Fleming *et al*., 2012) for the latissimus dorsi, triceps and vastus lateralis muscles. The LD in both conditions (on-water and ergometer) was recruited during the ipsilateral pull phase and remained largely quiet during the air phases and contralateral pull phase by elite sprint kayakers (Fleming *et al*., 2012).

Activation of the contralateral external oblique (EO) muscle during the pull phase of on-water paddling has been found by Brown (2009) to be associated with boat speed and paddle force production. The lower fibres of the trapezius (LT), pectoralis major (PM), erector spinae (ES) and gluteus medius (GM) muscle groups have not yet been assessed when kayaking on the ergometer or on the water. This study will be the first report on these muscle groups while paddling.

Muscle groups that have not previously been measured during kayaking

Electromyographic reports for the pectoralis major (PM) muscle during kayaking were not found in literature. This muscle is hypothesised to activate at the same time as the LD on the opposite side, as the push arm adducts at the shoulder. It is therefore expected to contribute towards the push of the aerial arm. Bench-press, the commonly performed exercise by paddlers to train pushing strength, targets this muscle.

The lower fibres of the trapezius (LT) muscle assist in scapula upward rotation during elevation of the humerus (Kibler, 1998). Reduced activation of this muscle during humeral elevation indicates downward rotation or inadequate control of upward rotation of the scapula (Kibler, 1991; Kibler, 1998, DePalma & Johnson, 2003). The upward rotation of the scapula is important for maintenance of the acromial humeral interval necessary for rotator cuff function; maintaining the instantaneous centre of rotation of the humerus in the glenoid, optimal rotator cuff strength-tension relationship and preventing soft tissue strain (de Palmer & Johnson, 2003).

It is therefore essential that the LT is active during air or push phase when the arm is elevated. As the LT also assists in scapula posterior tilting (DePalma & Johnson, 2003) it would also be beneficial for LD to activate as the arm is loaded during the pull phase. If the LT is not active during these movements (phases) the strength of the dynamic stabilisers of the shoulder are compromised and the joint is at risk of sustaining an injury through maligned repetitive strain (de Palmer & Johnson, 2003).

The shoulder elevates greatest during the air phase although it is loaded in increasing abduction during the water phase. The amount of shoulder abduction during the water phase is dependant on the width of the stroke. We hypothesise that the LT will activate most during the push phase (scapula upward rotation during humeral elevation) and will remain active during the pull phase.

The gluteus medius (GM) muscle is a hip abductor and is an important lateral pelvic stabiliser (Gottschalk *et al*., 1989). Its contraction prevents the pelvis from dipping towards the opposite side (Trendelenberg sign or contralateral hip adduction) through relative abduction of the contralateral hip (Hardcastle & Nade, 1985). If a heavy object is picked up while standing on both feet, the contralateral GM fires to prevent the pelvis dipping towards the weighted side. Therefore, we hypothesise that while paddling (and thus in a seated position), the GM will activate to counter-stabilise the resistance during the contralateral pull stroke, and in doing so, prevent contralateral hip adduction and laterally stabilise the pelvis.

Bilateral activation of the erector spinae (ES) muscles of the lumbar spine extend the spine and have been found to provide a stabilising role to the torso during rotation (Kumar *et al*., 2002). The ES are used as indicators of weight shifting in sitting as they contract in response to load (Sung *et al*., 2013). We hypothesise that both left and right ES will activate due to their stabilising contribution to rotation.

The activity of LD, EO and PM, three power-producing muscles, were selected for measurement, as well there stabilising muscles LT, ES and GM. It is hypothesised that these muscles groups would be activated according to the evidenced-based hypothesises described previously.

Muscle activation timing relative to the phase of the stroke cycle

Of particular interest was whether the timing of muscle activation may be associated with the previously found large variability and atypical lateral rolling of the boat with each stroke in the marathon paddlers. We hypothesise that a similarly large variability and atypical muscle activation will exist between these paddlers who do not receive the technical instruction of paddlers previously reported on in the literature. The activation of the muscle groups was tested during maximal paddling (complex task) as well as on a single arm pull device (simple task) to better investigate the technical or skill contribution to muscle ativation strategies.

Study aims and hypotheses

The electromyographic activity of muscle groups during kayaking is under-researched. This study aims to describe the activation of the pectoralis major, lower fibres of the trapezius, erector spinae and gluteus medius muscles for the first time during kayaking.

In summary the hypotheses of this study are:

1. The pectoralis major muscle will be most active during the contralateral pull phase.
2. The lower fibres of the trapezius will be active during the contra and ipsilateral pull phases.
3. The gluteus medius muscle will activate more during the contralateral pull phase compared to the ipsilateral pull phase.
4. The erector spinae muscles will activate bilaterally during the stroke cycle.

Methods

Male and female marathon paddlers were recruited for this study. Nineteen 200 m time trials (TT) were performed (males n = 11, females n = 8) on an indoor kayak ergometer.

The procedure of the ergometer time trials

All participants performed a 200 m ergometer time trial (TT) on a wind braked kayak ergometer (Dansprint, Sweden). Time trial time, average power and average stroke rate were recorded by the Dansprint software and are reported for each TT. Each participant performed a self-selected ‘dry-land’ warm up prior to their ergometer TT. On the ergometer, each participant was set up with an individualised seat distance, accounting for differences in leg length, to replicate positioning in the boat as closely as possible. They then completed an incremental five-minute warm up. This involved two minutes at 60 % of the participant’s perceived maximum and two minutes at 75%. This was followed by 30 strokes incrementally increasing up to 90% of their perceived maximum. The table below (Table 4.1) shows the ergometer resistance settings used to account for differences in body mass that would affect boat speed on the water. The ergometer was calibrated at the beginning of each testing session and settings were used as per the manufacturer's instructions by selecting the relevant resistance on the fan wheel according to body weight (Table 4.1).

Table 4. 1: Ergometer settings for adjusted resistance according to paddler's body weight. (Dansprint, Sweden)

Athlete Weight (kg)	<50	50 - 60	60 - 70	70 - 80	80 - 90	90 – 100
Fan Resistance	1	1 - 4	3 - 6	5 - 8	6 - 9	7 – 10

Indoor ergometers have previously been adapted to better represent the water (Begon *et al*., 2009). The same simple method was employed in this study to represent the lateral instability of the water as was used in Chapter 2, a round, inflated disc was placed on the seat of the ergometer (Figure 2. 8) so that the participant had to actively balance their trunk and pelvis during the time trial.

The procedure on muscle activation measurement with the use of electromyography

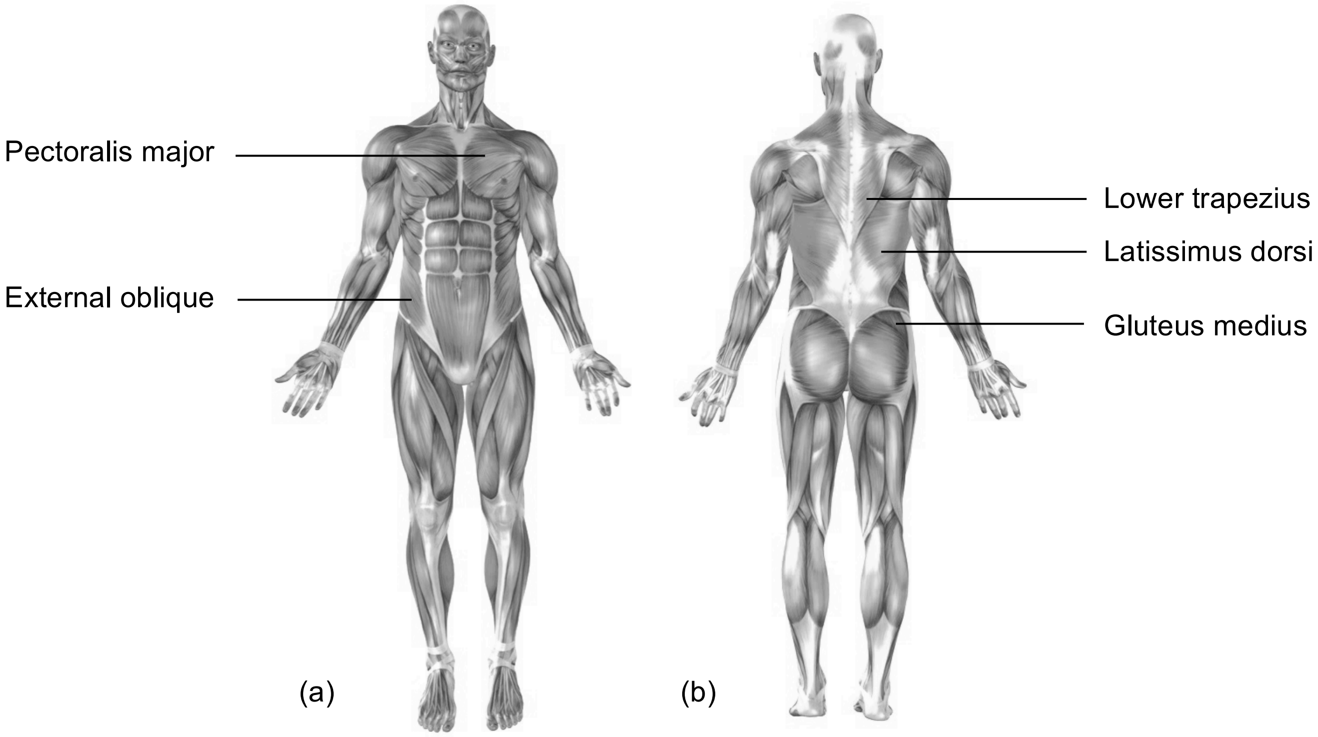

Figure 4. 1: Muscle groups selected for electromyographic analysis for muscle recruitment timing.

Displaying muscles for (a) anterior musculature and (b) posterior musculature. Erector spinae is not shown as it is the most superfical muscle layer.

The electromyography (EMG) activity of selected muscles was recorded using the telemetric EMG system (Telemyo 900, Noraxon, USA, Inc., Arizona, USA) during the 200 m maximal time trial and the single arm pull test (described subsequently). Two electrodes (Blue Sensor, Medicotest, Denmark) were placed on the belly of the right latissimus dorsi (LD), right lower trapezius (LT), left pectoralis major (PM) and bilaterally on the external obliques (EO), erector spinae longissimus (ES) and gluteus medius (GM) muscles (Figure 4.1, Appendix 3). Prior to placing the electrodes on the skin, the skin over the muscle was shaved and cleaned with ethanol. The placement and location of the electrodes were recorded and placed according to the recommendations by SENIAM (Surface EMG for Non-invasive Assessment of Muscles, http://www.seniam.org) and precise measurements used are included in Appendix 3 for reference. Two electrodes were carefully taped to the belly of each muscle, parallel to the muscle fibers with an inter-electrode distance of 20 mm. Data was captured at 2000 Hz. The wire-leads connected to the electrodes were secured with tape to avoid artefacts from upper limb movements during paddling; the signal was relayed via wifi to a computer. Before recording the EMG, each participant was asked to contract their muscles to verify the absence of crosstalk in the EMG signal.

The raw EMG signals were band pass filtered between 20 and 500Hz. This allowed noise or movement interference to be cut out below 20 Hz and above 500 Hz. The data was then rectified and smoothed using route mean squared analysis (RMS). All signals were expressed as a percentage of the highest RMS EMG amplitude recorded at any stage during the ergometer TT, as performed by Trevithick *et al*., 2007. The method of normalising EMG data so a maximal sprint has been shown to be a better representation of functional muscle activity compared to normalising EMG data to a maximum voluntary contraction (Albertus, 2008).

The magnitude of the amplitude of the EMG data can be affected by factors such as cross-talk from neighbouring muscles and the distance of the muscle from the electrode (adipose layers) (De Luca, 1997). Even after normalisation to max, the timing of muscle recruitment is described by De Luca (1997) as a superior, more robust measurement compared to the magnitude of amplitude. Therefore, we chose to focus the EMG analysis in this study on the timing of muscle recruitment within the kayak stroke relative to each phase and not on the values themselves.

In the results section, the measured muscles are reported in the following groups: The power producing muscles (Rt. LD, Lf. PM and bilateral EO), the stabilising muscles, (bilateral ES and bilateral GM) and the shoulder-stabilising muscles (Rt. LT).

The procure of biomechanical referencing and integration with EMG

A camera (HD Pro Webcam C920, Logitech) placed anterior to the ergometer was synchronised with EMG recording in MyoResearch XP (Noraxon, Arizona, USA) software. The video footage was used as a biomechanical reference to determine the phase of the kayak stroke. The EMG data was temporally normalised in custom written MATLAB^{TM} code (The Mathwork Inc.) for analysis of each phase of the stroke cycle, as described subsequently and presented in Table 4.2. Therefore, each phase represents a normalised timeframe that equally represented all phases within a stroke cycle.

A level two model of stroke analysis was performed, as defined by McDonnell *et al.* (2012). The water and air phase were analysed with the air phase being divided into two sub-phases; the preparation and recovery phases.

The horizontal bar of the ergometer and the paddle shaft were used to determine start and the end of each stroke phases (Table 4.2). When the tip of the paddle shaft dropped below and rose above the horizontal frame of the ergometer, the pull phase (representing the water or propulsion phase of the kayak stroke) was initiated and completed, respectively. The air phase consisted of two phases; the recovery and preparation phases. The recovery phase started as the pull phase ended and lasted until the paddle shaft was held in a horizontal position. The preparation phase started with the horizontal paddle shaft and concluded as the pull phase (as the paddle shaft tip dropped below the horizontal bar) on the other side began (Table 4.2).

Table 4. 2: The biomechnical references used to determine the change in the stroke phases of the ergomter time trial for the time-normalised data.

Displays the paddle shaft postions that dipict the phase of stroke as a percent of a stroke cycle from the beginning of the right pull to the beginning of the right pull of the next stroke cycle. These stroke phases were used in the analysis of the the EMG data. Each phase was time normalised.

% of stroke cycle:	0	33	67	100 / 0	33	67	100

The procedure of the single arm pull test

Following the ergometer TT, participants were tested on a single arm pull machine (Figure 2. 7), as described in Chapter 2 of this thesis. This piece of equipment is used internationally by sprint kayakers for kayak specific strength training since it uses the same body motions as those required for the pull phase of the kayak stroke (drawing the body towards an outstretched arm, using shoulder extension, retraction, elbow flexion, trunk and pelvis rotation).

It was used in the present study because it isolates one pull phase at a time, therefore reducing the complexity of movement and testing only the important, power-producing phase of the stroke cycle. The device can be used for right and left pull phases, however, only the right pull phase was tested in this study. Similar to the ergometer time trial, an air-disc was placed on the seat single arm pull device to represent the lateral instability of the water conditions.

Participants were familiarised with using the machine and the distance of the seat from the foot bar was selected to resemble their boat set-up. Each participant performed 10 maximal pulls with the aim of generating as much pulling power as possible. The muscle recruitment from the first 5 pulls has been included for analysis and is presented as a mean for each individual as well as a group mean for the males and female participants. The first 5 right pull phases from the ergometer time trial are compared against the single arm pulling movement. The resisted pull test followed the ergometer TT on the same day, therefore there were no differences in EMG electrode location between conditions.

Methods of statistical analysis

The data were analysed using Statistica Version 11 (StatSoft Inc. Tulsa, OK, USA). All data are resented as mean ± standard deviation (SD). Significance for all statistical analysis was determined by a p value of less than 0.05. The male marathon paddlers and the female marathon paddlers were analysed as two separate sub-groups.

The coefficient of variation (CV) was calculated for each muscle group during each phase of the stroke cycle. The EMG from each muscle group was analysed for distribution using the Shapiro Wilk test for normality. Dependent students t tests were performed for investigating differences in the right and left pull phases of each muscle group.

General linear models were performed for investigation of the difference in muscle activity between the two tasks (Rt. Single arm pull vs. Rt. pull phase on the ergo). A Tukeys honestly significant deference (HSD) test was then performed to determine within group effects of the side differences (left vs. right) and the differences between the two tasks (Rt. Single arm pull vs. Rt. pull phase on the ergo).

Results

Muscle activation timing during the maximal ergometer time trials

Figures 4.2 and 4.3 present the muscle activation of the power-producing and stabilsing muscle groups respectively, for the male (left) and female (right) participants. The x-axis depicts the various stroke phases, starting and ending with the beginning of the right pull phase. The dark grey blocks indicate the right pull phase and the light grey blocks the left pull phase. It is during these pulling phases that participants worked against the greatest resistance from the ergometer’s fan wheel. All participants were right hand dominant.

All power producing muscles had atypical findings. The right LD and left PM muscles were more active during the left pull phase compared to the right pull phase (Figure 4.2, Table 4.3 & 4.4). The external obliques were more active during the ipsilateral pull phase compared to the contralateral pull phase (Figure 4.2, Table 4.3 & 4.4).

During testing the recordings of the activation of one Rt. LD muscle, one Lf. EO and one Lf. GM was lost from the group of female participants. These were not from the same participant. In the male participants, there was data from one participant lost on his Rt. LD. The lifting of electrodes during the maximal TT disrupted the data.

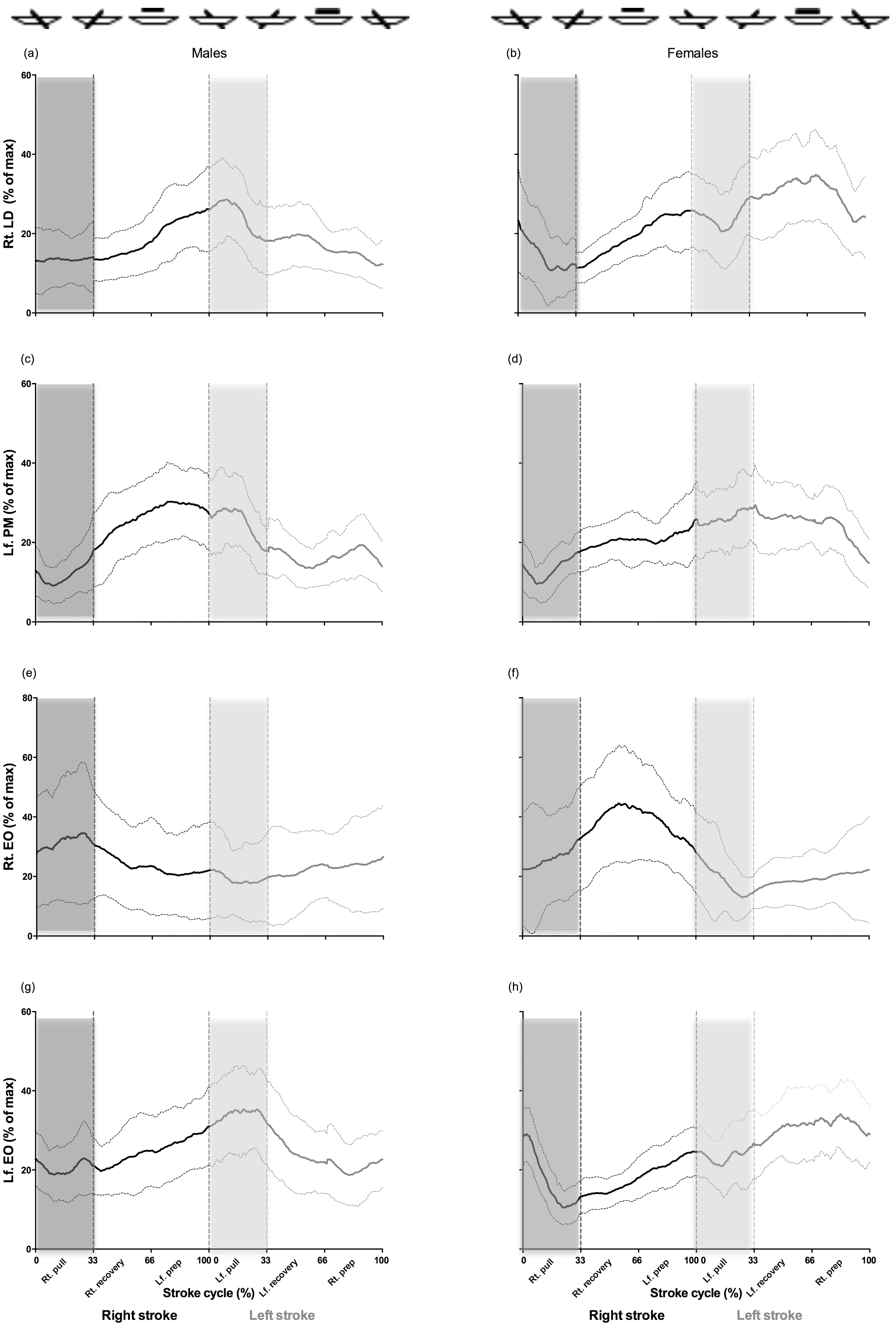

Figure 4. 2: Muscle activation of power-producing muscles during a maximal ergometer time trial.

Depicts the mean muscle activity (solid line) and ± SD (dashed lines) for Rt. LD (top panel), Lf. PM (second panel), Rt. EO (third panel) and Lf. EO (bottom panel).

The right and left ES of the lumbar spine were more active during the contralateral pull phase (Figure 4.3, Table 4.3 & 4.4) on both sides, for both sexes. Gluteus medius activity was greater during the ipsilateral pull phase compared to the contralateral pull phase (Figure 4.3, Table 4.3 & 4.4), for both sexes, on both sides.

The Rt. LT in the group of male paddlers showed consistent activation during the right and left strokes with a peak occurring during the left pull phase. In the group of female paddlers, the Rt. LT activity dropped during the right pull phase and increased again during the transition from the right to left pull phases, remaining constant for the lefts stoke (Figure 4.4, Table 4.3 & 4.4).

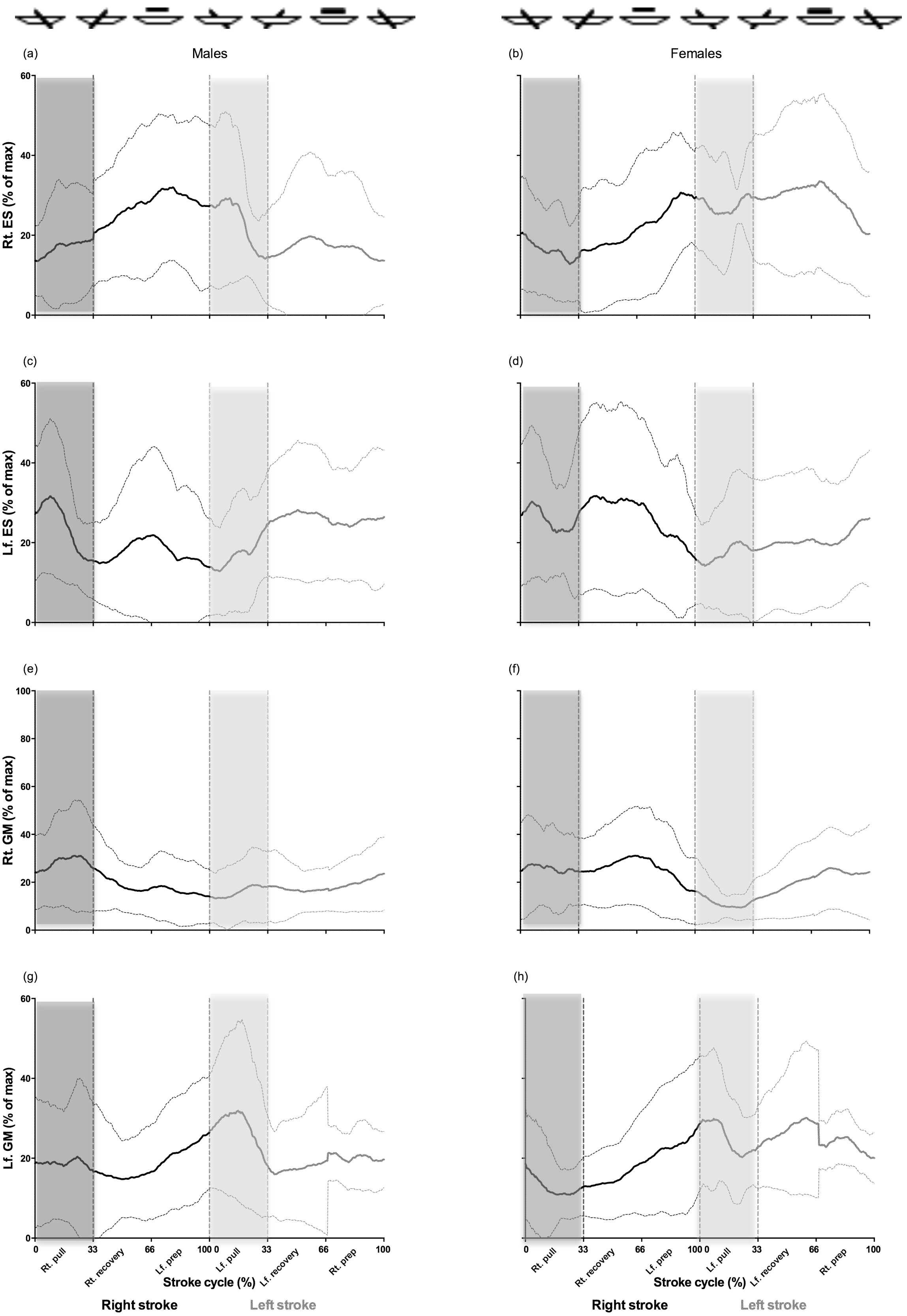

Figure 4. 3: Muscle activation of the stabilising muscles during a maximal ergometer time trial. *Depicts the mean muscle activity (solid line) and ± SD (dashed lines) for Rt. ES (top panel), Lf. ES (second panel), Rt. GM (third panel) and Lf. GM (bottom panel).*

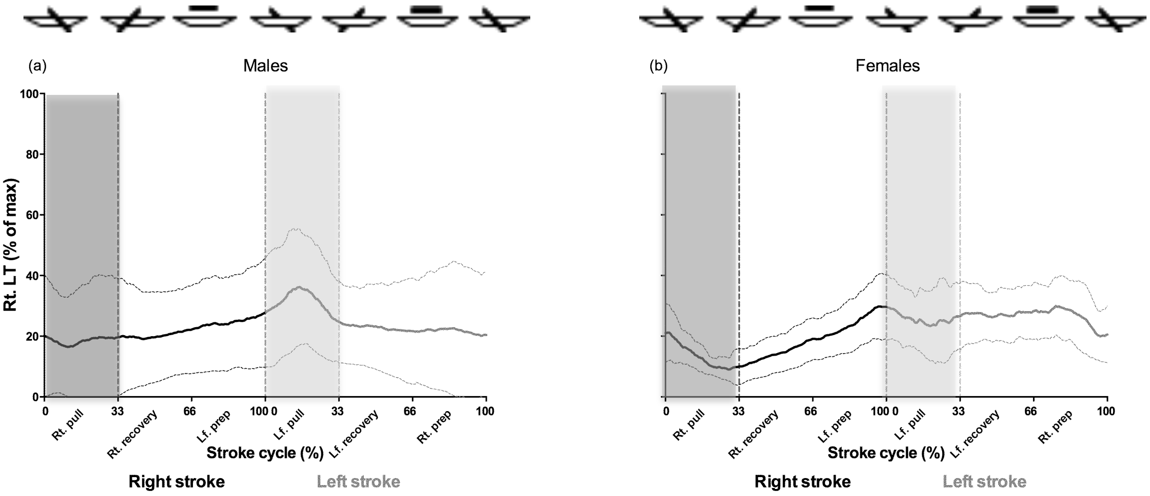

Figure 4. 4: Muscle activation of a shoulder stabilising muscles during a maximal ergometer time trial. *Depicts the mean muscle activity (solid line) and ± SD (dashed lines) for Rt. LT.*

Table 4. 3: Muscle activation of all measured muscle groups for the male marathon padlers during a maximal time trial.

*Displays the preparation, pull and recovery phases for the right and left strokes. * p < 0.05 for Rt. vs. Lf. pull.*

Muscle group		**Mean EMG ± SD (% of maximum EMG measured during time trial) and coefficient of variation (CV) (%) for male paddlers**					
		Right stroke			**Left stroke**		
		Preparation phase	**Pull phase**	**Recovery phase**	**Preparation phase**	**Pull phase**	**Recovery phase**
Rt. LD	**Mean ± SD**	**15.08 ± 13.78**	**14.23 ± 11.17**	**15.47 ± 12.63**	**24.24 ± 17.39**	**22.45 ± 12.86***	**15.08 ± 13.78**
	CV	91.38	78.50	81.64	71.74	57.28	91.38
Lf. PM	**Mean ± SD**	**17.90 ± 18.06**	**12.65 ± 7.50**	**17.90 ± 18.06**	**27.55 ± 17.26**	**23.49 ± 12.53***	**26.57 ± 16.92**
	CV	100.10	59.29	100.10	62.65	53.34	63.68
Rt. EO	**Mean ± SD**	**24.38 ± 15.24**	**30.81 ± 18.84***	**22.69 ± 9.61**	**21.40 ± 14.05**	**18.98 ± 11.45**	**24.38 ± 15.24**
	CV	62.51	61.15	42.35	65.65	60.33	62.51
Lf. EO	**Mean ± SD**	**20.36 ± 14.06**	**21.03 ± 13.46**	**23.01 ± 11.56**	**28.40 ± 13.30**	**33.49 ± 17.55***	**20.36 ± 14.06**
	CV	69.06	64.00	50.24	82.04	52.40	69.06
Rt. ES	**Mean ± SD**	**16.68 ± 16.07**	**17.98 ± 12.66**	**24.43 ± 14.77**	**30.34 ± 17.18**	**24.16 ± 11.77***	**16.80 ± 16.60**
	CV	96.34	70.41	60.46	56.62	48.72	98.80
Lf. ES	**Mean ± SD**	**25.28 ± 13.26**	**24.24 ± 12.04**	**18.14 ± 14.60**	**17.07 ± 17.72**	**17.52 ± 11.07**	**25.28 ± 13.26**
	CV	52.45	49.67	80.49	103.81	63.18	52.45
Rt. GM	**Mean ± SD**	**20.59 ± 12.15**	**27.28 ± 17.94**	**19.01 ± 10.34**	**17.36 ± 12.86**	**17.25 ± 12.54**	**20.59 ± 12.15**
	CV	59.01	65.76	54.39	74.08	72.70	59.01
Lf. GM	**Mean ± SD**	**20.14 ± 6.84**	**18.78 ± 15.07**	**15.60 ± 10.53**	**21.88 ± 12.91**	**27.55 ± 16.94***	**20.14 ± 6.84**
	CV	33.96	80.24	67.50	59.08	61.49	33.96
Rt. LT	**Mean ± SD**	**21.60 ± 19.95**	**18.54 ± 16.68**	**20.30 ± 14.37**	**24.76 ± 14.59**	**31.28 ± 14.50***	**21.60 ± 19.59**
	CV	92.36	89.97	70.79	58.93	46.36	90.69

Table 4. 4: Muscle activation of all measured muscle groups for the female marathon padlers during a maximal time trial.

*Displays the preparation, pull and recovery phases for the right and left strokes. . * $p < 0.05$ for Rt. vs. Lf. pull.*

Muscle group		**Mean EMG ± SD (% of maximum EMG measured during time trial) and coefficient of variation (CV) (%) for female paddlers**					
		Right stroke			**Left stroke**		
		Preparation phase	**Pull phase**	**Recovery phase**	**Preparation phase**	**Pull phase**	**Recovery phase**
Rt. LD	**Mean ± SD**	**32.33 ± 18.55**	**14.39 ± 6.75**	**13.01 ± 12.14**	**20.38 ± 20.20**	**22.09 ± 13.42***	**32.22 ± 18.55**
	CV	57.38	46.91	93.31	99.12	60.75	57.57
Lf. PM	**Mean ± SD**	**21.88 ± 11.51**	**32.32 ± 10.68***	**19.90 ± 14.32**	**21.70 ± 14.76**	**26.38 ± 10.94**	**21.88 ± 11.51**
	CV	52.61	33.04	71.96	68.02	41.48	52.61
Rt. EO	**Mean ± SD**	**20.66 ± 12.07**	**26.14 ± 12.67**	**40.57 ± 16.93**	**36.19 ± 11.91**	**18.53 ± 9.13**	**20.66 ± 12.07**
	CV	58.42	48.47	41.73	32.90	49.27	58.42
Lf. EO	**Mean ± SD**	**34.50 ± 17.55**	**18.77 ± 9.38**	**20.84 ± 17.57**	**24.61 ± 20.98**	**22.29 ± 9.68**	**34.50 ± 17.55**
	CV	50.87	49.97	84.31	85.25	43.43	50.87
Rt. ES	**Mean ± SD**	**27.09 ± 18.27**	**16.18 ± 8.93**	**18.02 ± 14.86**	**26.65 ± 14.74**	**27.53 ± 6.10***	**27.09 ± 18.27**
	CV	67.44	55.19	82.46	55.30	22.16	67.44
Lf. ES	**Mean ± SD**	**22.20 ± 14.51**	**25.87 ± 8.25***	**30.47 ± 22.50**	**22.62 ± 16.80**	**17.36 ± 12.33**	**22.20 ± 14.51**
	CV	65.36	31.89	73.84	74.27	71.03	65.36
Rt. GM	**Mean ± SD**	**22.89 ± 17.16**	**22.37 ± 10.20***	**28.69 ± 16.66**	**26.01 ± 16.99**	**11.65 ± 5.63**	**22.89 ± 17.16**
	CV	74.97	45.60	58.07	65.32	48.33	74.97
Lf. GM	**Mean ± SD**	**23.08 ± 4.70**	**12.82 ± 7.61**	**14.92 ± 9.19**	**23.05 ± 15.50**	**24.87 ± 9.18***	**23.08 ± 4.70**
	CV	20.36	59.36	61.61	67.25	36.91	20.36
Rt. LT	**Mean ± SD**	**25.90 ± 15.99**	**13.44 ± 7.62**	**14.26 ± 13.99**	**24.15 ± 22.11**	**25.71 ± 13.57***	**25.90 ± 15.99**
	CV	61.74	56.70	98.11	91.55	52.78	61.74

Individual variation

Figures 4.5 – 4.7 repeat the depiction used in Figures 4.2 - 4.4 but display each individual paddler's mean muscle activation during the stroke cycle. Tables 4.3 and 4.4 display large coefficients of variation (46 - 100 %). Comparison of the individual data was performed to gain better insight into the large SD and CV in the previous figures and tables (Figures 4.2 - 4.4, Tables 4.3 & 4.4).

The figures displaying data from each individual (Figures 4.5 - 4.7) reveal that the previously reported mean muscle recruitment (Figures 4.2 - 4.4) is not an accurate representation of the group, as it does not match the shape of any of the individual's muscle recruitment.

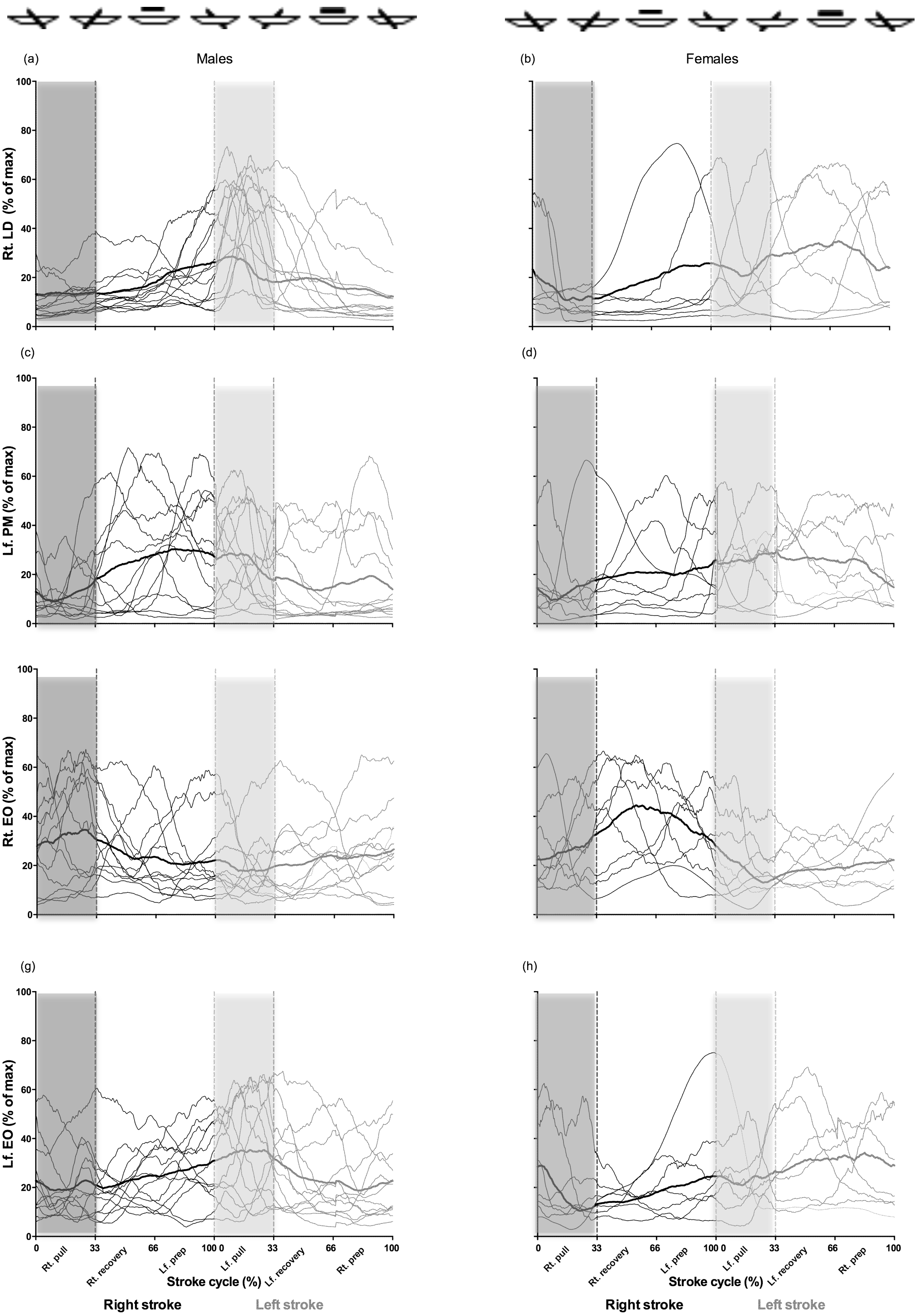

Figure 4. 5: Muscle activation of power-producing muscles for each participant during a maximal ergometer time trial.

Depicts each paddler's muscle activity (fine lines) and mean muscle activity (thick line) for Rt. LD (top panel), Lf. PM (second panel), Rt. EO (third panel) and Lf. EO (bottom panel).

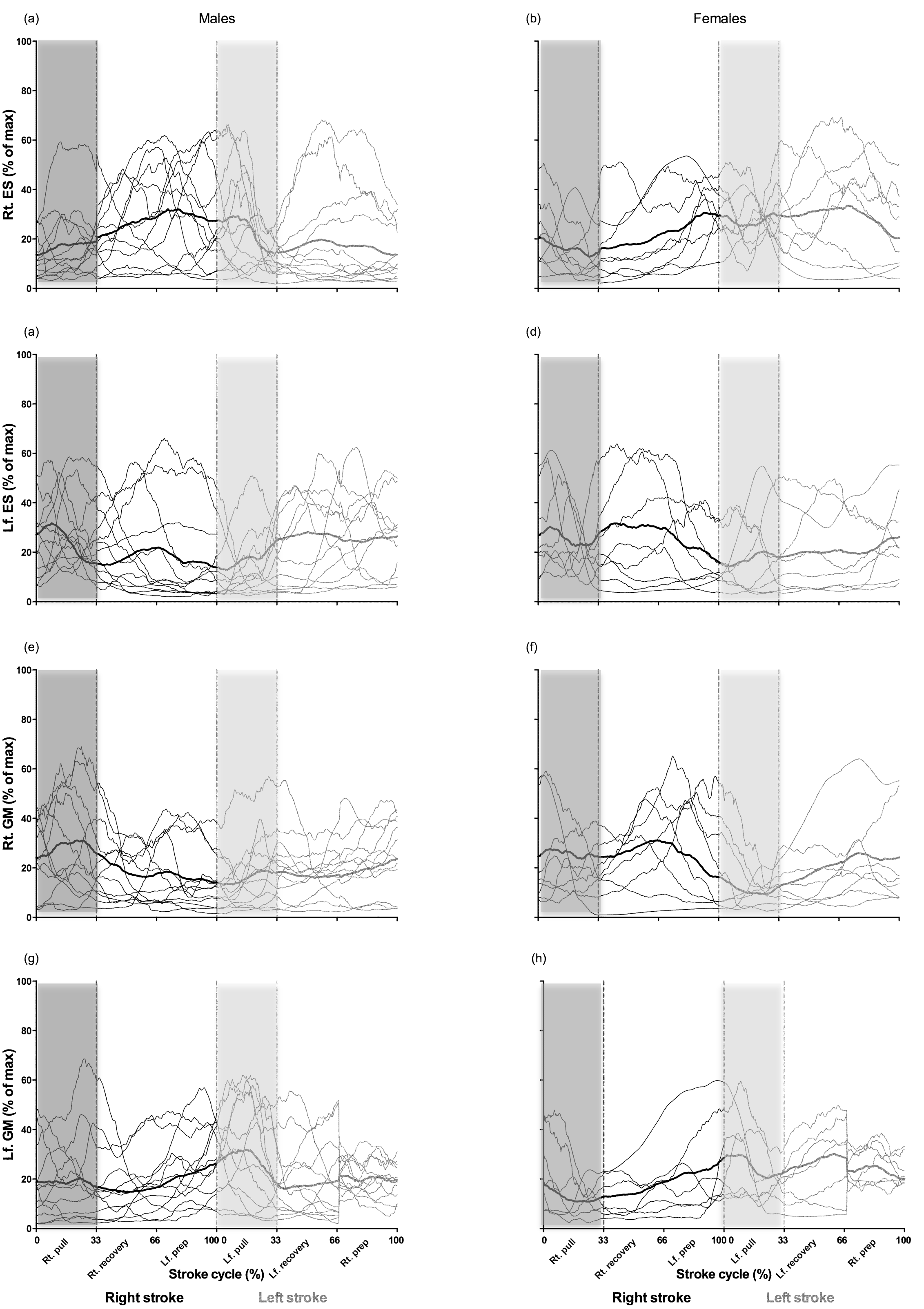

Figure 4. 6: Muscle activation of stabilising muscles for each participant during a maximal ergometer time trial.

Depicts each paddler's muscle activity (fine lines) and mean muscle activity (thick line) for Rt. ES (top panel), Lf. ES (second panel), Rt. GM (third panel) and Lf. GM (bottom panel).

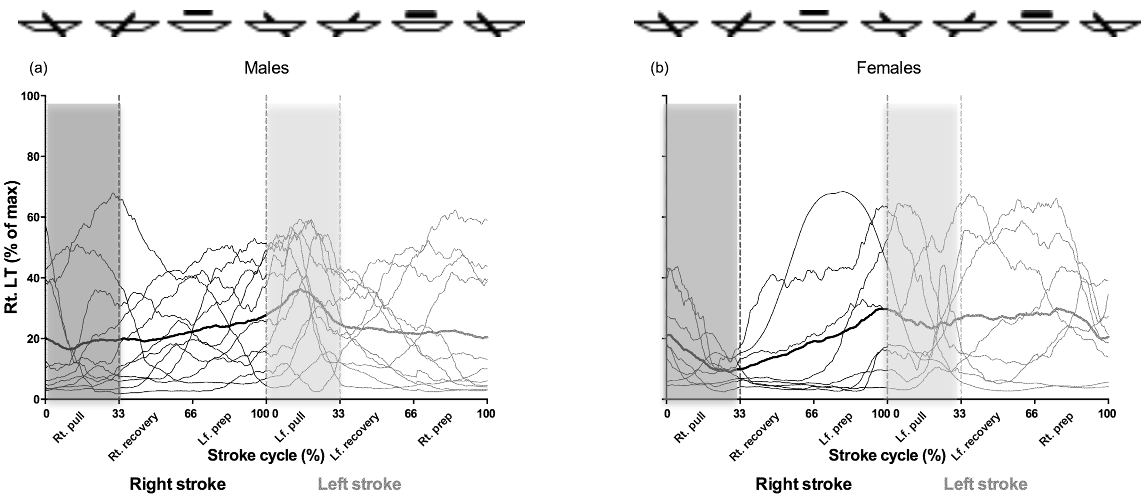

Figure 4. 7: Muscle activation of a shoulder stabilising muscles for each participant during a maximal ergometer time trial.

Depicts each paddler's muscle activity (fine lines) and mean muscle activity (thick line) for Rt. LT.

Muscle activation timing during the single arm pull test

Figures 4.8 – 4.10 and Table 4.5 display the muscle activation during the first five contractions on the single arm pull device, and compare this to the mean muscle activation during the pull phase of the first five strokes during the ergometer time trial. The fine lines represent the individual data, the thick solid line represents the mean from the single arm pull and the thick dotted line represents the mean of the right pull phase from the previously conducted ergometer time trial (phase between the y-axis and the vertical dark grey dashed lines Figures 4.2 – 4.7).

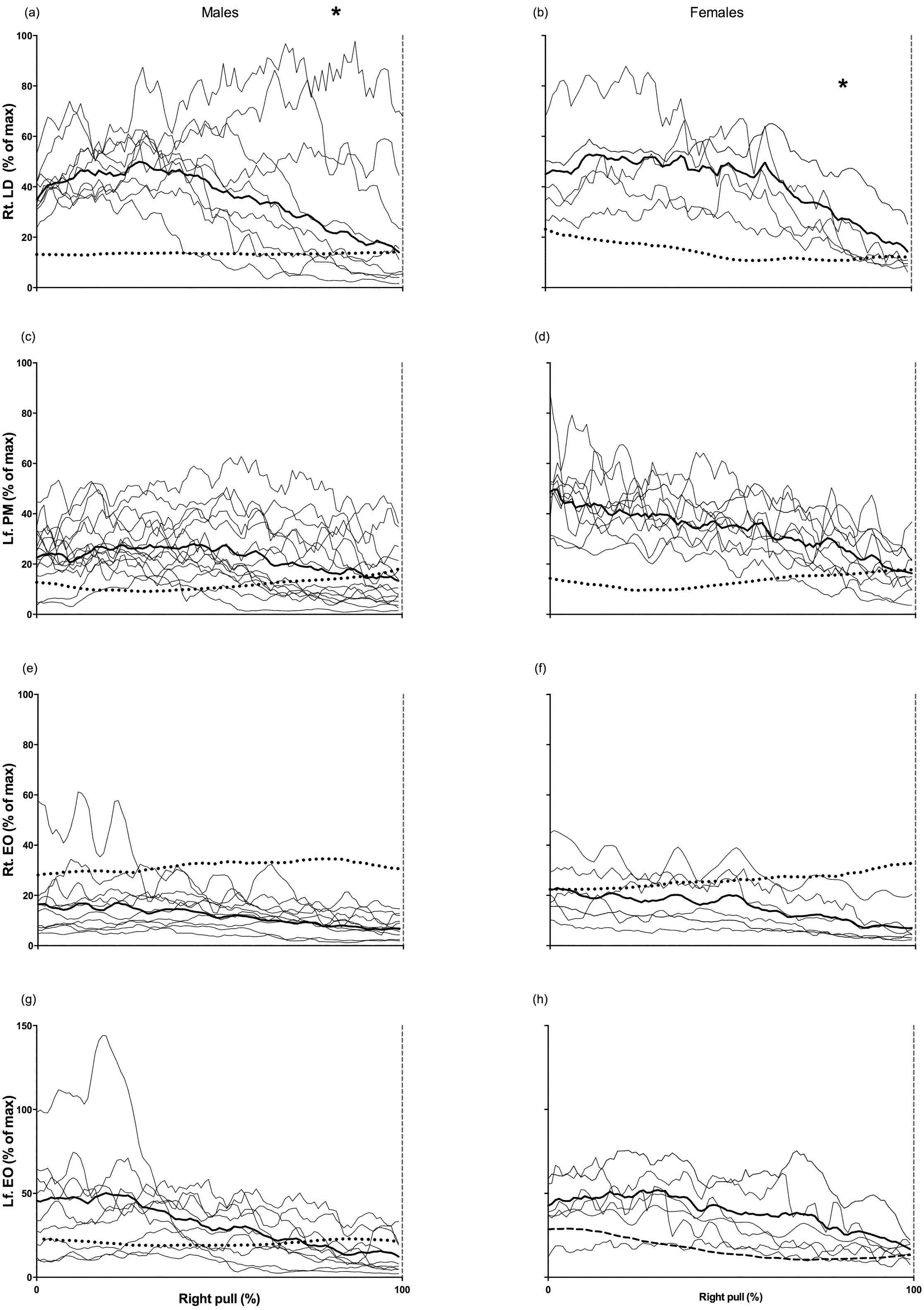

Figure 4. 8: Muscle activation of power-producing muscles during the single arm pull test on the right and the right pull phase from the maximal ergometer time trial.

Depicts each paddler's muscle activity (fine lines) and the mean muscle activity (thick line) during the single arm pull test, compared against the right pull phase from the ergometer time trial (dotted line) for Rt. LD (top panel), Lf. PM (second panel), Rt. EO (third panel) and Lf. EO (bottom panel). $p < 0.05$ for single arm pull vs. Rt. Pull phase on the ergometer.*

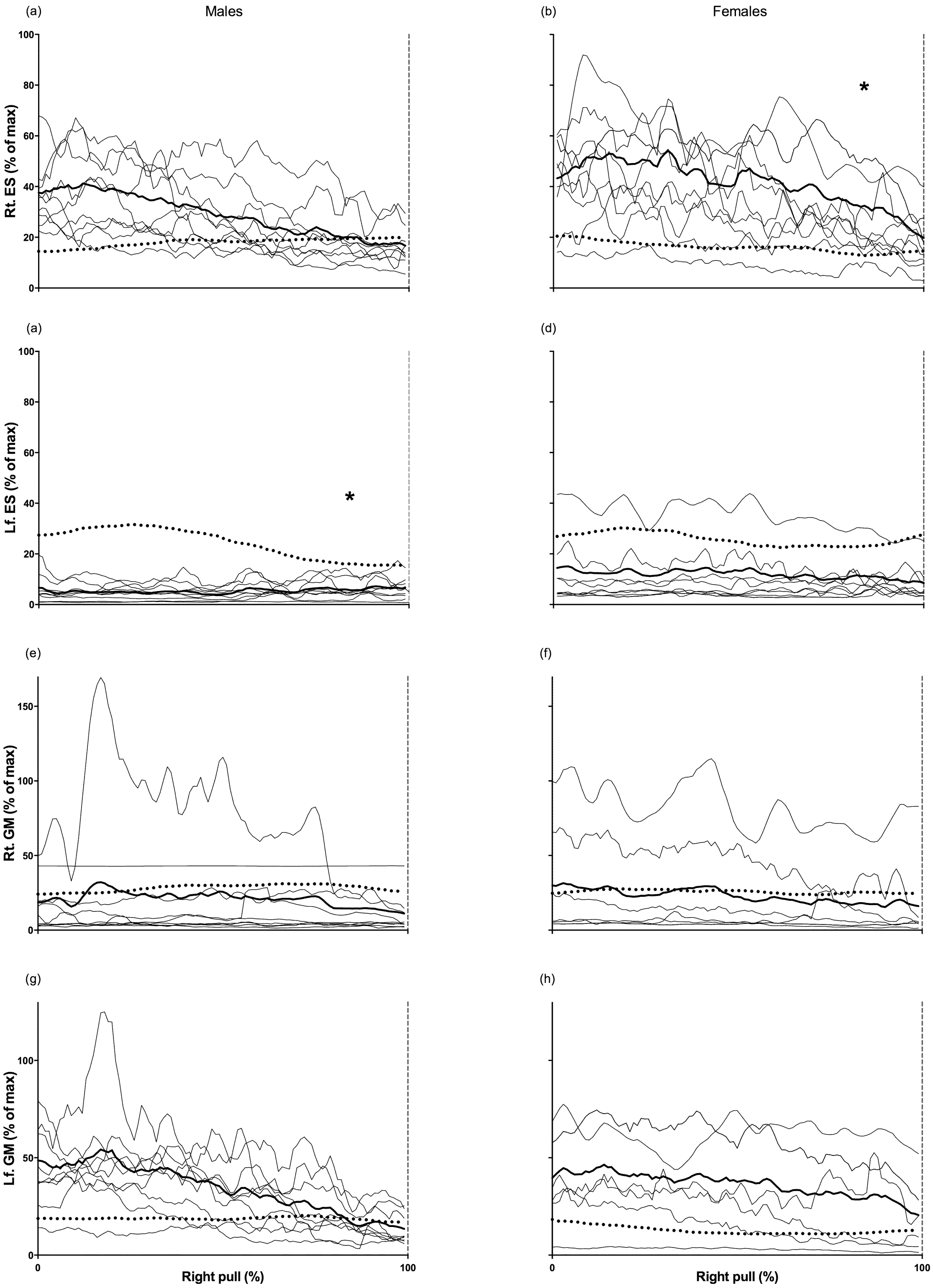

Figure 4. 9: Muscle activation of stabilising muscles during the single arm pull test and a maximal ergometer time trial.

*Depicts each paddler's muscle activity (fine lines) and the mean muscle activity (thick line) during the single arm pull test, compared against the right pull phase from the ergometer time trial (dotted line) for Rt. ES (top panel), Lf. ES (second panel), Rt. GM (third panel) and Lf. GM (bottom panel). * $p < 0.05$ for single arm pull vs. Rt. Pull phase on the ergometer.*

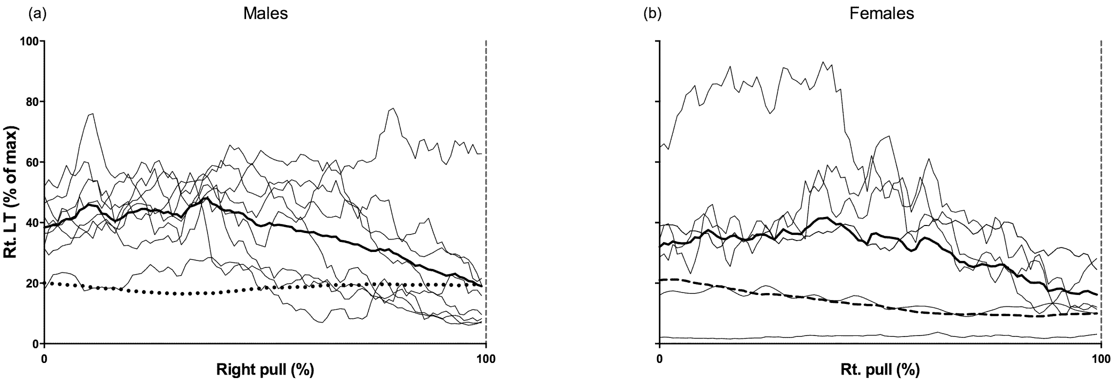

Figure 4. 10: Muscle activation of a shoulder stabilising muscle during the single arm pull test and a maximal ergometer time trial.

*Depicts each paddler's muscle activity (fine lines) and the mean muscle activity (thick line) during the single arm pull test, compared against the right pull phase from the ergometer time trial (dotted line) for Rt. Lower trapezius * $p < 0.05$ for single arm pull vs. Rt. Pull phase on ergometer.*

Muscle activation was greater during the single-arm pull for the Rt. LD, Rt. LT, Lf. PM, Lf. EO, Rt. ES and Lf. GM compared to the pull phase during the ergometer time trial (Table 4.5). In contrast, muscle activation of Rt. EO and Lf. ES were greater during the ergometer time trial (Table 4.5).

Table 4. 5: Muscle activation of all measured muscle groups for male and female marathon paddlers during a single arm pull motion and the right pull phase on the ergometer.

Displays the mucsle activation during five single arm pulls to the first five right pull phases on the ergometer.
**p < 0.05 for single arm pull vs. right pull phase.*

	Mean EMG per muscle group (% of maximum EMG measured during time trial)			
	Males		Females	
Muscle Groups	**Single arm pull, on the right side** (mean of 5 reps)	**Right pull phase from the ergometer** TT (first five strokes)	**Single arm pull, on the right side** (mean of 5 reps)	**Right pull phase from the ergometer TT** (first five strokes)
	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD
Rt. LD	40.21 ± 18.16*	13.70 ± 10.52	40.92 ± 10.93*	15.21 ± 7.03
Lf. PM	22.94 ± 12.88	12.61 ± 6.25	33.65 ± 8.35	15.40 ± 10.44
Rt. EO	12.53 ± 6.61	29.45 ± 18.78	15.42 ± 9.24	24.24 ± 12.50
Lf. EO	29.81 ± 13.74	20.48 ± 11.93	39.01 ± 16.43	21.15 ± 11.43
Rt. ES	27.64 ± 10.03	18.82 ± 15.00	41.22 ± 17.32*	16.18 ± 9.45
Lf. ES	5.31 ± 2.71	25.00 ± 12.30*	11.96 ± 12.02	25.81 ± 11.38
Rt. GM	19.04 ± 21.12	28.18 ± 18.30	23.05 ± 29.37	18.97 ± 11.30
Lf. GM	32.15 ± 13.60	14.36 ± 7.82	36.35 ± 23.74	17.17 ± 13.66
Rt. LT	36.78 ± 11.57	18.29 ± 15.28	30.83 ± 17.50	12.45 ± 5.59

Discussion

Overview of the paradoxical findings of muscle activation timings

A combination of the push and pull ability required for paddling is well accepted (van Someren & Howatson, 2008; Garcia – Pallares *et al*., 2009; McKean & Burkett, 2009). As one arm is pulling on the resistance of the water of the submerged paddle to draw the boat past it, the other arm (with the aerial paddle blade) is pushing the paddler and the boat forwards, against the resistance of the submerged paddle blade.

It is not surprising therefore that the right latissimus dorsi, a muscle anatomically positioned to pull the body towards an outstretched arm, has been found to be active at the same time as the left pectoralis major muscle, which is designed to adduct, or push the arm towards the midline. Both of these muscles have also been found to activate during rotation to the side of the LD (right side in this case) (McGill, 1991) (Figure 4.2, Tables 4.4 & 4.5). What is surprising however, is that the maximal contractions occurred during the left pull phase.

Therefore, compared to previous electromyographic studies on kayaking (Trevithick *et al*., 2007; Brown, 2009; Fleming *et al*.; 2012), this sample of marathon paddlers presented with atypical strategies of muscle recruitment and will be described subsequently.

Another clinically applicable and novel finding of the present study, was the large variation in activation strategies between kayakers revealed by the large coefficient of variance (Tables 4.4 & 4.5) and the busyness of Figures 4.5 - 4.7.

Ipsilateral LD and contralateral PM during the pull phase of the ergometer TT results

Two of the female paddlers and one of the male paddlers used their Rt. LD as its anatomical function prescribes for concentric activation (extending the shoulder and rotating the trunk to the ipsilateral side), thus their activations agreed with previous investigations of neuromuscular contribution during kayaking (Trevithick *et al*., 2007; Brown, 2009; Fleming *et al*., 2012). The remaining participants however, used their Rt. LD during the left pull phase and during the air phase from the left to the right stroke, therefore using this muscle during the push rather than the pull phase.

Similarly, the left PM was found to be most active during the left pull phase, when the left arm was pulling on the water resistance with the shoulder in an abducted position (Figure 4.2, Tables 4.4 & 4.5) rather than during the push phase, as expected.

This suggests that the PM was recruited to provide support or control of the pull forces (which were being generated from other muscle groups) rather than contribute to the push forces as was hypothesised.

If the LD (previously described as a prime mover) was not generating a pulling force during the ipsilareral pull phase, other muscle groups need to be considered. Further research, including bilateral muscle activation analysis with intra-stroke biomechanical referencing is need to further explore the mucles activation timings of marathon paddlers.

Bilateral EO and GM muscle groups during the pull phase of the ergometer TT results

The EO, a powerful trunk rotator towards the contralateral side, was found to be more active during ipsilateral pull phase. The muscle was therefore bracing the trunk isometrically or eccentrically rather than rotating it concentrically, depending on the movement of the trunk during this phase. Recruitment of the EO of the contralateral stroke during on-water paddling has been found to be associated with boat speed and paddle force production

(Brown, 2009) and ipsilateral trunk rotation contributes to efficiency during tests on an ergometer with a sliding seat (Begon *et al*., 2010).

In the GM muscle groups our hypothesis was again disproved, with both groups recruiting the ipsilateral GM more than the contralateral GM to the stroke side (Figure 4.3, Tables 4.4 & 4.5). The GM's were therefore not counter-stabilsing the pelvis during the pull phase as we had anticipated. If the paddlers were shifting their weight away from the stroke side (rolling away from the stroke as found in chapter 3), in which case the GM muscles were providing a counter balance by laterally stabilising the pelvis as hypothesised, but just in the oppoiste direction.

The paddlers were not found to recruit bilateral muscle groups in opposing manners, so that the left and right GM, ES and EO activations were not mirrored during the left and right strokes. This shows variation in the muscle co-ordination between sides while paddling and builds on Chapter 4's finding of asymmetrical paddle forces and boat kinematics as these differences in recruitment strategies have possible implications for power transfer and weight distribution in the boat while paddling on the water.

Ipsilateral LT during the pull and push phases of the ergometer TT results

As discussed extensively in Chapter 2, the function of the LT is to move the scapula and therefore the glenoid (Kibler, 1998). As the humerus is lifted the glenoid moves with it to maintain the humeral head in the centre of the shoulder joint. The LT aslo assits the serratus anterior muscle in posteriorly tilting the scapula (Kibler, 1998).

In the ergometer TT the LT was most active during the right push (left pull) and least active during the righ pull phase (13.44 ± 7.62% of max vs. 25.90 ± 15.99% of max, Figure 4.4, Table 4.3) for the males. In the group of female paddlers, the LT was most active during the left exit phase and least active during the right pull phase (18.54 ± 16.68% of max vs. 31.28 ± 14.50% of max, Figure4.4, Table 4.4). The validity of the mean results are brought into question when the data from each individual is graphed in Figure 4.7.

The phasic varaiablity between mucle activations of the particiapnts

The large standard deviations around the means and high coefficient of variation values (46 - 100 %). resulted in few statistically significant findings (Tables 4.3 & 4.4). This prompted the individual's data to be analysed, revealing large individual variation of both magnitude and phasic variability (Figures 4.5 – 4.7) for all muscle groups tested.

The inter-individual varaibility has implications for understanding the complexity of the technical aspects of kayaking. The data from this study reveals that each particiapant was recruiting their muscles in differing patterns. Further investigations into the muscle activation timing coupled with accurate three-dimensional kinematics would help to further explore these findings.

The inter-individual variability in Figures 4.5 – 4.7 triggers the consideration of what intra-individual variability exists. Chapter 6 explores the intra-individual variability of two participants.

Muscle activations during the right pull phase on the ergometer and on the single arm pull device

Further confirmations of the atypical ergometer muscle activation patterns are provided when comparing the activity measured during the single arm pull. When these two groups of top level marathon paddlers (males and females) were asked to perform a one-sided stroke (Figures 4.8 - 4.10) their muscle recruitment patterns were similar to those reported in the literature for the pull phase of paddling (Trevithick *et al*., 2007; Brown, 2009; Fleming *et al*., 2012). These tests were performed on the same day, with the same electrode placements and with approximately an hour between them, and still the results are so different.

The marathon paddlers now used their Rt. LD and Lf. PM to pull and push respectively during a right pull action, and used the contralateral EO to push the torso toward the pull side (Figure 4.8, Table 4.5), which was hypothesised for optimal technique. Further, they recruited their Rt. ES and their Lf. GM significantly more than the other side (Figure 4.9, Table 4.5), thus agreeing with our initial hypotheses for these muscles. Force plates on the seat and footrest would provide greater insight into the relationship between torso and pelvic muscle recruitment and weight distribution. The Rt. LT was also activated better during this single arm movement on the right pull action, indicating better function of this dynamic scapula stabilising muscle group (Figure 4.10, Table 4.5).

Conclusion

During a maximal time trial on an ergometer, marathon paddlers activated muscles in opposing phases of the kayak stroke to what has previously been documented in the literature for sprint paddlers. Novel muscle groups tested also revealed paradoxical timing to what was hypothesised. All muscles tested displayed large inter-individual variability.

When these paddlers performed a simpler one-sided pull movement, to replicate the pull phase of the kayak stroke, the muscle activation strategies matched the hypotheses and what has been found in the literature for sprint paddlers.

Further research integrating paddler and boat kinematics with muscle activation timing, will assist in determining the performance implications of these findings.

Chapter 5: Practical and clinical applications from the findings of this thesis.

Data from the previous studies (in the thesis) are discussed in this chapter for application on an individualised basis. The content from each chapter (chapters 2 – 4) is taken in turn and interpreted for an individual, providing a summary of technical advice for coaches, trainers and athletes. This process facilitates maximal gain of the research for clinical and practical application to kayaking.

A two-step process for attaining and maintaining optimal shoulder biomechanics, recommended for optimising kayaking technique and for shoulder health in paddlers.

Step one: Screening for sub-optimal paddling specific adaptations

The principle behind preparation and training involves repeating similar movements over and over again, therefore refining the action so that it is performed better than before. With repetition comes adaptation, which is the goal of the training. It is important to ensure that these developed adaptations are only beneficial, and do not have other implications beyond improving the practised task. Further, it is important to determine if individualised strength imbalances or compensation patterns are developing due to the repetitive nature of paddle training that could be predisposing the individual to injury.

Paddlers have been found (in this thesis and from other research sources), to have certain adaptations that have been identified as intrinsic risk factors for shoulder injury (McKean & Burkett, 2009). The repetitive nature of paddling is likely the cause of these strength and mobility adaptations (Edwards, 1993).

These adaptions (limited shoulder rotation and weak scapular stabilisers compared to upper body strength, McKean & Burkett, 2009) have an impact on shoulder biomechanics and have been found to result in scapula downward rotation and anterior tilting both which impair the function of the shoulder and result in probable changes to the stroke kinematics (Kugler, 1996; Donatelli *et al*., 2000; Kibler, 2006). It is hypothesised that an upward rotating scapula that remains in neutral tilt during shoulder loading (the water phase of the kayak stroke and during strength training) is necessary for a wider stroke. A wider stroke has been described to optimise the use of the lift forces and lose less energy to drag resistance from the water.

Therefore, any person that is paddling frequently is advised to seek professional assistance for the assessment of movement, strength and mobility as described below. This assessment can be a helpful step in the prevention of intrinsic risk factors on an individual level, so that paddling-related adaptations do not affect shoulder and thus paddling biomechanics and so predispose the athlete to shoulder injury.

Paddlers have been found to have a high incidence of shoulder injures (Edwards, 1993), being largely being repetitive strain injuries of the tendons around the shoulder (rotator cuff and biceps tendons).

Interactions along the kinetic chain were beyond the scope of this thesis, however it is suspected that asymmetries in the pelvis and legs could affect the paddler's position in the boat and therefore paddling technique. Practical experience has revealed that asymmetries in the pelvis can cause asymmetries in the control of the boat and therefore uneven work for the back and shoulders. If a paddler presents with a long-standing shoulder injury aggravated by paddling, it is advised that a whole body assessment is conducted as paddling is not limited to the upper body but integrates all segments of the body.

From this thesis, it is recommended that the screening process for shoulders with the aim of identifying intrinsic risk factors for shoulder injuries should include thoracic spine extension range, shoulder rotation range, scapula kinematics and shoulder rotation strength ratios. These are discussed below.

Shoulder rotation range

Common limitations to shoulder range in paddlers has been found in internal rotation, as the ability to posteriorly tilt the scapula and posteriorly translate the humerus during active control of internal shoulder rotation was poor (Chapter 2).

Shoulder blade (scapula) position and movement

The shoulder is a ball-and-socket joint, with the head of the humerus, from the arm, being ‘the ball’ and the scapula forming ‘the socket’. Therefore, optimal movement of the shoulder requires optimal movement of the scapula (the socket) (Kibler, 1991). Movement of the scapula is determined by the flexibility and strength of the muscles attaching onto it (Kugler, 1996; Donatelli *et al*., 2000; Kibler, 2006). Paddlers have been found to (a) have shoulder blades that are not optimally positioned for the best shoulder movement and (b) be unable to move their scapulae smoothly and without disturbance (scapula dyskinesis) (Chapter 2). It is likely these scapulae dysfunctions are due to imbalances in strength and tone of the muscles surrounding and attaching to it (Kugler, 1996; Donatelli *et al*., 2000; Kibler, 2006).

Paddlers, coaches and strength trainers are therefore advised to incorporate exercises that build on the control and strength of scapula stabilisers (serratus anterior, subscapularis and lower fibres of the trapezius muscle) in training as well as stretches for the pectoral and bicep muscles, in order to improve the position and movement of the shoulder blades.

Upper back (thoracic spine) extension

The position of the upper body has been found to influence strength and biomechanics of the shoulders (Kebaetse *et al*., 1999). Paddlers typically have poor upper back extension ability (Chapter 2) and therefore it is suggested that the mobility of upper spine is addressed.

From previously established intrinsic risk factors for shoulder injuries, commonly found in paddlers and discussed above, the checklist below is proposed for paddlers wishing to be proactive in the prevention of developing, and correcting, these risk factors around the shoulders. These include the following:

- Control of full rotation of the shoulders (both external and internal rotation range)
- Co-ordination of scapula movements with arm movements, including strength training and paddling.
- Strength of scapula stabilisers relative to upper body strength
- Thoracic spine extension range and strength
- Co-ordination in integrating the whole kinetic chain of the paddling motion, including the legs, pelvis, spine and shoulder blade with shoulder and arm movements.

Step two: Evidence-based strategies to overcome sub-optimal paddling specific adaptations

The images below were selected from the intervention programme used in Chapter 2 of the thesis (Appendix 1). They were selected as they address more than one of the targets set above (refer to appendix 1 for a full description of each exercise). Exercise descriptions have been included in appendix 1; however, professional assistance is highly recommended for assistance in the correct execution and appropriate progressions of each. The instructions that accompany these exercises are important and they should be strictly adhered to. If pain or discomfort is experienced during or after the completion of these exercises it is strongly suggested that the athlete/coach seek professional help. These exercises performed incorrectly can cause harm.

It is advisable that assessment is an on going part of injury prevention in paddlers and with a continual cycle of assess, intervene, re-asses and adapt intervention. Prevention of intrinsic factors has been emphasised but the importance of managing extrinsic factors such as training volume, technique and training conditions must also be considered for the prevention of shoulder injuries. Further, it is encouraged that the process of achieving the previously mentioned targets should be accompanied by the integration of these into paddling and daily habits.

The photographs below depict examples of exercises that target shoulder and scapular stabiliser strengthening:

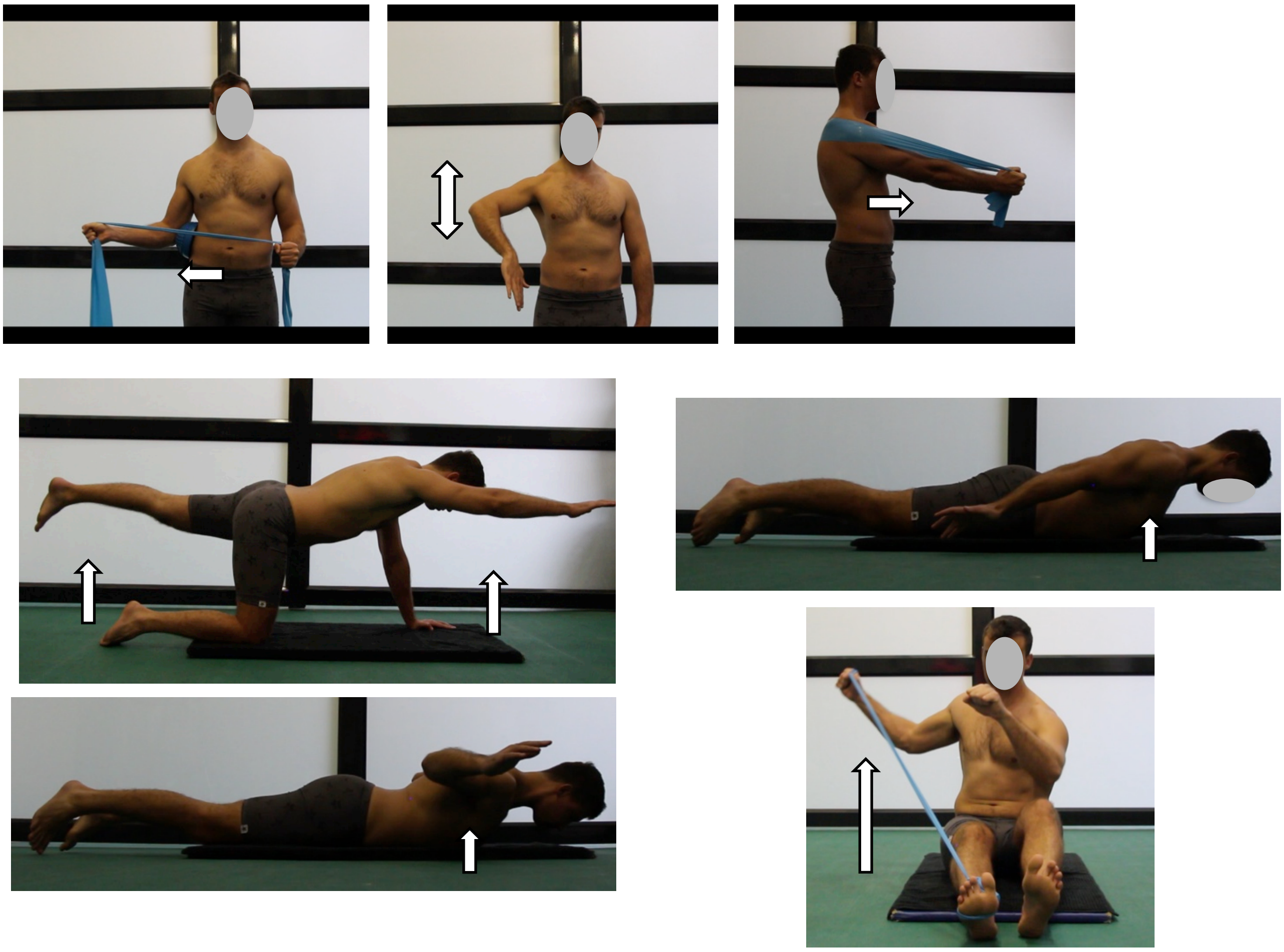

Figure 5. 1: Photographs of exercises that address risk factors to shoulder injuries.

Tips for on-water biomechanical analysis of the boat and paddle.

Chapter 3 of this thesis analysed of the behaviour of the boat and paddle during on-water kayaking, and the following practical advice is provided for coaches so that these objective measurements can assist in the technical assessment, monitoring and training of athletes.

Reliable repeatability of on-water testing requires consistency in the paddle, boat and environmental conditions, which allows measurements, obtained at different times, to be comparable. Comparison of a boat's acceleration between pre-, mid- and peak-season intervals, allows for specific performance assessment of the prescribed training for that individual or team boat.

These objective assessment measurements include paddle torque, forward acceleration of the boat and three-dimensional orientation (pitch, roll and yaw) of the boat during a stroke cycle.

Paddle torque

Paddlers were found to have disparity between left and right strokes when measuring the amount and timing of applied paddle force (Chapter 3). Clinically these asymmetries can have implications for the paddler and for the boat kinematics. Uneven loading through the body can lead to the development of areas of increased strain and compensation movement strategies, both of which could contribute of repetitive strain injuries. Asymmetrical paddle forces can also disturb the boat position differently.

When analysing paddle torque data, both the magnitude and timing of the force applied during the water phase are important, and the data has been found to vary between male and female paddlers (Chapter 3). Females were found to apply a more even distribution of torque during the water phase, while the males have an early peak in their torque, representing a stronger catch of the water and a second peak later on in the water phase.

In instances where a paddler is working on practising specific application of paddle force, having their force application visually represented can be very useful.

By including the left and right paddle torque on the same set of axes, clear comparisons between sides can be made for determining possible discrepancies in power application as shown in Figure 5.2.

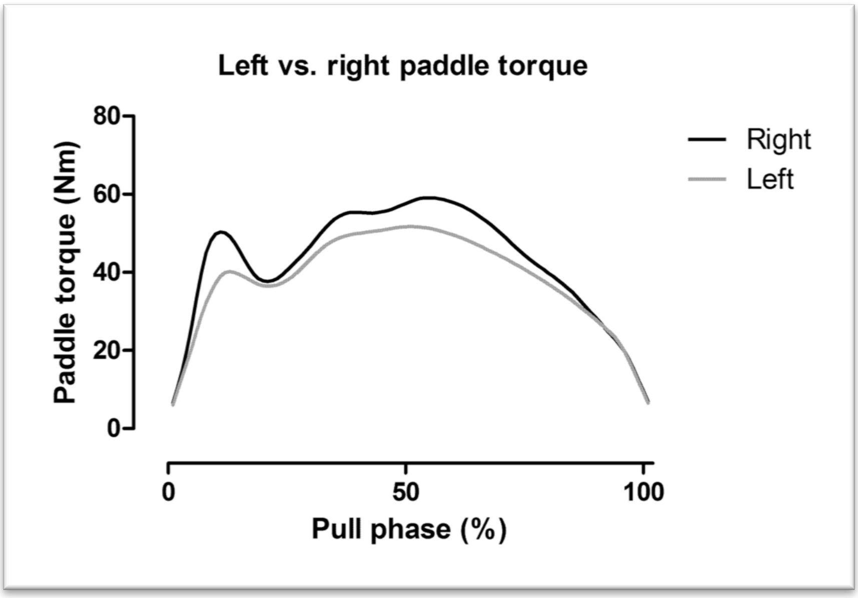

Figure 5. 2: Comparison of mean left and right paddle torque during a 200meter on-water time trial.

The graph above (Figure 5.2) shows left vs. right paddle torque during a 200 m time trial for a paddler. Differences between sides are easily identifiable; right stroke (black line) has a higher peak value and a higher mean value compared to the left (grey line) and the initial peak on the right is sharper compared the initial peak on the left.

Information on fatigue-related changes can be analysed by including the start portion and the end portion of the time trial, for left and right strokes on the same set of axes, as shown in Figure 5.3 below.

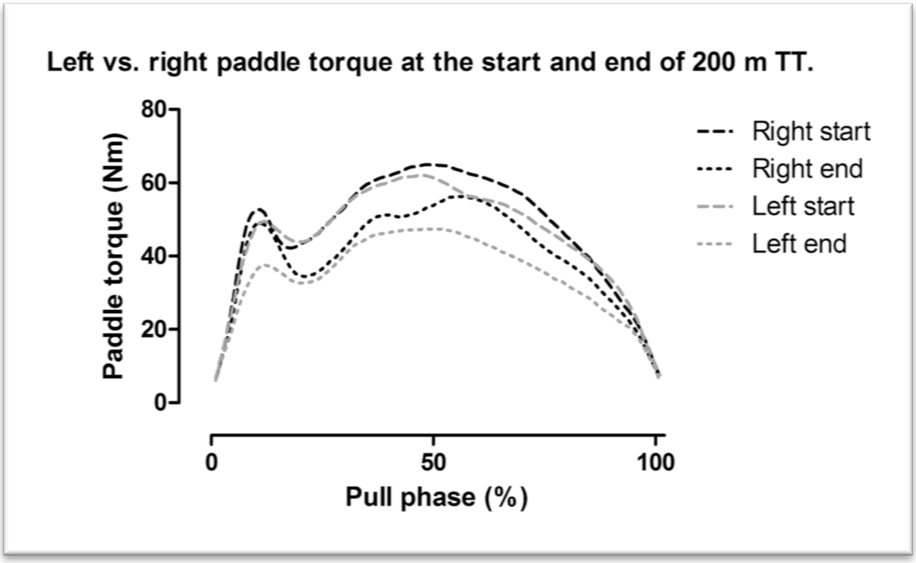

Figure 5. 3: Comparison of left and right paddle torque at different time intervals during a 200 meter on-water time trial.

In this case (Figure 5.3), the first five strokes can be compared to the last five strokes for both sides (right in black and left in grey) during a time trial.

Any two points can be selected from a time trial and inserted into the graph above, in this instance the initial and the end five strokes have been averaged and used. Highlighting two points from the fatigue graph (left vs. right paddle torque at the start and end of a 200 meter time trial), the distance between the two grey lines is greater than the distance between the two black lines. This shows that the right side (black lines) is able to sustain paddler force better than the left side (grey) shown by the gap between the two black lines being less than the gap between the two grey lines. Further, Figure 5.3 shows hardly any change in torque during the initial catch of the water on the right over the distance, as both right initial peaks are similar. This is not the case for the left stroke. Coaches and athletes through specific focus on force timing and strength training on the left side can address this.

NOTE: Due to the properties of hydrodynamics and force vectors, it is not only the amount of paddle force that propels the boat forwards, but also the shape (depth and width) of the pathway of the paddle through the water and the timing during the water phase when the force is applied (Rottenbacher *et al.*, 2011).

Forward acceleration and deceleration of the boat with each stroke

During each water phase of the paddle stroke, the boat accelerates forwards (Plagenhoef, 1979; Mann & Kearny, 1980; Aitken & Neal, 1992; Timofeev *et al*., 1996; Sperlich & Baker, 2002; Michael *et al*. 2009; Rottenbacher *et al*., 2011; Brown *et al*., 2011). When the paddle is removed from the water in preparation for the stroke on the other side, the boat slows down and decelerates due to aero and hydrodynamic drag (Mann & Kearny, 1980). The use of a GPS to determine boat speed has been found to be inaccurate between morning and afternoon recordings, likely due to the change in location of satellites (Janssen & Sachlikidis, 2010). Securing a high frequency accelerometer to the boat allows accurate measurement of its forward movement.

The graphs below (Figures 5.4 & 5.5) show the mean acceleration of a K1 during the water (positive acceleration) and the air (negative acceleration) phases of the right (black) and left (grey) strokes.

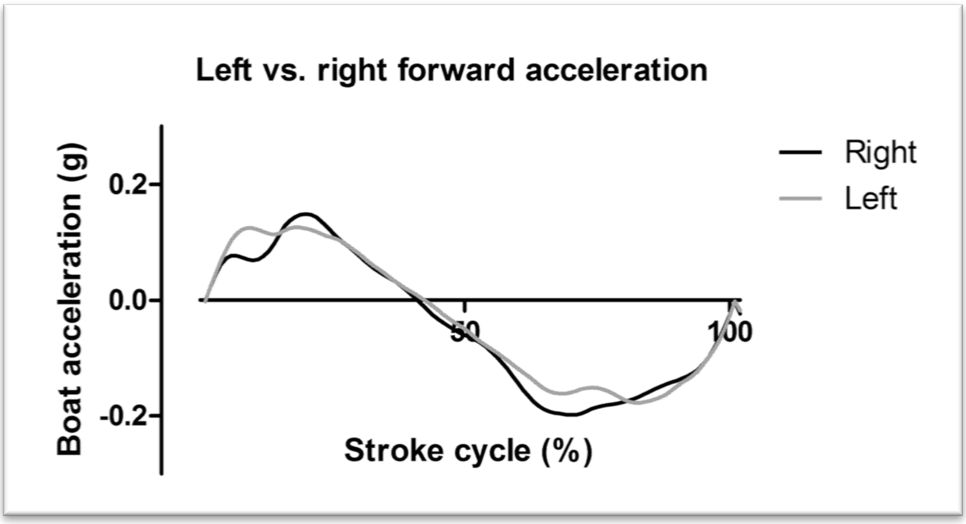

Figure 5. 4: Comparison of mean left and right forward acceleration of the boat during a stroke cycle

Although a precise point on the graph of paddle exit is still to be determined, it is hypothesised that this occurs approximately when the acceleration crosses the x-axis and becomes negative.

Each paddler has been found to have a unique acceleration profile. Inter-individual variation has been found in the smoothness, height and width of the acceleration peaks and troughs, when graphed as above (Figure 5.4).

In this example (Figure 5.4), discrepancies exist for acceleration profiles during the left and right strokes: earlier peak acceleration and less deceleration occur during the left stroke.

Coupling this information with video footage and/or information on the three-dimensional movements of the boat during these phases, along with paddle torque profiles, will give greater insight into the origins of these discrepancies. Recall from the previous graphs showing paddle torque (Figures 5.2 & 5.3) that this paddler showed greater torque during the right catch phase. This may have increased hydrodynamic drag and produced the delayed acceleration peak on the right stroke. This is a marker of inefficiency because greater torque is producing relatively less acceleration. These factors all have potential performance implications which coaches can manage and optimise using this form of analysis.

Similar to the paddle force, the acceleration graph below (Figure 5.5) displays the average of the first five and the last five strokes during the left and right stokes of a 200 meter time trial.

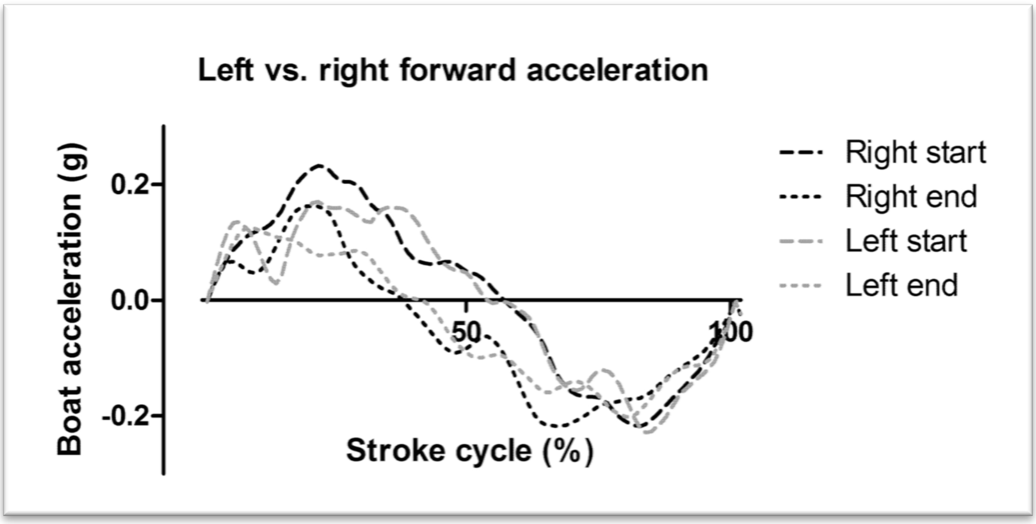

Figure 5. 5: Comparison of left and right forward acceleration of the boat at different time intervals during a 200 meter on-water time trial.

In the acceleration graph above (Figure 5.5), information on the difference between the first five strokes and the last five strokes is available, as well as the right compared to left strokes at these time points. This is important information for analysing the difference between these two time points in the race. One could also compare the middle portion of the race to the end of the race or the start of two different races (under similar environmental conditions using the same equipment). Determine the question and appropriate data can be applied.

The data used for the examples of paddle torque and acceleration was obtained from the same paddler, during the same time trial.

Due to speed having a squared relationship with drag (the higher the speed the greater the drag experienced) (Horner, 1965) it must be considered that lower, longer peaks of boat acceleration forwards, will be more energy efficient compared to higher, shorter peaks.

Boat movements in three-dimensions

Alternating unilateral strokes causes accessory movements of the kayak (Michael, 2009; Brown, 2009). These three dimensional accessory movements of the boat include pitch (nose lifting or dipping like a see-saw), roll (sideways dipping) and yaw (sideways ‘snaking’ of the nose). Control of these accessory movements is of interest to reduce the wetted surface area of the boat and thereby increase the efficiency of the boat’s movement through the water (Jackson, 1995).

The length of the boat creates longitudinal stability, resulting in less deviation of the pitch and yaw of the boat compared to its roll, which has been found to be highly sensitive (Chapter 3). Not only the magnitude but also the direction of the yaw and the roll of the boat with each stroke has been found to be inconsistent both between and within groups of sprint and marathon paddlers (Chapter 3). The direction of the pitch however, was found to change similarly for all paddlers during a stroke cycle (Chapter 3).

The findings of three-dimensional boat orientation of groups of sprint and marathon paddlers (Chapter 3) are summarised below and technical recommendations follow.

Pitch ('see-sawing' motion)

During the pull or water phase of the stroke, the nose of the boat was found to sink. Once the paddle had exited the water, the nose lifted.

Sprint paddlers were found to sit in a 'nose up' position while the nose of the boast of marathon paddlers were more level. The differences in the kayaks used as well as the boat set-up are likely to have caused these differences.

Roll (side dipping)

Regarding the roll, all sprint and some male marathon paddlers who participated in this research, rolled their boats towards the side of the water phase. The majority of the male marathon paddlers and all of the female marathon paddlers rolled their boats away from the stroke side. Differences in boat configuration, race distance and race conditions could attribute to these differences in direction of the roll of the boat. Further variation was evident in the timing of the roll, with some paddlers starting the pull phase with minimal roll while others achieved their peak roll at this point in the stroke cycle.

Yaw ('snaking' movement)

Similarly to the roll, there were paradoxical movements with regards to the yaw of the boat. The nose of the sprinters boats' (and some of the male marathon paddlers') was pulled slightly towards the side of the stroke during the water phase. In contrast, the noses of most of the male and all of the female marathon paddlers' boats were directed away from the stroke side during the respective water phases. Similarly to pitch, all boats corrected this deviation once the paddle exited the water.

It must be considered that the paradoxical boat kinematics of the marathon paddlers compared to the sprint paddlers could require an effort to maintain lateral stability in rough water conditions over longer distances. Further, the use of a pull strap / bar at the feet of sprint paddlers may be the point required to counter-balance the roll of the boat, therefore allowing it to roll towards the stroke side by sprint paddlers (using foot strap/bar). Marathon paddlers who need to exit and enter the boat quickly during competition may not find this addition to the boat convenient and traditionally they do not use a pull bar or strap.

The following series of graphs serves as an example of the variation found in the three-dimensional boat kinematics. Data from the same three paddlers is used as a representation of individual technical qualities of pitch, roll and yaw. These technical differences likely influence or are influenced by the paddle’s pathway through the water, the timing of muscle activation and efficiency of the boat’s pathway through the water.

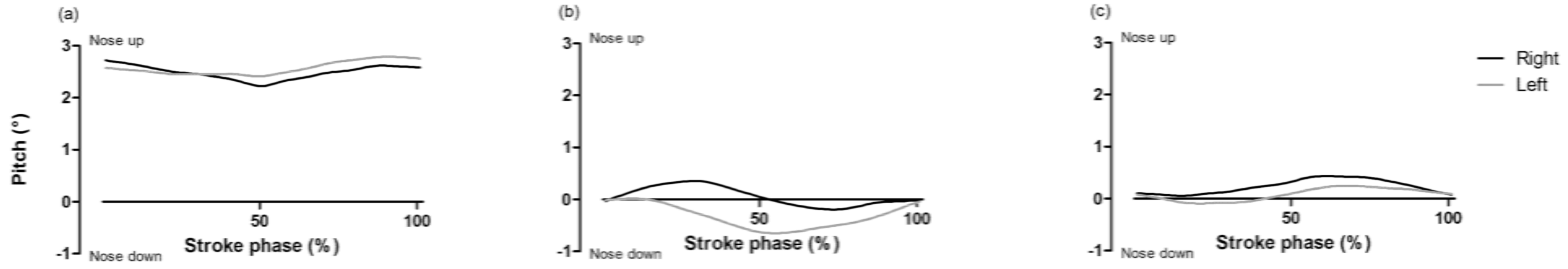

Figure 5. 6: Three examples of the changes in the pitch of the boat during right and left stroke cycles of a 200 meter time trial. *Displaying three different individuals' data: positive values indicate the lifting of the nose of the boat and negative values indicate the dipping of the nose of the boat. The paddle is exited from the water at roughly 50% of the stroke cycle.*

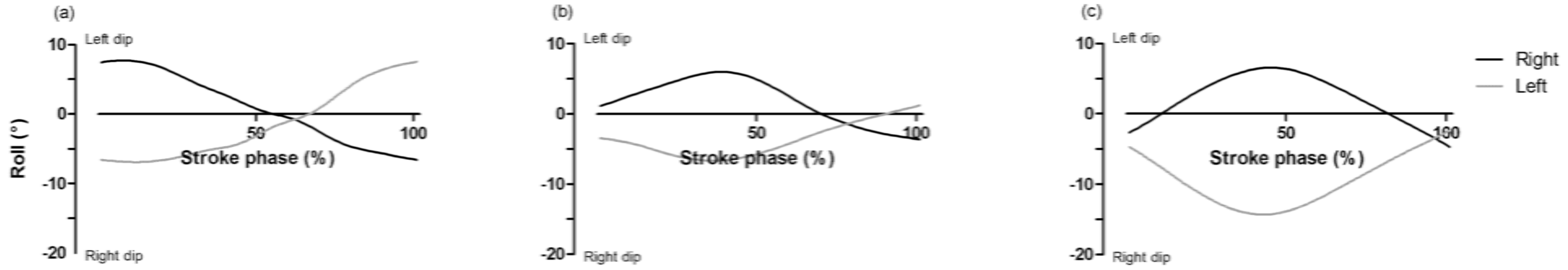

Figure 5. 7: Three examples of the changes in the roll of the boat during right and left stroke cycles of a 200 m time trial. *Displaying three different individuals' data. Positive direction of the graph indicates the roll of the boat towards the left and a negative direction of the graph indicates the roll of the boat towards the right. Positive values represent the boat is rolled to the left and negative values indicate that the boat is rolled to the right. The paddle is exited from the water at roughly 50 % of the stroke cycle.*

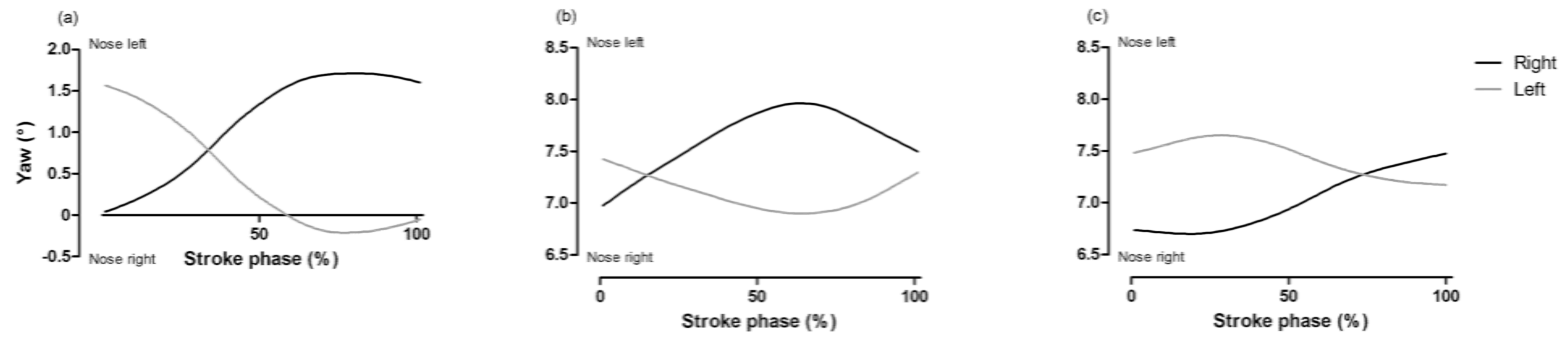

Figure 5. 8: Three examples of the changes in the yaw of the boat during right and left stroke cycles of a 200 m time trial. *Displaying three different individuals' data. Positive direction of the graph indicates the nose of the boat directing towards the left and a negative direction of the graph indicates the nose of the boat directing towards the right. Due to external factors the relative change in yaw is of interest and therefore the relative values and not the actual values on the y-axis are considered. The paddle is exited from the water at roughly 50 % of the stroke cycle.*

The inter-individual variability seen in the three-part graph series above (Figures 5.6 – 5.8) reveals important information about individual technique. Coaches, trainers and athletes are encouraged to be mindful of the movements of the boat when considering kayaking technique.

Recommended boat kinematics

Previous descriptions, which consider the hydrodynamic interactions of the paddle with the water, advise paddlers to shift weight onto the submerged paddle (Mann & Kearny, 1980). This strategy, adopted by the sprint paddlers and three of the male marathon paddlers in the study (Chapter 3) is hypothesised to permit better grip of the paddle in the water, for greater efficiency from the paddle force in displacing the boat forwards. If inadequate weight is place onto the submerged paddle blade, it will be thrust upwards and slip posteriorly though the water (Mann & Kearny, 1980). This slip of the paddle backwards uses more resistant drag forces for boat propulsion. In order to use predominantly lift forces for boat propulsion, a wider stroke is advocated (Kendal & Sanders, 1993; Sanders, 1998).

In a setting where there are not unpredictable disturbances of the water, using a wider stroke and rolling the boat towards the stroke side during the water phase is recommended (Sanders, 1998). Therefore trunk rotation using a straighter arm is suggested as optimal technique, favouring the use of the larger back and stomach muscles as power producers during the water phase (Sanders, 1998). Early use of the elbow flexors (biceps brachii) during the water phase would keep the paddle close to the boat and displace the paddle backwards in the water, and is therefore considered unfavourable.

Canoeists use a ‘J’ shaped stroke on one side of the boat, and keep the direction of the boat straight, which demonstrates that the yaw (direction of the nose of the boat) of the boat is manipulated by the shape of the stroke. The elite sprint paddlers have been described in previous literature as using wider strokes when compared to other groups of paddlers (Brown *et al.*, 2011), therefore pulling the nose of the boat marginally toward the stoke side.

Female marathon paddlers in our study presented with less dipping of the nose of the boat and also a smaller peak at the catch of the water phase (Chapter 3). It is hypothesised that a strong catch, when the vertical components of the force are greatest (Mann and Kearny, 1980), causes an inefficient dip of the nose of the boat. Therefore efficient travel of the boat does not benefit from a strong catch.

In the case of a long-standing or recurrent injury that is aggravated by on-water paddling, it is advised that beyond correcting the intrinsic risk factors to shoulder injury discussed previously, the boat and paddle biomechanics of the athlete should be assessed. Particular attention to right versus left discrepancies is advised, as well as to technical changes due to fatigue. Asymmetries in technique likely cause uneven loading and soft tissue stress that could contribute to an overuse injury. Therefore, for effective management and prevention of kayaking-related injuries, both prehabilitation exercises and correction of biomechanical asymmetries are advised with the goal of reducing the uneven loading of the kinetic chain through balancing strength and movement.

Summary of practical and clinical applications of on-water biomechanical analysis

The application of the above analysis methods of paddle torque, boat acceleration and the boat's three-dimensional movements (pitch, roll and yaw) can be far-reaching. It can allow for objective feedback directly to the athlete for specific training of kayaking technique; it can also be used as a method to monitor and optimise technical performance, to manage and prevent injuries and to contribute to objective team-boat selection. It is advised that one reliable method is used repeatedly, therefore allowing for accurate comparisons to be made over-time. Video footage can offer further detail on the paddler's body movements as well as the pathway of the paddle through the water.

In the case of injury, it is useful to determine the contribution of the two sides to paddle and boat kinematics and how these change in the presence of fatigue or even pain.

A summary of the aspects to consider when analysing paddle force data are listed below:

- The peak (or maximal) paddle force
- The time (percent in the pull phase) at which the peak paddle force occurred
- The rate of the initial application of force (the gradient of the first portion of the graph)
- The mean paddle force
- The general roundedness/fatness of the graph.

The acceleration graphs allow for accurate objective performance analysis of an individual's technique. Aspects to consider when analysing acceleration data include:

- Maximum and minimum acceleration
- Mean acceleration for the pull phase
- Mean acceleration of the air phase
- Mean acceleration of the whole stroke cycle (pull and air phases)
- Percentage of stroke cycle that the acceleration becomes negative.

The timing and the amount or range of the pitch, roll and yaw of the boat are unique to paddlers from different disciplines and sexes (Chapter 3). Information on an individual's boat and paddle biomechanics allows for greater insight into the factors that contribute to boat speed and individual performances.

Muscle activation timing during kayaking

Efficient paddling involves use of the legs, torso and arms in a co-ordinated fashion during the stroke cycle (Begon *et al.*, 2010). The use of electromyography (EMG) is a useful tool for assessing the 'unseen' components of kayak technique. It involves placing electrodes on the muscle in question to be able to read the electrical activity within the muscle. This provides an indication of the muscle's activation status. When EMG is used with video analysis, the muscle activation pattern or timing can be matched to movement.

In chapter 4 of this thesis describes marathon paddlers who participated in this study performing a single-arm pull test, which incorporated trunk, leg, shoulder and arm movements similar to those of the water phase of paddling. The muscles they used during this test for the right pull were: the right lats, left pecs, left more than right external obliques, right more than left lower back (erector spinae) and left more than right glutes. These findings agreed with previous findings from testing sprint paddlers on the water and on the ergometer as well as with hypotheses based on each muscle's anatomical function.

When the same marathon paddlers were tested during maximal kayaking on an indoor ergometer, their muscle activations changed. Their right lats were more active during the left pull phase compared to the right pull phase. Essentially, they were using their lats during the push phase rather than during the pull phase for that side. The other muscles listed above also worked in an opposing sequence compared to the single arm pull test, and therefore did not agree with previous literature and evidence-based hypotheses.

It is likely that these opposing muscle activations adopted during maximal paddling compared to a single arm pull testing contribute to the paradoxical three-dimensional boat biomechanics described previously.

The latissimus dorsi contributes to shoulder extension and trunk rotation to the same side (Grant, 1943) and is well described as being a 'prime mover' during the pull or water phase of kayaking (Trevithick *et al*., 2007; Brown, 2009; Fleming *et al*.; 2012). Below (Figure 5.9) is an example of intra-individual variation from the study conducted in chapter 4. It displays how 2 paddlers use their lats during different phases of the stroke cycle and how this changes uniquely over a 200 meter ergometer time trial. The values displayed in the Figure 5.9 represent the level of muscle activity during the different phases of the stroke cycle as a percentage of the maximal muscle activation.

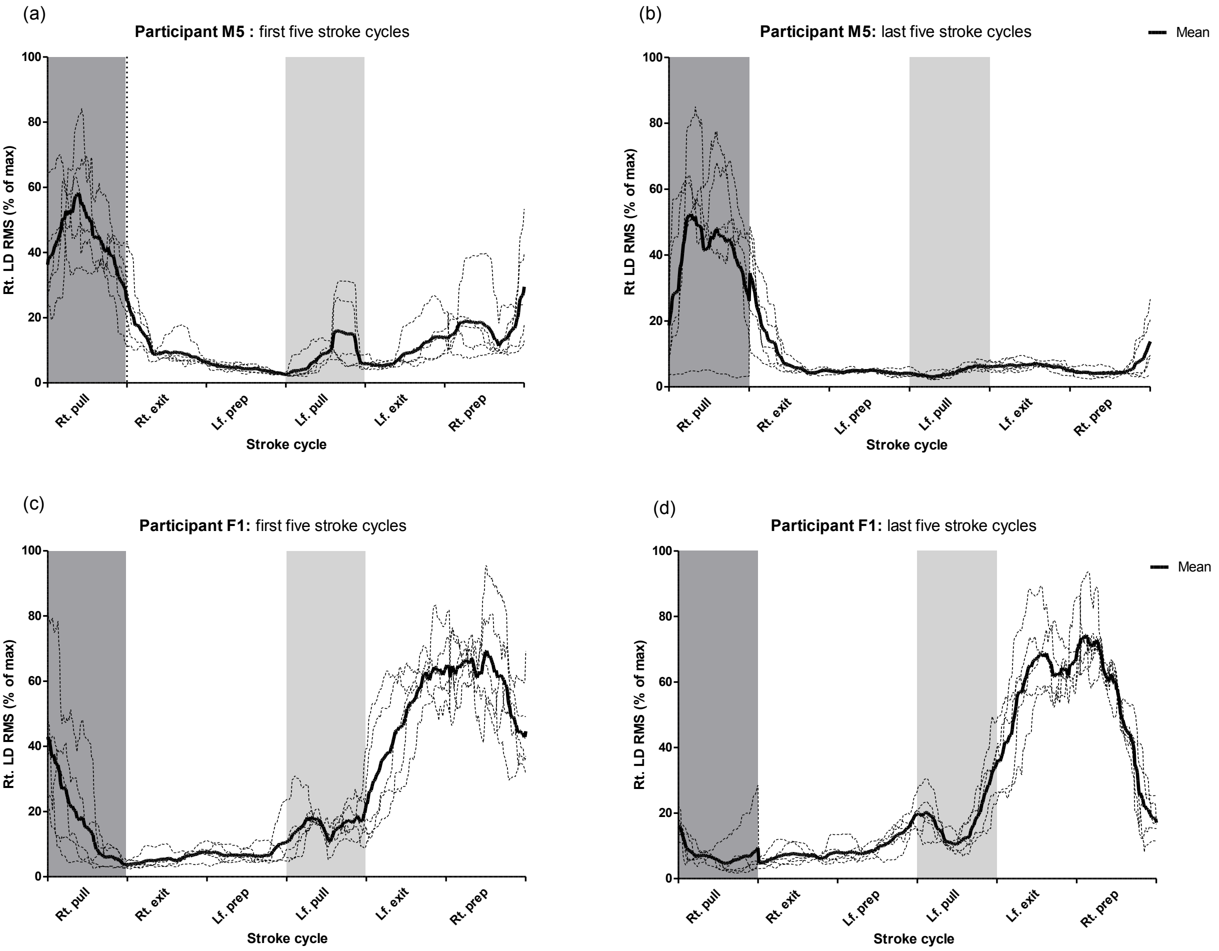

Figure 5. 9: Comparison of intra-individual changes in muscle activation timing of the right latissimus dorsi (Rt. LD) during a maximal 200 meter time trial on an ergometer.

Displaying individual strokes (dashed lines) and the mean (dark solid lines) for two different paddlers (top, a & b, and bottom panels, c & d), for the first five strokes (on the left, a & c) and the last fives strokes (on the right, b & d).

The dark grey blocks in Figure 5.9 highlight the right pull phase and the light grey blocks, the left pull phase. The dark lines indicate the mean of the five strokes and the fainter dashed lines represent the muscle activity for each of the five strokes. The graph on the left reports on the first five strokes and the graph on the right reports the last five strokes of the time trial. The top two graphs contain data from one participant and the bottom two graphs are from another participant.

During the right pull phase in the first five strokes (dark grey blocks in Figure 5.9 a & c) both paddlers use their right lats. For participant F1 (bottom graphs, Figure 5.9 c & d), this is not maintained in the last five strokes, whereas for participant M5 (top graphs, Figure 5.9 a & b) it is. This shows start versus end stroke differences within and between individuals. It is interesting to note that paddler F1 uses lats most when not working against water resistance (air phase between the left and right strokes). In contrast participant M5's Rt. lats activation peaks during the Rt. water phase and remains largely quiet during all in the other phases of the stroke cycle.

Due to inter and intra individual variations (Figures 5.9 a-c) it is advantageous to know what muscles are being activated and at what phase of the stroke cycle. As technical training (involving individual attention to kayaking technique from a coach during on-water paddling sessions, as well as supervised strength training) is aimed at refining the use of particular muscle groups, elite paddlers are encouraged to seek muscle activation testing, using EMG analysis during maximal kayaking.

It is common for coaches to teach unique techniques. EMG testing is a method that can measure if the paddlers are achieving the planned motor pattern.

Coaches and trainers are encouraged to involve the training of the co-ordination of the correct muscle patterns while supervising paddling and strength training sessions. The muscle activity sequencing for the pull or water phase on the right is suggested to involve the right lats, left pecs, left external obliques, right lower back and left gluteus medius muscles.

Conclusion

Elite and sub-elite paddlers have been found to have clinical predispositions for shoulder injury. A proactive approach to reduce the likeliness of shoulder injury is therefore promoted. Through establishing normal biomechanics of the shoulder girdle and correct use of the kinetic chain an aspect of injury predisposition can be reduced. Addressing on-water and strength training factors such as technique, conditions and volumes of training will further reduce kayakers’ risk of having shoulder injury.

High inter and intra-individual variability of kayaking biomechanics reveals value in the measurement and monitoring of sport specific testing. It is suggested individual profiling of paddle torque, boat forward acceleration and three-dimensional boat kinematics are performed on an individual level.

Analysis of muscle recruitment timing in paddlers has also revealed variance that likely affects stroke and boat kinematics. Specific muscle testing and training is therefore essential for addressing the unseen components of kayaking.

The unstable environment of the boat on the water creates the opportunity for individual differences within a similar task. It is therefore important that a holist approach is adopted for performance analysis of kayakers. Methods involving on-water biomechanics of the paddle and boat as well as muscle activations are advocated in addition to the commonly practised video analysis. Biomechanical analysis of paddling is therefore best conducted on the water using familiar equipment to assist in the pursuit of individual technical improvements. This information encourages the immersion of paddlers, trainers and coaches in the technical specificities required for an individual athlete to perform more optimally.

Chapter 6: Conclusions

The complex relationship between the athlete-kayak-paddle system makes the sport of kayaking interesting to study and to optimise. Further, inter-individual differences prevent the simple case of a 'one size fits all' solution. This thesis aimed to address scientific questions around kayaking performance and injuries following a holistic, integrated and individualised approach.

This undertaking began by first designing an intervention to train and prevent common previously identified intrinsic risk factors of shoulder injury. This included training scapula control and symmetrical shoulder rotation and strength to prevent the adaptations associated with paddling, encouraging optimal biomechanics of the shoulder joint and kinetic chain to be used during paddling.

Thereafter, advancements to technical developments for measuring boat and paddle biomechanics during on-water kayaking were presented with regards to different technical attributes between male sprint, male marathon and female marathon paddlers.

The final study of this thesis performed a novel documentation of neuromuscular strategies of marathon paddlers and related these findings to the previous chapter on boat and paddle kinematics.

The conclusions drawn from each study are summarised briefly in the following pages.

Study 1: addressing injury risk factors for shoulder injuries in paddlers

An evidence-based, 10-week prehabilitation programme was designed to address previously identified intrinsic factors for shoulder injuries. The programme was supervised and administered to nine kayakers twice a week. It included a variety of exercises that used low resistance through range, and which were progressed over time. The shoulder was challenged through full rotation ranges ensuring scapula retraction and upward rotation. The whole kinetic chain was involved, training integrated movement of the legs, torso and arms.

Pre- and post-intervention testing revealed that there were changes to the scapula position and movements that have been described by previous research as beneficial for shoulder function and injury prevention. There was also improved thoracic spine extension ability as well as single arm pulling ability in the intervention group compared to a control group. Both groups were part of the same paddling squad and continued with the same on-water training during the 10 weeks.

The exercises used in this study can be considered as initial methods for preventing shoulder injuries and maintaining healthy joints in kayakers. Arising out of this study is a need for future research on larger groups of kayakers, and which include objective kinematics and kayak performance.

Study 2: analysis of boat and paddle kinetics and kinematics during on-water paddling of sprint and marathon paddlers

Performance testing on the ergometer may obscure the performance implications of the direction and timing of paddler forces as there are no hydrodynamic interactions and no boat movements or other subtle biomechanical factors involving weight distribution adjustments.

This study aimed to provide novel three-dimensional kinematics of the kayak, since it was unknown whether previously documented asymmetries in paddle force generation also exist with respect to the movement of the boat. Paddle torque and boat biomechanics for male sprint, male marathon and female marathon paddlers were measured to investigate within and between group differences of paddle torque, boat forward acceleration, boat pitch, roll and yaw.

The paddle force was not found to be associated with greater forward acceleration for within-group statistical analysis. Thus, the ability to generate force does not translate simply into the forward movement of the kayak. Other technical attributes contribute to the resultant forward acceleration of the boat with each stroke.

The direction of the pitch during a stroke cycle was consistent for all groups, with the nose of the boat dipping towards the water during the water phase of the stroke. The direction of the sideways roll and the yaw of the boat was not found to be homogeneous between these groups of paddlers.

Elite male sprint paddlers rolled and yawed their boats towards the stroke side during the pull phase, whereas the female marathon paddlers deviated (rolled and yawed) their boats away from the stroke side. The male marathon paddlers showed large inter-individual variation in the direction and timing of their boats' roll and yaw within a stroke cycle.

It has been a trend in biomechanical analysis of kayaking to measure the upper body movements of paddlers (forward reach and trunk rotation); we strongly suggest that athletes and coaches also consider the movement of the boat when analysing kayaking technique, as this has been found to be highly individual with potential performance implications.

Study 3: Neuromusclular co-ordination of muscles in the torso and pelvis of endurance trained flatwater kayakers during a time trial and a shorter, simpler pull action

The inter-individual variability of the three-dimensional boat kinematics of the marathon paddlers in the previous study led us to question the neuromuscular activation patterns of these paddlers. The muscle recruitment timing of marathon paddlers was also found to be highly variable between individuals for the different phases for the kayak stroke.

In this study, power producing muscles as well as stabilising muscles were investigated for their activation during the different phases of the stroke cycle.

This study revealed that not all paddlers use their latissimus dorsi (LD) as the prime mover during the propulsion phase of their stroke, as has previously been documented for ergometer and on-water paddling. In contrast, the marathon paddlers tested used their LD most during the contra-lateral propulsion phase. Similarly, the activity of stabilising muscles (lower trapezius, erector spinae, gluteus medius), measured for the first time in this study, did not conform to our hypotheses, demonstrating different activation strategies. Not all the paddlers used the same activation strategies suggesting different contributions and interactions that lead to individual kayaking technique.

When the propulsion phase of the stroke was isolated by a specific single-arm pulling device, the patterns of muscle activation for the power producing muscles (latissimus dorsi, external obliques and pectoralis major) conformed to those previously observed in sprint paddlers. Similarly, the stabilising muscle (lower trapezius, erector spinae, gluteus medius) activation patterns during the one-sided stroke activated according to their anatomical function and therefore agreed with our hypotheses for the propulsion phase of paddling.

This apparent difference in muscle recruitment strategy during the complicated task of maximal paddling on the ergometer compared to the simpler, shorter task may be a consequence of technical capabilities (skill and effort) in the sample of marathon paddlers.

The relative timing of muscle activation may also have implications for stroke width, lateral stability of the boat and shoulder function. The timing of muscle activation, with reference to the applied resistance to the water, is important during the pursuit of optimising kayaking technique for improved efficiency, health and performance. Further research integrating muscle activation timing, paddle, person and boat kinematics would help to determine their implications for performance.

Thesis conclusion

Coaches, trainers and athletes have been provided with strength and flexibility exercise to increase the variance of movements that paddlers perform in an effort to reduce the intrinsic risk of shoulder injuries.

Individualised analysis and description of sprint and marathon kayakers' on-water paddling techniques have been reported, including their paddle torque generation, boat forward acceleration and three-dimensional boat kinematics (pitch, roll and yaw) of left and right strokes throughout an interval or race.

Measurement of neuromuscular co-ordination during paddling revealed large inter- and intra-individual variability that may be related to performance, boat kinematics and injury.

The purpose of this thesis was to advance the technology and develop the expertise for objective measurement and evidence-based coaching of kayaking technique. This will ultimately enable individual critique of kayaking biomechanics of sprint and marathon paddlers. We believe the process of research and the results of this thesis contribute significantly to achieving this purpose.

The integrated approach to the scientific questions around kayaking technique and related injuries employed in this thesis was aimed at elevating the standard of measuring and interoperating kayaking biomechanics and performance. The intra-stroke analysis including presentation of inter- and intra-individual variability of the boat, paddle and person have endeavoured to achieve this.

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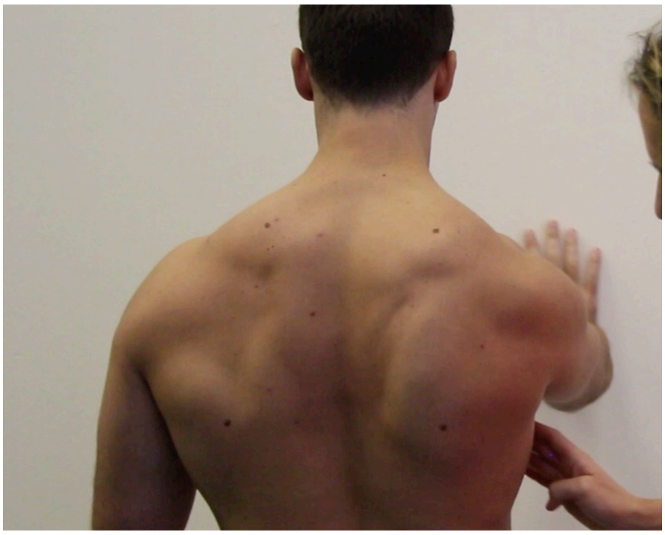
Appendix 1: Details on the 10-week prehabilitation programme

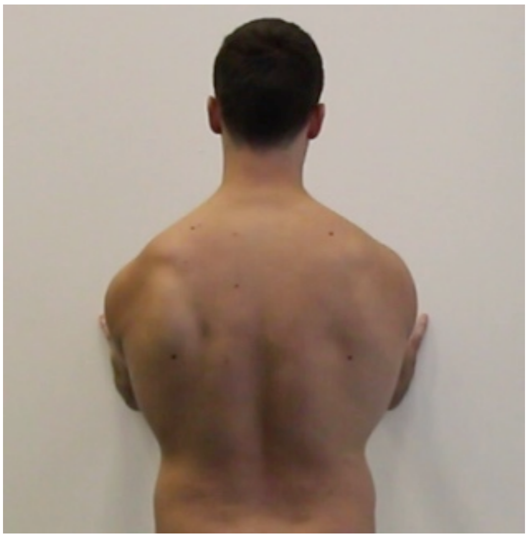
The prehabilitation programme was divided into three core aspects; flexibility, strength and motor control training, which are explained subsequently. All exercises were performed on both shoulders and detailed descriptions of each exercise, their progressions and technical pointers can be found in more detail subsequently.

The exercises were progress by increasing complexity, resistance, range, repetitions and speed while decreasing verbal and tactile feedback.

1. An example of scapula downward rotation and anterior tilting an the right:



2. An example of scapula winging on the left:



Flexibility training

Sleepers stretch with PNF "hold and relax" technique.

Flexibility: Increase the flexibility of the external rotators and the posterior shoulder joint capsule.

Exercise description	Common mistakes	Exercises progression
Shoulders were stacked on top of each other, lower shoulder and elbow was flexed to 90°. Passive internal rotation performed to the lower shoulder by applied pressure at the wrist. Apply pressure to the top of the wrist followed by pressure to the front of the wrist. Hold for 3 s, relax. Resist in both directions. X 5 each side.	Lower shoulder protracting forward.	Increasing range of internal shoulder rotation, manual resistance and repetitions up to 15.

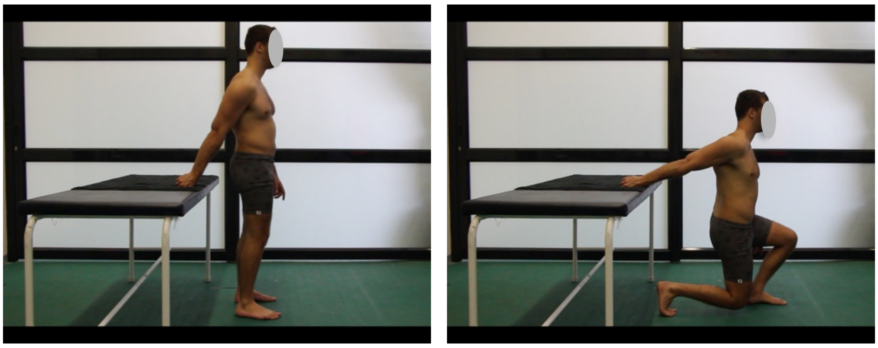
Pectoral stretching with PNF “hold and relax” technique.

Flexibility: Increasing flexibility of all the fibers of the pectoralis major and minor muscles.

Exercise description	Common mistakes	Exercises progression
Shoulder abducted to 90°, elbow flexed to 90° with elbow placed on a corner of a wall or doorframe or partners elbow. Trunk rotated added away from the shoulder being stretched. Activate the back of the shoulder, then press elbow into the wall. Hold for 3 s, relax. X 5. Repeat with the shoulder at 130° of abduction.	Anterior translation of the head of the humerus.	Increasing range of trunk rotation, and repetitions up to 15.

Biceps stretching

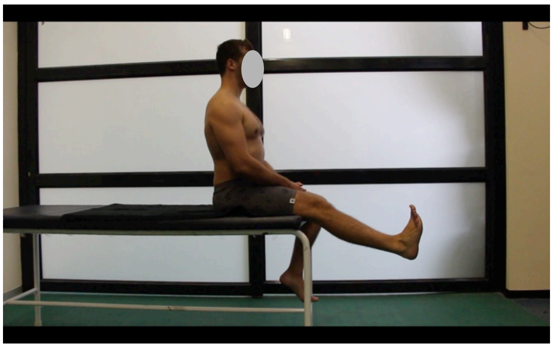
Flexibility: Increase the flexibility of the biceps brachii



Exercise description	Common mistakes	Exercises progression
Thumb placed into a closed fist and place on table surface with thumb facing down. Turn away from the table/fist, with the elbow in extension activate the triceps followed by pressing into table. Hold 3 s x 5.	Rotation in the trunk.	Lower body into a lunge, step further from the table / fist.

Hamstring stretching

Flexibility: *increase hamstrings and hip extensors flexibility.*



Exercise description	Common mistakes	Exercises progression
In sitting or lying, hip is at 90° of flexion and knee is held in a relaxed bent position. The bent knee is actively straightened. Hold for 3 s x 5.	Lumbar spine flexion and posterior pelvic tilt.	Increase knee extension. Facilitate with the use of a rigid strap under the ball of the foot.

Strenght and motor control training.

Subscapularis activation

Motor control and strength training for subscapularis.

Exercise description	Common mistakes	Exercises progression
Arm supported with elbow at height, elbow flexed to 90 °. Retract scapula and the draw the humerus into the center of the joint. Subscapularis is palpated in the axilla to ensure it is activation. Gentle longitudinal distraction force to the distal humerus gives resistance to the subscapularis. Hold for 10 s x 3	Over activation of PM and LD.	Added wrist flexion or extension, and shoulder internal and external rotation. Perform unsupported and free weights or resistance band.

Shoulder external rotation in neutral

Strength training for shoulder external rotators (infraspinatus, teres minor) and scapula stabilisers (lower fibres of trapezius, serratus anterior).

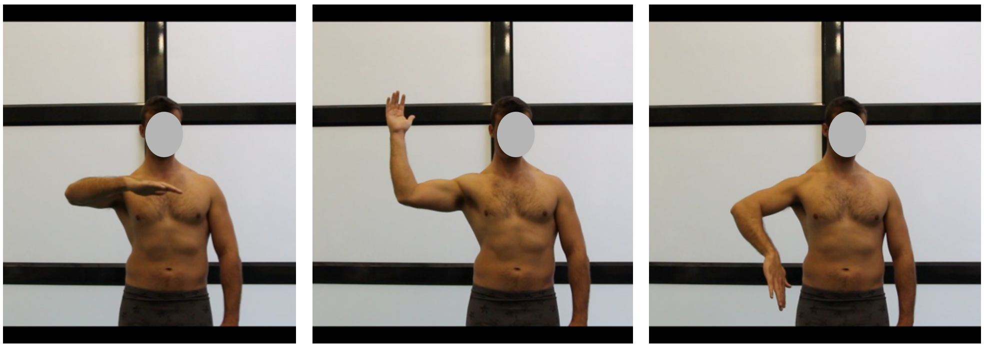
Exercise description	Common mistakes	Exercises progression
Elbows tucked in at the side and flexed to 90°. Retracted scapula. Externally rotate shoulder, so that the hand goes outward and as far back as possible. X10	Trunk rotation, wrist extension.	Perform in side lying. Add resistance band of progressive strengths.

Shoulder external rotation, in 90° scaption

(humeral elevation 30° anterior to the frontal plane)

Strength training for shoulder external (infraspinatus, teres minor, suprapinatus) and internal rotators (subscapularis) as well as scapula stabilisers (lower fibres of trapezius, serratus anterior).

Motor control training for maintaining a centered humerus in the glenoid cavity during dynamic movements using the above mentioned muscles.

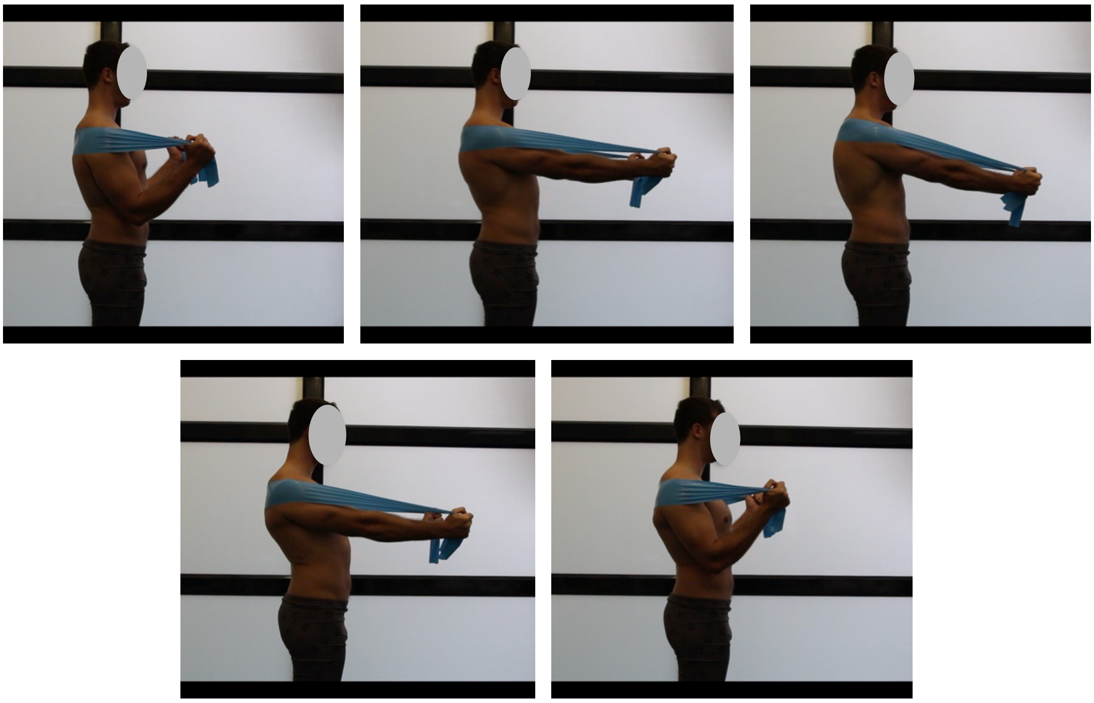


Exercise description	**Common mistakes**	**Exercises progression**
Shoulder in 90° scaption, elbow flexed to 90°, external and internal shoulder rotation. X 10	External rotation: extension in the thoracic and lumbar spine. Elbow extension. Internal rotation: scapula anterior tilting and anterior translation of the head of the humerus. Increase in elbow flexion.	Add resistance band attached to a point behind/in front at elbow height for internal and external rotation respectively. Increase the strength of the resistance band.

Scapula hug

Strength: Serratus anterior strengthening

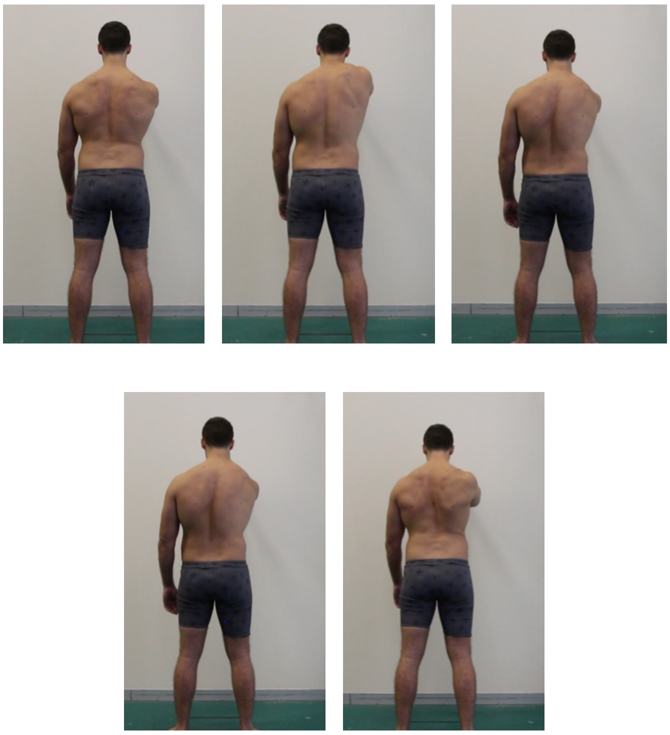
Motor control: co-ordination of maintaining shoulder depression with active shoulder protraction, as well as dissociating thoracic flexion with scapula protraction.



Exercise description	Common mistakes	Exercises progression
Sequential steps of: scapula retraction (maintained against resistance), elbow extension, scapula protraction, scapula retraction, elbow flexion. Performed slowly, with control. X 10.	Excessive use of thoracic spine flexion and lumbar extension.	Increase the strength of the resistance band.

Scapula clock

Motor control: kinaesthesia of the scapula and dissociation between the scapula and the torso.



Exercise description	Common mistakes	Exercises progression
Palm flat on a wall at shoulder height, fingers spread wide and facing upwards, shoulders square to the wall, elbow straight. The scapula is moved in four directions. Elevation (12 o'clock), depression (six o'clock), protraction (three o'clock) and retraction (nine o'clock).	Thoracic spine flexion, extension and rotation. Elbow flexion.	N/A

Window washers

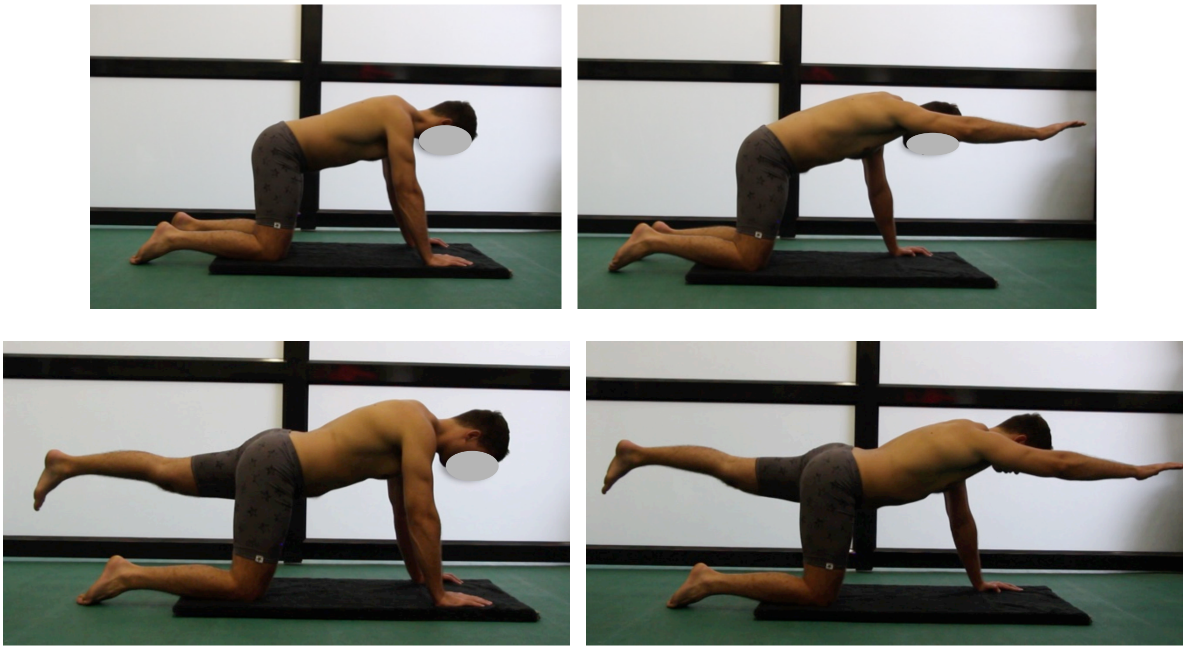
Motor control: Scapula kinaesthesia is practiced as well as co ordination of the scapula and glenohumeral stabilisers

Strength: strengthening of the scapula and glenohumeral stabilisers.

Exercise description	Common mistakes	Exercises progression
With a hand on the wall at shoulder height and scapula in a neutral tilt and retracted, the hand is moved on the wall in small rotatory movements in both clockwise and anticlockwise directions.	Scapular wining and anterior tilting.	Increase in range (size of the circles), work across the body and above shoulder height.

4 point kneeling

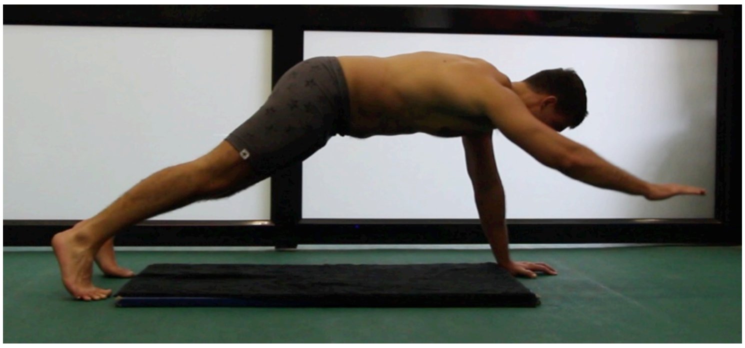
Strength: Strengthens shoulder and pelvis stabilisers.



Exercise description	Common mistakes	Exercises progression
Hands below shoulders and knees below hips. Stomach muscles engaged by drawing belly button up towards the spine and scapulae posteriorly tilted. Add shoulder retraction and lift alternate limbs while maintaining hip and shoulder postures. X 10.	Uneven weight across hands and knees, pelvic rotation, scapula winging, collapsing into the shoulders	Lift opposite arm and leg, lift ipsilateral arm and leg.

Front, side and backwards planks

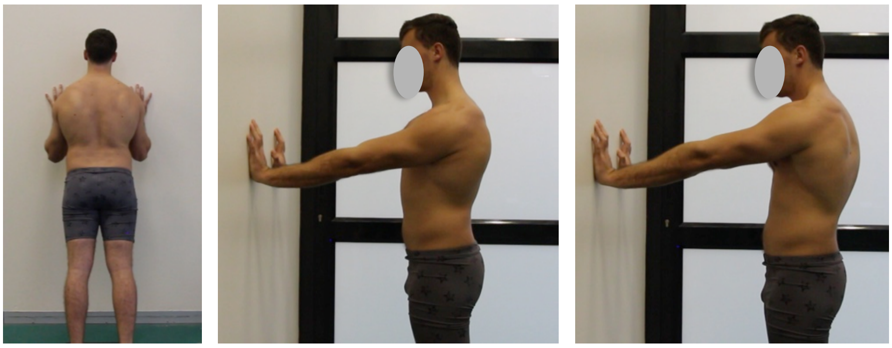
Strength: Shoulder pelvis and trunk stabiliser strengthening.



Exercise description	Common mistakes	Exercises progression
Front plank: Weight bearing only through the elbows and toes the body is held in a straight line. Side plank: Side lying and weight bearing only through the elbow, forearm and side of the bottom leg, the rest of the body is held in a straight line. Back plank: supine with knees bent to 90 °, press up so that the elbows, forearms and feet are the only parts weight bearing. Lifts hips as high as possible, keeping all toes on the floor. Hold 30 s each	Uneven weight across hands and knees, pelvic rotation, scapula winging, collapsing into the shoulders. Lifting hips too high, as displayed in the picture above.	Front plank: lift limbs alternately, lift opposite arm and leg, straighten elbows for high plank. Side plank: lift top leg. Back plank: lift legs alternatively.

Wall press ups

Strength: Scapular stabiliser strengthening (serratus anterior).

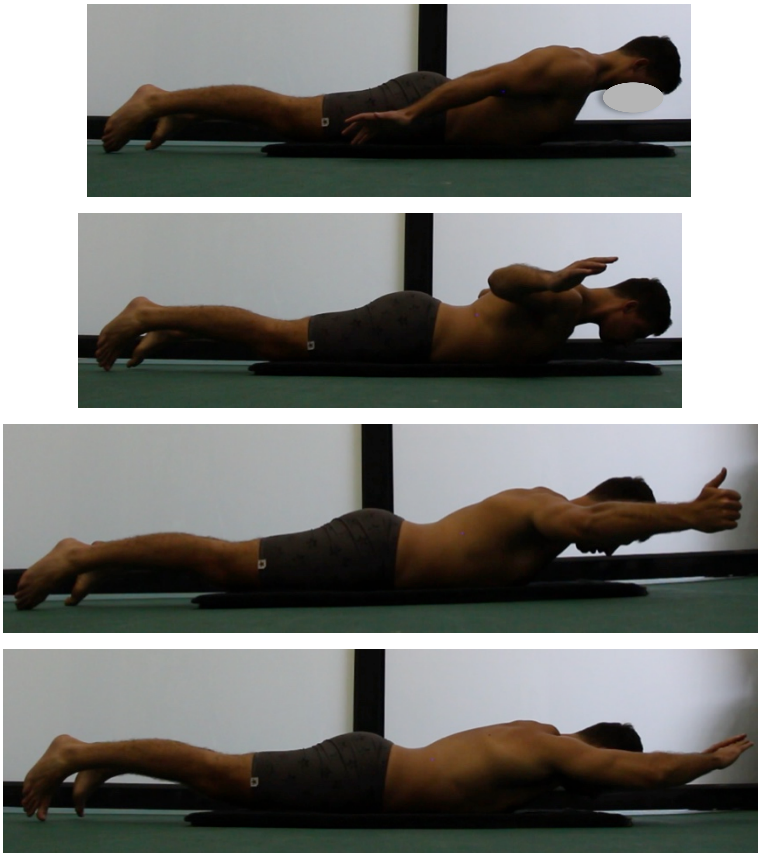


Exercise description	Common mistakes	Exercises progression
Arm distance from wall, hands on wall at just below shoulder height. Bend elbows keeping them close to the body.	Scapular wining and anterior tilting.	Scapula protraction at the end of the movement as in the third picture above. Add resistance band in each hand that passed behind the scapulae.

Scapula retraction

Strength: Strengthening for scapulae upward rotators, shoulder retractors, external rotators and depressors.

Motor control: Co-ordination training of the above muscle groups.



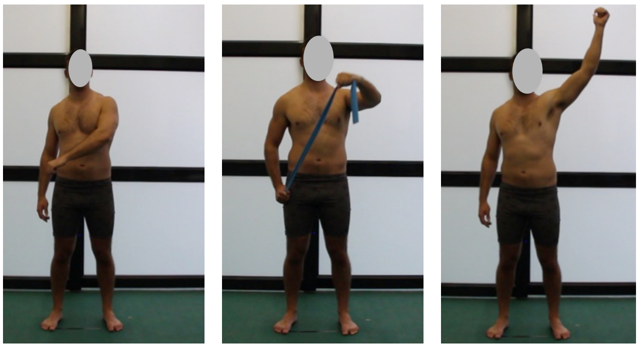
Exercise description	Common mistakes	Exercises progression
Head, shoulders and arms are lifted off the floor. Variations include: 1. holding the lifted position, 2. pulsating the arms while in extension 3. internal and external shoulder rotation with elbow extension. Hold 15 s.	Scapula elevation, shoulder internal rotation, cervical spine extension.	“w” shape with arms, ensuring high hands, 130 ° sh. elevation, full sh. flexion.

PNF upper limb diagonal 2 flexion pattern

Motor control: Increase the co-ordination of synergistic shoulder muscles

Strengthen: posterior shoulder muscles.

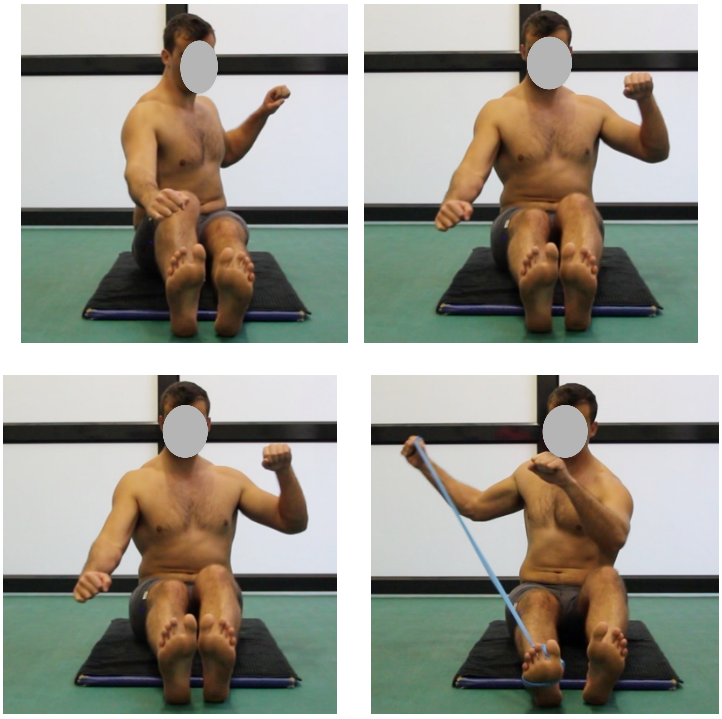
Flexibility: increase flexibility in anterior shoulder and chest muscles.



Exercise description	**Common mistakes**	**Exercises progression**
From adduction, internal rotation of shoulder to flexion, external rotation and scapula retraction.	Limited rotation range, pelvic asymmetries.	Add a resistance band by holding it at the level of the opposite hip. Decrease pelvic stability by standing on one leg, or on a soft surface, maintaining alignment and balance.

Segmental kinetic chain training for the pull phase of the kayak stroke.

Motor control: Corrected movements and co-ordination of the pull phase of the kayak stroke.



Exercise description	Common mistakes	Exercises progression
Pelvis and trunk rotated away, shoulder retracted and scapula posterior titled. Rotate trunk towards with a locked shoulder and delayed elbow flexion. Ensuring the LD and LT are contributing. As hand levels with hip, shoulder external rotation with elbow flexion and end range of trunk rotation. Ipsilateral knee extension was then added during the beginning of the pull phase, to assist the pelvic and trunk rotation. X15. (Greater detail is found on the next page.)	Poor trunk rotation, dipping of forwards most shoulder, early elbow flexion, scapula anterior titling and downward rotation against resistance	Add resistance of a band tied to the foot.

Kinetic chain training of the pull phase of the kayak stroke

The focus of training the kinetic chain was on the co-ordination of the movements and muscle activations rather than on strength. Only light resistance was used. This three-phase, complex-patterned exercise was only included in the last 3 weeks of the programme, after a foundation of scapula training and segmental activation had been practised.

During all phases of the kinetic chain training of the pulling action, the scapula was encouraged to remain neutrally tilted on the chest wall (relative posterior tilt) and to move (upwardly rotate) as the humerus elevated and abducted. As the humerus extended back towards the torso scapula retraction was encouraged.

Phase 1

The movement was first practiced with the trunk and legs remaining fixed. Heels were grounded and participants were instructed to sit up straight. Only a forward reach and pull were involved. The ipsilateral latissimus dorsi was encouraged to activate with a delay in elbow flexion, in order to facilitate a wider stroke during the pull (Sanders, 1998). The exit phase, at the end of the pull was practised with shoulder external rotation being the principal movement.

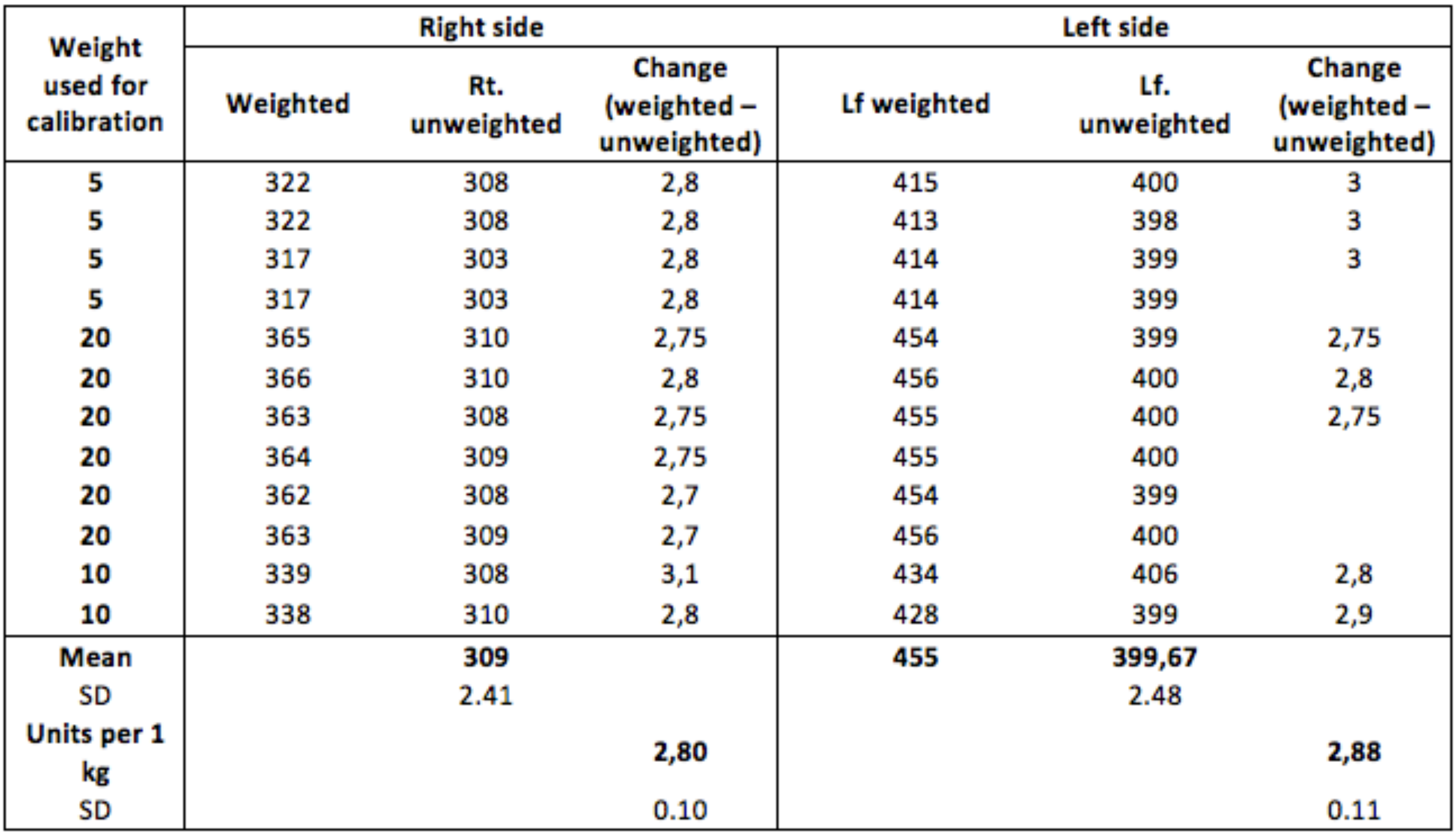
Phase 2

Trunk rotation was added, starting the pull with the trunk rotated to the opposite side. Level shoulders and even weight bearing through both heels and sit-bones was instructed in order to bring awareness to the natural weight sift that rotation produces.

Phase 3

The next phase was to add the legs and the push arm. At he beginning of the pull, the ipsilateral hip and knee were flexed and extended through the pull. The opposite arm simultaneously mimicked the push phase. Pectorals and external obliques were encouraged to contribute towards the push activation. As the pull arm reach 90° of elbow flexion the trunk was square and as the exit phase started the trunk rotated to the pull side.

Appendix 2: Paddle callibration calculations



Weight used for calibration	Right side			Left side		
	Weighted	Rt. unweighted	Change (weighted – unweighted)	Lf weighted	Lf. unweighted	Change (weighted – unweighted)
5	322	308	2,8	415	400	3
5	322	308	2,8	413	398	3
5	317	303	2,8	414	399	3
5	317	303	2,8	414	399	
20	365	310	2,75	454	399	2,75
20	366	310	2,8	456	400	2,8
20	363	308	2,75	455	400	2,75
20	364	309	2,75	455	400	
20	362	308	2,7	454	399	
20	363	309	2,7	456	400	
10	339	308	3,1	434	406	2,8
10	338	310	2,8	428	399	2,9
Mean		**309**		**455**	**399,67**	
SD		2.41			2.48	
Units per 1 kg			**2,80**			**2,88**
SD			0.10			0.11

Appendix 3: Electrode placement for electromyography measurement

Electrode placements for the muscle groups measured in Chapter 4 are listed in the table below. These are taken from the Seniam website (http://www.seniam.org).

Muscle group	Location of electrode placement	Orientation
Latissimus dorsi	4 finger width lateral from spinous process of T10	In the direction of the line from the posterior superior iliac spine (PSIS) to the posterior acromion
Pectoralis major	2 findger width below the coricoid process	In the direction of the line from the xiphisternum to the acromion process
External obliques	2 finger width from the anterior superior iliac spine (ASIS) on the line from the ASIS to the xipisternum	In the direction of the line from the lateral 12th rib to the pubic symphysis
Gluteus medius	50% on the line from thesuperior iliac crest to the greater trochanter	In the direction of the line from the superior iliac crest to the trochanter
Erector spinae longissimus	2 finger width lateral from the spinous process of L1.	Vertical
Lower fibers of trapezius	2/3 on the line from the superior medial boared of the scapula to the 8th thoracic vertebra	In the direction of the line between T8 and the posterior acromion