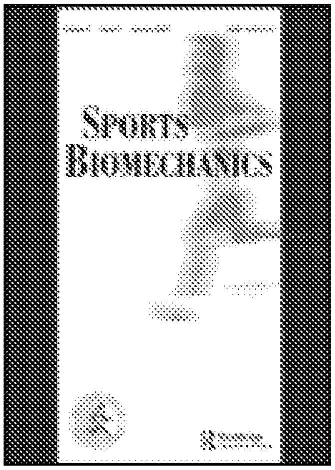

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Scapulohumeral kinematic assessment of the forward kayak stroke in experienced whitewater kayakers

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Abstract
By understanding the normal humeral and scapular kinematics during the kayak stroke, inferences about the relationship of kayaking technique and shoulder injury may be established. The purpose of this study was to describe scapular and humeral kinematics and to compare dominant versus non-dominant symmetry in healthy whitewater kayakers performing the forward stroke. Twenty-five competent whitewater kayakers (mean age: 34.1 ± 9.4 years, mean height: 1.768 ± 0.093 m, mean mass: 78.2 ± 13.0 kg) underwent humeral and scapular kinematic assessment, using an electromagnetic tracking device, while kayaking on a kayak ergometer. Paired *t*-tests were used to determine symmetry. Scapular and humeral kinematic means and standard deviations at six time points during the kayak stroke were described. Scapular and humeral kinematics were shown to be similar upon bilateral comparison. The greatest potential for injury during the forward stroke may be at thrust paddle shaft vertical when the humerus is maximally elevated in internal rotation and adduction as subacromial structures may be mechanically impinged. The relationship between scapulohumeral kinematics related to injury at other time points are also described.

Keywords: *Kinematic analysis, scapula, shoulder injury, whitewater kayak*

Introduction

Whitewater kayaking is a sport in which the athlete is seated in a short plastic kayak wearing a sprayskirt around their waist (to keep water out) and uses a paddle which has blades on both ends for propulsion. Whitewater kayaking primarily comprises navigating down rivers which contain fast moving water, usually due to changes in gradient, while maneuvering around obstacles in the water such as boulders, waves, or hydraulics. The International Scale of River Difficulty grades rivers I–VI based on their difficulty, with grade I whitewater being the easiest and grade VI being extreme and exploratory (Fiore & Houston, 2001). Effective propulsion in kayaking occurs through synchronous movements of the torso and upper extremities as the paddle is manipulated in the water (Mann & Kearney, 1980).

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The forward stroke is the primary stroke used in whitewater kayaking and is utilized approximately 70% of the time during whitewater slalom racing (Hunter et al., 2008). The objective of this stroke is to propel the kayak in a forward direction (Hunter et al., 2007). A proficient forward stroke would ideally be symmetrical on both sides as this would propel the kayak straight and distribute forces equally on the body (Lovell & Lauder, 2001). The forward stroke occurs with coordinated movements between the upper extremity on the draw side (the side the paddle is entering the water) and the thrust side (the side the paddle is in the air) (Mann & Kearney, 1980). At the initiation of the stroke, when the paddle enters the water, the draw shoulder is in front of the thrust shoulder. This shoulder position results in torso rotation away from the side of paddle entry. The draw elbow is extended and the draw shoulder is flexed in an attempt to place the paddle in the water as far toward the front of the boat as possible. The thrust shoulder is abducted and the thrust elbow is flexed at the same time to help facilitate forward paddle entry (Figure 1) (Mann & Kearney, 1980).

Greater than 60% of injuries in kayakers have been reported to occur in the upper limb (Fiore & Houston, 2001). Shoulder injuries are the most common anatomical location of injuries in whitewater kayakers accounting for approximately 30% of all injuries (Fiore & Houston, 2001). As the humerus is elevated in an internally rotated position, through the kayak stroke, the potential for mechanical impingement of subacromial structures is a risk factor for shoulder injury (Hagemann et al., 2004) with repetitive use as the primary culprit (Fiore & Houston, 2001). Existing kinematic research into kayak technique does not discuss injury predisposition and has focused solely on flatwater kayaking (Plagenhoff, 1979; Mann & Kearney, 1980; Lovell & Lauder, 2001; Trevithick et al., 2007).

The relationship between scapular and humeral kinematics during humeral elevation has been studied extensively (Lukasiewicz et al., 1999; Ludewig & Cook, 2000; Myers et al., 2005; Rundquist & Ludewig, 2005). Internal impingement and subacromial impingement of the rotator cuff have demonstrated altered scapular kinematic patterns which directly relate to the mechanisms of injury for those pathologies (Ludewig & Cook, 2000; Laudner et al., 2006). However, little research has detailed upper extremity kinematic patterns during sporting tasks (Meyer et al., 2008). Movements of the scapula, while kayaking, have not been previously defined in relation to humeral kinematics and may provide inferences for

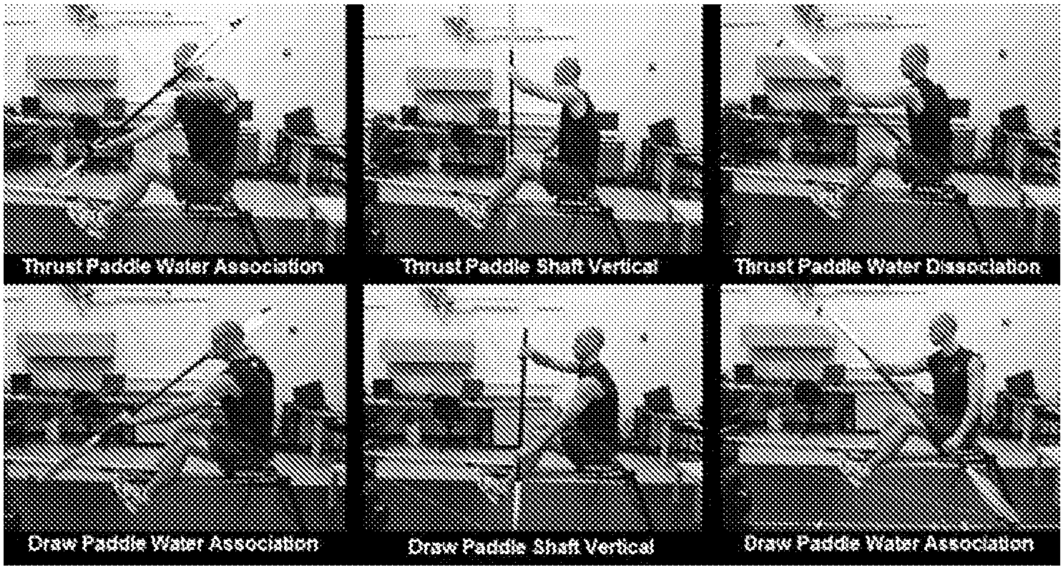

Figure 1. Description of the six time points of the kayak stroke based on kinematic position.

understanding rotator cuff impingement or fatigue related shoulder injuries found in whitewater kayakers. Such an analysis would provide important information to trainers, coaches, clinicians, and athletes in regard to shoulder movement patterns of whitewater kayakers. The aims of the present study were to provide a description of scapular and humeral kinematics of healthy recreational whitewater kayakers performing the forward stroke as they may relate to rotator cuff injury. A secondary purpose was to describe symmetry of the dominant and non-dominant sides during the paddle stroke as asymmetrical loading has been related to injuries in kayakers (Lovell & Lauder, 2001).

Methods

Participants

Twenty-five recreational whitewater kayakers (23 males, mean age: 34.1 ± 9.4 years, mean height: 1.76 ± 0.093 m, mean mass: 78.2 ± 13.0 kg) participated in the study. Each participant reported confidence in kayaking grade III or more difficult whitewater and had no history of shoulder, neck, or back pain which inhibited their kayaking ability in the past one year. This study was approved by the institutional review board at the University of Pittsburgh. All participants provided informed consent in accordance with institutional guidelines.

Instrumentation and setup

Three dimensional scapular and humeral kinematic data were collected using the Motion Star electromagnetic tracking device (Ascension Technologies, Burlington, VT) and Motion Monitor software (Innovative Sports Training, Inc, Chicago IL). The device consists of an extended range transmitter, that creates an electromagnetic field, and standard receivers that detect the electromagnetic field emitted by the transmitter. The receivers were attached to specific body segments as described in the previous literature (Karduna et al., 2001; Myers et al., 2006). The electromagnetic tracking device recorded the position and the orientation of the receivers about the x, y, and z axes relative to the transmitter (global coordinate system). The global x-axis was directed medial/lateral (positive to the right), the global y-axis was directed vertically (positive pointing superior), and the global z-axis was directed anterior/posterior (positive pointing backward). By digitizing the anatomical landmarks with a stylus, the orientation of one body segment was calculated with respect to the other. Data were collected at 100 Hz. Kinematic data were collected in the region determined to have the least position (0.7 mm) and orientation (0.27°) error (Myers et al., 2006). Kinematic error associated with metal in the magnetic field was tested by analyzing a known distance between two receivers with and without the kayak ergometer in the field. The discrepancy between these conditions yielded less than 0.01 mm difference between these two conditions. Calibration of the system was performed as outlined by Meskers et al. (1998).

A total of six receivers (dimensions: 25.4 mm × 25.4 mm × 20.3 mm) were used for bilateral scapular kinematics assessment. The first receiver was attached to the spinous process of the seventh cervical vertebrae. Two scapular receivers were attached bilaterally on the flat portion of the acromion processes, and another two receivers were attached bilaterally to the mid-shaft of the posterior humerus. Spinal and scapular receivers were secured on the skin using double-sided adhesive disks and athletic tape (3M Health Care, St. Paul, Minn). Humeral receivers were additionally secured using athletic tape and a velcro strap to minimize skin-receiver movement (Figure 2.). The sixth receiver was attached to the

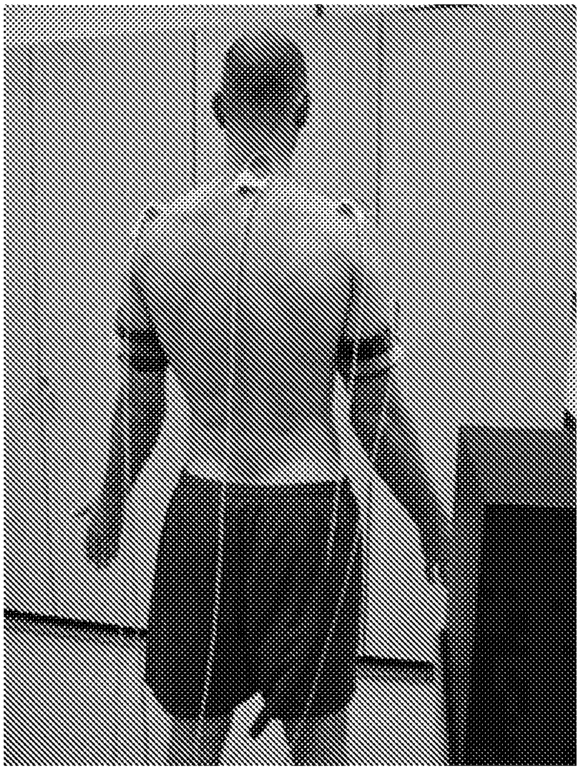

Figure 2. Demonstration of receiver positions for kinematic setup.

stylus that was used to palpate and digitize the anatomical landmarks on the upper arm, scapula, and thorax. The anatomical landmarks digitized included the eighth thoracic vertebrae, xiphoid process, seventh cervical vertebrae (just inferior to the receiver), jugular notch, sternoclavicular joint, acromioclavicular joint, medial scapular border where it intersects with the scapular spine, inferior angle, medial epicondyle, lateral epicondyle, and the glenohumeral joint center. Landmarks on the humerus and the scapula were digitized bilaterally. Because the glenohumeral joint center cannot be palpated, it was estimated as the point that moves least with respect to the scapula when the humerus is passively moved through several short arcs (Meskers et al., 1998). Digitization of these anatomical landmarks on each segment allowed construction of the local coordinate system for each body segment; thorax, scapula, and humerus. Using local coordinate systems of the thorax, scapula, and humerus, the orientation of the humerus relative to the thorax and position and orientation of the scapula with respect to the thorax were calculated.

Scapula and humerus positions and orientation were described at six time points during the kayak paddle stroke. Propulsion of the kayak occurs in two phases; a push phase and a pull phase (Mann & Kearney, 1980). The stroke progresses through three time points (paddle water association, paddle shaft vertical, and paddle water dissociation) on each side of the body for a total of six time points. The six time points of the kayak stroke are shown in Figure 1. From the time the paddle enters the water until the paddle shaft is vertical forward pushing of the thrust side (horizontal adduction of the thrust shoulder with extension of the elbow) moves the draw side backward to propel the kayak. From paddle shaft vertical until the blade exits the water, pulling of the draw side paddle with the draw segments (extension of the draw shoulder with slight flexion of the elbow) continues to move the draw-side paddle backward to propel the kayak forward. During the propulsion, torso rotation toward the side of the draw segment should occur concurrently with upper extremity movement to maximize energy transfer up the kinetic chain. The definitions of the time points (Mann & Kearney, 1980) were modified for the current study to allow identification of the corresponding time points using the kinematic data from the electromagnetic tracking device. The kinematic time points were identified from the position of the humeral receivers relative to the global coordinate system. Paddle water association was defined as the point where the humeral receiver had the greatest excursion along the negative z-axis (anterior). The humerus would be most anterior at this point in an attempt to reach forward to place the paddle in the water to initiate the stroke. Paddle shaft vertical was defined as the point with greatest vertical difference (y-axis) between the humeral receivers. At the time of paddle water dissociation the paddle becomes horizontal as it is taken out of the water to initiate the stroke on the opposite limb. Therefore this position was defined as the point with minimal vertical difference (y-axis) between the humeral receivers.

Scapulothoracic orientations (upward/downward rotation, anterior/posterior tipping, and internal/external rotation) and positions (elevation/depression and protraction/retraction) and humeral orientations (elevation, plane of elevation, and axial rotation) at the six time points were calculated as average of values from ten repetitions.

Procedures

Once the set up for the data collection using the electromagnetic tracking device was complete, participants were seated on an ergometer (Vasa Inc, Essex Junction, VT, USA) to perform a ten-minute warm-up. Participants were allowed to adopt their normal hand grip on the paddle. Stroke rate was standardized for all subjects via a metronome at 30 strokes per minute, which was determined to be a comfortable pace through pilot testing and minimized sensor movement error. To the authors' knowledge, the number of strokes per minute used in recreational whitewater kayaking is unknown. It has been reported that during whitewater slalom world championships, men's stoke rate was on average approximately 62 strokes per minute (Hunter et al., 2008). This is unlikely to be representative of recreational kayakers as these counts were obtained during the highest level of competition. One stroke was considered the time frame over which the paddle on one side of the body completed one full cycle, e.g. paddle water association on the dominant side to paddle water association on the same side. Following the warm-up session, the participants were asked to perform the kayak task for five minutes. Ten strokes during the third minute of the kayaking task were used for analysis as pilot testing showed no kinematic differences over a 10-minute time frame. The participants were not aware when data collection was occurring in attempt to record their normal kayaking stroke.

Data reduction

Raw scapular and humeral kinematic data were filtered with a dual pass fourth-order Butterworth filter with a cut-off frequency of 10 Hz which was determined to be optimal based on pilot testing. The position and orientation data of the receivers and the digitized anatomical landmarks were used to construct local coordinate systems for the thorax, scapula, and humerus. The coordinate systems used were in accordance with recommendations from the International Shoulder Group of the International Society of Biomechanics (Wu et al., 2005). When the subject stood in an anatomical position, the coordinate system for each segment was vertical (y-axis), horizontal to the right (x-axis), and anterior (z-axis). Orientation of the scapula was determined as rotation about the y-axis of the scapula (internal/external rotation),

rotation about the z-axis of the scapula (upward/downward rotation), and rotation about the x-axis of the scapula (anterior/posterior tipping). Euler angle decompositions were used to determine the scapular and humeral orientation with respect to the thorax. The rotation sequence of the Euler angle was chosen based on the recommendation of the International Shoulder Group (Wu et al., 2005). The scapula is attached to the thorax via the clavicle; a rigid body with a fixed length, therefore the position of the scapula could be described as the orientation of the clavicle with respect to thorax. Anatomically, the vector extending from the sternoclavicular joint to the acromioclavicular joint represents the orientation of the clavicle (Karduna et al., 2001) The scapular protraction/retraction angle was calculated as the angle formed between the vector extending from the sternoclavicular joint to the acromioclavicular joint projected onto the transverse plane of the thorax and the frontal plane of the thorax, and the scapular elevation/depression angle was calculated as an angle formed between the vector projected onto the frontal plane of the thorax and the transverse plane of the thorax. Neutral position of the scapula and humerus were defined as the kinematic values obtained while the participants stood still with their arm rested by their side. The mean humeral and scapular positions and orientations of the ten strokes collected were calculated for descriptions and statistical analyses. All calculations and data reduction were performed using Matlab 12.0 (Mathworks, Natick, MA).

Data analysis

Humeral elevation, plane of elevation, axial rotation, as well as both position and orientation of the scapula were analyzed at the six time points of the kayak stroke. Mean values and associated standard deviations from all participants were used to describe the scapular and humeral kinematics of the kayak stroke. Kinematic stroke to stroke reliability was found to be acceptable (intraclass correlation coefficient (ICC)(3,k) range 0.76–0.99, standard error of measurement (SEM) 1.02–4.85°) as calculated from pilot testing.

Paired t-tests (SPSS version 16.0, SPSS Science Inc, Chicago, Ill) were used to compare limb differences for all variables assessed. The dominant limb was determined as the limb which did not release control of the paddle for water entry. An α level of 0.05 was set before all analyses.

Results

Scapular and humeral kinematic variables did not differ between the dominant and non-dominant side. (Tables I–VI).

On the whole, the forward kayak stroke was performed in the middle of expected range of motion values for the shoulder (Norkin et al., 1995). Thrust paddle shaft vertical was the time point in which mean humeral elevation, humeral adduction, humeral internal rotation, scapular upward rotation, posterior tilt, internal rotation, elevation, and retraction were maximal throughout the stroke. The scapular kinematics follow the expected trend, based on humeral elevation, to maximize clearance of the greater tuberosity underneath the acromion (Ludewig & Reynolds, 2009).

Discussion and implications

The general pattern of humeral kinematics found in the current study was similar to previously documented reports of flatwater kayaking technique (Plagenhoff, 1979; Mann & Kearney, 1980). The mean values for humeral elevation ranged from 18°to 76° as

Table I. Draw paddle water association kinematic descriptive variables with dominant and non-dominant comparisons.

Kinematic Variable	Dominant ± *SD*	Non Dominant ± *SD*	Mean Difference (95% CI)	*p*-value
Humeral Elevation	63.38 ± 11.66	63.31 ± 16.60	0.07 (-8.15, 8.28)	0.99
Humeral Plane of Elevation	67.93 ± 6.30	69.91 ± 11.38	1.98 (-6.48, 2.53)	0.37
Humeral Axial Rotation	25.32 ± 16.00	19.29 ± 8.23	6.04 (-13.23, 1.15)	0.10
Scapular Upper Rotation	1.96 ± 7.10	3.87 ± 5.91	1.91 (-4.60, 0.76)	0.15
Scapular Internal Rotation	38.40 ± 8.84	37.78 ± 9.55	0.62 (-4.53, 5.78)	0.80
Scapular Anterior Tilt	-11.82 ± 7.73	-12.14 ± 8.06	0.32 (-1.80, 2.43)	0.76
Scapular Protraction	18.53 ± 5.60	20.66 ± 6.58	2.13 (-5.40, 1.14)	0.19
Scapular Elevation	18.24 ± 7.88	19.68 ± 9.25	1.44 (-4.51, 1.64)	0.34

Note: All values in degrees.

Table II. Draw paddle shaft vertical kinematic descriptive variables with dominant and non-dominant comparisons.

Kinematic Variable	Dominant ± *SD*	Non Dominant ± *SD*	Mean Difference (95% CI)	*p*-value
Humeral Elevation	37.22 ± 17.53	37.97 ± 13.62	0.75 (-8.79, 7.47)	0.85
Humeral Plane of Elevation	32.87 ± 9.23	35.10 ± 8.91	2.23 (-5.29, 0.84)	0.15
Humeral Axial Rotation	2.25 ± 28.07	4.22 ± 21.41	1.97 (-16.86, 12.91)	0.79
Scapular Upper Rotation	-4.94 ± 7.21	-2.93 ± 5.87	2.01 (-4.82, 0.81)	0.15
Scapular Internal Rotation	31.24 ± 8.58	32.06 ± 8.27	0.82 (-5.15, 3.50)	0.70
Scapular Anterior Tilt	-13.98 ± 7.39	-13.55 ± 6.59	0.43 (-2.72, 1.87)	0.71
Scapular Protraction	20.79 ± 4.22	22.90 ± 5.21	2.11 (-4.96, 0.73)	0.14
Scapular Elevation	14.38 ± 6.89	15.60 ± 7.25	1.22 (-3.57, 1.12)	0.29

Note: All values in degrees.

Table III. Draw paddle water dissociation kinematic descriptive variables with dominant and non-dominant comparisons.

Kinematic Variable	Dominant ± *SD*	Non Dominant ± *SD*	Mean Difference (95% CI)	*p*-value
Humeral Elevation	20.07 ± 16.30	18.43 ± 16.17	1.64 (-7.68, 10.96)	0.72
Humeral Plane of Elevation	33.08 ± 9.06	36.70 ± 15.02	3.62 (-8.13, 0.89)	0.11
Humeral Axial Rotation	-11.71 ± 21.89	-15.23 ± 22.22	3.52 (-11.03, 18.08)	0.62
Scapular Upper Rotation	-6.30 ± 7.08	-4.00 ± 6.26	2.30 (-5.73, 1.13)	0.18
Scapular Internal Rotation	26.82 ± 8.44	30.00 ± 8.63	3.18 (-7.57, 1.02)	0.15
Scapular Anterior Tilt	-16.09 ± 8.36	-14.95 ± 6.05	1.14 (-3.76, 1.47)	0.37
Scapular Protraction	21.95 ± 4.82	24.09 ± 5.31	2.15 (-5.17, 0.87)	0.15
Scapular Elevation	14.52 ± 6.63	16.34 ± 8.30	1.82 (-4.13, 0.49)	0.12

Note: All values in degrees.

the arm moved through the stroke. The movement of the humerus, from paddle water association to paddle water dissociation, went from a relatively elevated and slightly externally rotated position near the sagittal plane into a less elevated and neutrally rotated position nearer to the frontal plane, while the paddle pulled the boat in a forward direction. As the stroke continued into paddle water association on the contralateral limb, the humerus re-elevated, while maintaining a slightly externally rotated position. Throughout the last two time points on the contralateral limb (paddle shaft vertical and paddle water dissociation) the humerus remained elevated but internally rotated and returned near to the sagittal plane for contralateral paddle water dissociation. This cycle then repeated itself for the next stroke.

Table IV. Thrust paddle water association kinematic descriptive variables with dominant and non-dominant comparisons.

Kinematic Variable	Dominant ± *SD*	Non Dominant ± *SD*	Mean Difference (95% CI)	*p*-value
Humeral Elevation	17.94 ± 6.67	22.73 ± 14.73)	4.79 (-12.49, 2.92)	0.21
Humeral Plane of Elevation	48.84 ± 15.32	47.80 ± 18.34)	1.04 (-4.75, 6.84)	0.71
Humeral Axial Rotation	-5.66 ± 24.90	-13.35 ± 21.75)	7.69 (-1.95, 17.34)	0.11
Scapular Upper Rotation	2.05 ± 7.92	0.17 ± 10.03)	1.88 (-2.11, 5.86)	0.34
Scapular Internal Rotation	27.03 ± 8.82	24.74 ± 10.27)	2.83 (-2.58, 7.14)	0.34
Scapular Anterior Tilt	-14.57 ± 8.28	-14.67 ± 7.94)	0.10 (-2.36, 2.55)	0.94
Scapular Protraction	25.23 ± 5.57	22.68 ± 5.74)	2.55 (-0.71, 5.81)	0.12
Scapular Elevation	17.63 ± 7.19	16.51 ± 7.39)	1.12 (-1.90, 4.14)	0.45

Note: All values in degrees.

Table V. Thrust paddle shaft vertical kinematic descriptive variables with dominant and non-dominant comparisons.

Kinematic Variable	Dominant ± *SD*	Non Dominant ± *SD*	Mean Difference (95% CI)	*p*-value
Humeral Elevation	73.99 ± 12.89	71.66 ± 14.39	0.33 (-3.27, 7.93)	0.40
Humeral Plane of Elevation	84.67 ± 10.69	85.79 ± 8.86	1.11 (-4.36, 2.14)	0.49
Humeral Axial Rotation	21.16 ± 7.71	25.02 ± 10.88	3.86 (-8.68, 0.96)	0.11
Scapular Upper Rotation	13.82 ± 6.28	14.14 ± 8.91	0.32 (-3.47, 2.83)	0.83
Scapular Internal Rotation	41.91 ± 9.67	42.21 ± 9.91	0.30 (-4.69, 4.08)	0.89
Scapular Anterior Tilt	-10.75 ± 7.14	-9.44 ± 7.62	1.31 (-3.64, 1.03)	0.26
Scapular Protraction	21.97 ± 8.26	20.56 ± 6.15	1.42 (-2.54, 5.38)	0.47
Scapular Elevation	24.70 ± 7.96	25.02 ± 7.69	0.32 (-2.85, 2.21)	0.80

Note: All values in degrees.

Table VI. Thrust paddle water dissociation kinematic descriptive variables with dominant and non-dominant comparisons.

Kinematic Variable	Dominant ± *SD*	Non Dominant ± *SD*	Mean Difference (95% CI)	*p*-value
Humeral Elevation	73.17 ± 13.04)	71.40 ± 13.58)	1.77 (-5.77, 9.32)	0.63
Humeral Plane of Elevation	78.14 ± 11.56)	78.14 ± 8.94)	<0.01 (-3.41, 3.41)	0.99
Humeral Axial Rotation	20.25 ± 9.31)	24.19 ± 9.22)	3.94 (-9.03, 1.14)	0.12
Scapular Upper Rotation	9.25 ± 6.20)	8.48 ± 7.59)	0.78 (-2.25, 3.81)	0.60
Scapular Internal Rotation	41.46 ± 9.06)	42.12 ± 8.67)	0.66 (-5.63, 4.32)	0.79
Scapular Anterior Tilt	-10.91 ± 7.17)	-9.63 ± 7.72)	1.27 (-3.02, 0.48)	0.15
Scapular Protraction	20.39 ± 7.27)	19.11 ± 5.80)	1.28 (-2.06, 4.61)	0.44
Scapular Elevation	22.77 ± 8.60)	22.82 ± 7.45)	0.05 (-2.70, 2.60)	0.97

Note: All values in degrees.

Prior investigation into scapular kinematic patterns has provided insight on healthy and pathological scapular movements during a standardized humeral elevation task (Ludewig et al., 1996; Lukasiewicz et al., 1999; Ludewig & Cook, 2000; Tsai et al., 2003; Myers et al., 2005; Myers et al., 2006). While the specific motion differences found among shoulder pathologies differ, common themes exist such as decreased upper rotation and posterior tipping of the scapula as the humerus moves toward higher elevation angles (Lukasiewicz et al., 1999; Ludewig & Cook, 2000). It has been theorized that scapular upper rotation and posterior tilting aid in maintaining sufficient subacromial space to prevent impingement of subacromial structures and subsequent deficits in these movements may predispose injury (Flatow et al., 1994; Ludewig & Cook, 2000).

The role of the scapula has been reported to act as a stable base for distal muscle attachment while shoulder movements occur (Wiater & Flatow, 1999). Prior reports of scapular muscle activity while kayaking uphold this stability role (Trevithick et al., 2007). While scapular kinematics were not collected, scapular muscle activity of upper trapezius, serratus anterior, and rhomboid major were used as indicators of scapular mobility (Trevithick et al., 2007). These muscles were noted to have high consistency of activation which was well below maximum contraction, indicating that they were being used more to provide stability for muscle attachments of humeral stabilizers (rotator cuff) and prime movers (deltoid and biceps) than mobility of the scapula (Trevithick et al., 2007). Proper kayak stroke technique has been reported to be a combined effort of torso rotation along with the push-pull action at the shoulder (Mann & Kearney, 1980). A stable scapula would allow paddle movement and consequently kayak propulsion to be accomplished through active torso rotation to maximize energy transfer up the kinetic chain (Puntam, 1993). Kayaking with a stable scapula would encourage propulsion to come from the larger and stronger muscles of the torso and provide a stable base on which the humeral muscles may act. This would facilitate dynamic humeral stabilization through rotator cuff contraction while allowing humeral movement to manipulate the paddle in the water (Trevithick et al., 2007). Additionally, the use of torso rotation versus upper limb movement has been advocated as correct paddle stroke technique (Fiore & Houston, 2001).

Kayakers are reported to be at high risk of subacromial impingement (Hagemann et al., 2004). A scapula which is more stable, i.e. has less mobility, may be at greater risk for impingement with functional and sporting tasks as the humerus is elevated without corresponding scapular movements (Ludewig et al., 1996; Kibler, 1998). The greatest potential for mechanical irritation of subacromial structures during the kayak stroke may be related to the positions of the humerus and scapula at thrust paddle shaft vertical. At this time the paddle is vertical and the humerus is at its peak mean elevation and peak mean internal rotation while adducted near the sagittal plane. This humeral position effectively minimizes the subacromial space (Hyvonen et al., 2003; Thigpen et al., 2006). This time point also has the greatest mean scapular upper rotation, elevation, and posterior tipping which act to maximize subacromial space. If the scapula is utilized for stability while kayaking, the scapular movement patterns observed (upper rotation, elevation, and posterior tipping) may be inadequate to limit subacromial tissue damage over many repetitions. Additionally, if other factors compromise scapular mobility this may also compress or injure subacromial structures related to humeral position and minimizing subacromial space.

Pathologic internal impingement is a condition in which the posterior rotator cuff tendons (supraspinatus and/or infraspinatus) become mechanically pinched between the posterior superior glenoid labrum and the humerus (Davidson et al., 1995). At draw paddle water dissociation the humerus has a low mean angle of elevation and is near the frontal plane (horizontally abducted) with maximal scapular external rotation and posterior tilt, when the paddle would be taken out of the water. Conditions which limit scapular external rotation and/or posterior tilt, such as posterior shoulder tightness or pectoralis muscle tightness, could predispose whitewater kayakers to pathologic internal impingement. Decreased scapular posterior tilt has been associated with pathologic internal impingement in baseball players (Laudner et al., 2006).

Shoulder muscle fatigue has also been shown to alter scapular kinematics (Tsai et al., 2003). Specifically, scapular posterior tipping, external rotation, and upper rotation have been described to decrease following a fatiguing external rotation protocol of the rotator cuff (Tsai et al., 2003). As noted above, these kinematic scapular motions are important while kayaking to maintain coordinated movement with the humerus and prevent subacromial and pathologic internal impingement of the rotator cuff tendons. Cardiovascular or shoulder muscle fatigue associated with whitewater kayaking could also lead to altered scapular kinematics. The kayakers in the current study were paddling at a comfortable set pace of 30 strokes per minute. If this pace were replicated while kayaking on a river approximately 1,800 paddle strokes would occur per hour. Fatigue of the shoulder muscles is probable with such large repetition. Unconditioned athletes may be at risk of shoulder injury secondary to fatigue altered scapular kinematics or humeral head instability due to rotator cuff muscle fatigue.

Humeral and scapular kinematic data at corresponding time points did not significantly differ upon bilateral comparison. The mean difference across scapular variables was less than 3.5° and mean humeral differences did not exceed 7.7° (Tables I–VI). The variability in the data may be due to the fact that all participants were recreational whitewater kayakers. As such, they did not have coaching which could aim to provide a more efficient and consistent stroke between individuals. Within an individual, stroke to stroke accuracy had a SEM of 1.02–4.85° which is slightly lower than prior reports of scapular kinematic analysis during sports tasks (Meyer et al., 2008). Similar dominant to non-dominant kinematics were anticipated given that this was a group of experienced recreational whitewater kayakers without any report of injury. Bilateral symmetry of the kayak stroke may allow for equal distribution of forces as injury has been related to an asymmetric force distribution during the paddle stroke (Lovell & Lauder, 2001). Given the reported incidence of shoulder injury in whitewater kayakers, kinematic investigation of paddle stroke symmetry in injured kayakers should be considered.

As with all studies, there are several limitations which warrant mention. The kayak task in the current study was performed using a kayak ergometer. The lower body postures used while kayaking on the ergometer in this study would be different than sitting in a kayak. However, previous research has shown upper limb kinematics differ slightly when kayaking on an ergometer compared to on the water (Begon et al., 2008). This difference was hypothesized to be related to the lack of balance required to kayak on an ergometer as opposed to on water kayaking (Begon et al., 2008). The kinematic patterns found may differ or dominant to non-dominant asymmetry may exist when kayaking under different conditions. Also, motion artifact, due to sensor movement on the skin, may impose error to the results. Scapular tracking using an electromagnetic device during a humeral elevation task has been validated against bone fixed sensors previously which is a slow and controlled motion (Karduna et al., 2001). The paddle stroke occurred at higher velocities than the validation study. This may have increased the sensor on skin movement. Humeral axial rotation range of motion measurement has also been reported to have increased measurement error compared to other humeral and scapular kinematic variables (Ludewig et al., 2002). This variable was included for comprehensiveness but the large ranges of values indicate humeral axial rotation should be considered with some caution. Although experienced kayakers participated in this study, some bilateral kayak stroke variation would be expected within individuals that may not be adequately described upon group comparisons. Finally, the stroke rate used for the current study was regulated. This pace was determined to be comfortable through pilot testing; however the imposition of a stroke rate may have affected the motions found. A regulated stroke rate was used in attempt to decrease variability in kinematics associated with differing paces between participants.

Conclusion

Descriptions of the kinematic patterns of the humerus and scapula during the kayak stroke were related to common shoulder pathologies found in recreational whitewater kayakers.

Recreational whitewater kayakers without injury exhibit symmetrical scapulohumeral kinematics during the forward kayak stroke while kayaking on an ergometer. The scapular motions described may provide an understanding of how kayak stroke kinematics relate to shoulder injury. Future research should aim to determine if the proposed connections exist between scapulohumeral kinematics and shoulder injury in whitewater kayakers.

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