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Scapular orientation following repetitive prone rowing: Implications for potential subacromial impingement mechanisms



ELECTROMYOGRAPHY

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ABSTRACT

While fatigue of the rotator cuff demonstrably causes superior humeral head migration and concomitant risk of impingement, the relationship between specific muscular fatigue, scapular dyskinesis and impingement risk is less clear. The purpose of this study was to examine changes in scapular orientation following a simulated prone rowing fatiguing protocol that targeted the scapula stabilizing muscles while attempting to alleviate rotator cuff muscular demands. Scapular orientation and muscle activity were collected from participants before and immediately after the fatiguing task. This task fatigued both the stabilizing (upper and middle trapezius, and latissimus dorsi) and rotator cuff (supraspinatus, and infraspinatus) muscles. The upper extremity muscle fatigue pattern caused by the protocol did not elicit any significantly changes in three-dimensional scapular position with all post-fatigue changes being $\leq 1^{\circ}$ (p = 0.17-0.58). These results indicated that scapular reorientation is likely not the dominant mechanism of fatigue-induced subacromial impingement development. However, the substantial variability present in the kinematics prevents complete exclusion of scapular dyskinesis as a secondary causal mechanism of impingement.

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1. Introduction

The dimensions of the subacromial space, which is between the inferior surface of the acromion and the superior aspect of the humeral head, are strongly associated with rotator cuff pathological mechanisms. A reduction in the subacromial space can lead to impingement of interposed tissues including the supraspinatus tendon, subacromial bursa, shoulder capsule, and long head of the biceps tendon (McFarland et al., 1999; Michener et al., 2003; Bey et al., 2007). This impingement often causes an inflammatory response and precedes shoulder pain and/or rotator cuff tearing (Michener et al., 2003).

Multiple mechanisms have been suggested or demonstrated as potential causes for subacromial space width changes. Rotator cuff fatigue (supraspinatus, infraspinatus, subscapularis, and teres minor), results in superior humeral translation due to the inability of these muscles to maintain adequate compression of the humeral head in the glenoid cavity (Chen et al., 1999; Teyhen et al., 2008). Further, a simulated superior shift of the humeral head also reduced the subacromial space width, implicating rotator cuff fatigue as contributory to subacromial impingement risk (Chopp and Dickerson, 2012). Similarly, fatigue-induced scapular dyskinesis has also been suggested to be a causal mechanism of subacromial space reduction. Scapular dyskinesis occurs when the scapular stabilizing muscles (upper, middle, and lower trapezius, serratus anterior, and latissimus dorsi) are unable to preserve typical scapular movement, and is considered potentially harmful when it results in increased anterior tilting, downward rotation, and pro-traction, all of which reorient the acromion to reduce the subacromial space width (Tsai et al., 2003; Borstad et al., 2009). However, there has been no conclusive study indicating the sign of scapular dyskinesis occurring as a direct result of solely scapulothoracic muscle fatigue.

Scapular orientation changes in an impinging direction (downward rotation, anterior tilt, and protraction), have been reported. Borstad et al. (2009) used a "modified push-up plus" as a fatiguing protocol, which elicited fatigue from the serratus anterior, upper and lower trapezius, and the infraspinatus. Their resulting kinematics included decreased posterior tilt (-3.8°) , increased internal rotation (protraction) (+3.2°), and no change in upward rotation. Tsai et al. (2003) fatigued the external rotators using a resistive elastic band, which resulted in less posterior tilting, external rotation, and upward rotation, with the largest fatigue-induced differences ranging from 2.4° to 4°. Both studies concluded that upper extremity muscle fatigue results in abnormal scapular kinematics in a direction that may cause subacromial impingement. Though these changes are small in magnitude, researchers suggest that kinematic differences as small as 4–5° may be meaningful (Ebaugh et al., 2005).

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Contrastingly, other studies that attempted to fatigue the scapula stabilizers either produced orientation changes in the opposite direction or no changes at all. This suggests that scapula dyskinesis may not contribute to fatigue-induced subacromial space reduction (McQuade et al., 1998; Su et al., 2004; Ebaugh et al., 2006; Suzuki et al., 2006). Following a global upper extremity fatiguing task that exhausted the infraspinatus, serratus anterior, upper trapezius, posterior deltoid, and anterior deltoid, Ebaugh et al. (2006), measured increased upward rotation and retraction and no difference for scapular tilt, McQuade et al. (1998) induced fatigue in the upper trapezius, serratus anterior, and middle deltoid by instructing participants to elevate their arm with maximum effort; this also resulted in increased scapular upward rotation and retraction. In their pilot study, Suzuki et al. (2006) noted that their exertion circuit, which consisted of seven exercises, induced scapular muscle fatigue while sparing the rotator cuff. However, no electromyographic (EMG) data were recorded to substantiate this claim. Nevertheless, Suzuki et al. (2006) and Su et al. (2004) both demonstrated that fatiguing scapula stabilizers did not induce a significant increase in upward rotation in healthy participants. Further a fatiguing protocol that globally fatigued the upper extremity muscles caused impingement-sparing scapular orientation changes (upward rotation and posterior tilt) (Chopp et al., 2011).

Determining the effects of upper extremity muscular fatigue and the associated mechanisms of subacromial space reduction is important from a prevention and rehabilitation perspective. Scapular orientation changes subsequent to fatigue generally alleviate this risk. However, changes in scapular orientation following targeted fatigue of scapular stabilizing muscles are currently unverified. Prone rowing exercises, in which a patient lies prone on a bench and flexes the elbow from 0° to 90° while the shoulder flexion angle moves from 90° to 0° using a resistive weight, are clinically recommended to strengthen the scapular stabilizers while minimally activating the rotator cuff (Escamilla et al., 2009; Reinold et al., 2004). The ability of this prone rowing task to solely target the scapular stabilizers will be investigated to help clarify whether scapular dyskinesis is a possible mechanism of fatigue-induced subacromial impingement risk.

Therefore, there are two primary goals of this study: (1) to determine whether a popular clinical exercise (prone rowing) performed to exhaustion can isolate and fatigue the scapular stabilizing muscles (upper, middle, and lower trapezius, serratus anterior, and latissimus dorsi) without fatiguing the rotator cuff, and (2) to quantify the influence of the muscular fatigue induced by prone rowing on three-dimensional scapular orientation. Results from this study will help to strengthen best practice recommendations for rehabilitation and treatment programs intended to reduce subacromial impingement risk.

2. Methods

2.1. Participants

Fifteen right-hand dominant males participated in this collection. Sample size was determined by a power analysis using the results from the previous study (Chopp et al., 2011); fifteen participants were required for adequate power. The mean height, weight, and age were 1.79 (SD 0.07) m, 74.2 (SD 9.9) kg, and 22 (SD 3) years, respectively. Participants were excluded from the study if they reported any upper extremity pain or injury within the past year, or any bony structural damage (humeral head, clavicle or acromion fracture, or joint dislocation). The study was approved by the Office of Research Ethics, and each participant provided informed consent.

2.2. Instrumentation

2.2.1. Scapular tracking and motion capture

Trunk and scapular kinematic data were collected at 50 Hz using eight Vicon MX20 System cameras (Vicon, Oxford, UK). Reflective markers were placed over ten anatomical landmarks (sternal notch, xiphoid process, C7 vertebra, T8 vertebra, acromion, medial point on the scapular spine, inferior angle of scapula, acromial angle of scapula, medial epicondyle, lateral epicondyle) according to ISB recommendations (Wu et al., 2005). Additional marker clusters were placed over the posterior-lateral acromion (Van Andel et al., 2009) and the right upper arm to reduce skin motion artefacts (Ludewig and Cook, 2000). A static calibration was collected with participants standing in a neutral position (upright posture with arms down by the side) to establish the relationship between the clusters and the scapular landmarks.

2.2.2. Surface electromyography

Muscle activity was measured for seven muscles using surface electromyography (EMG). Muscles examined included: supraspinatus, infraspinatus, upper trapezius, middle trapezius, lower trapezius, serratus anterior, and latissimus dorsi. Noraxon Ag-AgCl bipolar surface electrodes (Noraxon, Arizona, USA) were placed over the belly of each muscle using published placements (Cram and Kasman, 1998; Hintermeister et al., 1998). Prior to electrode placement, the area was shaved and cleaned with alcohol to minimize impedance. A ground electrode was placed over the clavicle. EMG signals were collected using a Noraxon T2000 telemetered system (Noraxon, Arizona, USA). The raw EMG signals were band-pass filtered from 10 to 500 Hz and differentially amplified (common-mode rejection ratio >100 dB at 60 Hz, input impedance 100 M Ω) to produce maximum signal in the range of the A/D board. The signal was converted from analog to digital at 1500 Hz (16 bit A/D card, ±3.5 V range).

2.3. Experimental protocol

The experiment was conducted in one session lasting approximately two hours. The protocol consisted of five parts: (1) muscle-specific maximum voluntary contractions, used to normalize EMG data, (2) pre-fatigue kinematic and EMG trials, (3) anthropometric scaling of a weight used during the fatiguing protocol, (4) a prone-rowing fatiguing task and (5) post-fatigue kinematic and EMG trials.

2.3.1. Maximum voluntary contractions (MVCs)

Participants performed three repetitions of muscle-specific maximal voluntary contractions (MVCs). A 2-min rest period was provided between each exertion to reduce the likelihood of fatigue (Knutson et al., 1994; Chopp et al., 2010).

2.3.2. Pre-fatigue trials

Pre-fatigue trials consisted of obtaining muscle activity levels during isometric holds and three-dimensional scapular orientations measurements at varying humeral elevation angles in the scapular plane. These data were later compared to post-fatigue trials. To avoid residual fatigue from MVCs, participants were given approximately 30 min of rest prior to the pre-fatigue measurements. Muscle activity was recorded while the participants' right arm was positioned at 45° of shoulder abduction in the frontal plane while lying prone on a bench. During the collection, participants held a 1 kg weight in their hand with their thumb facing down. The scapular orientation was measured at three scapular plane elevation angles with their right elbow fully extended (Chopp et al., 2010). Each trial was held statically for five seconds while data was captured. All arm angles were positioned by the experimenter using a manual goniometer.

2.3.3. Fatiguing protocol

The fatiguing protocol consisted of a simulated prone rowing exertion repeated until exhaustion. The task consisted of repetitively lifting a weighted bottle from 90° shoulder flexion with 0° elbow flexion to 0° shoulder flexion with 90° elbow flexion at a controlled speed of 42 bpm (Fig. 1) until fatigued. A thick Velcro strap was used to fasten the participant's body to the bed to minimize torso movement. During the protocol, tactile feedback and verbal coaching were continuously provided by the researcher to promote scapular retraction and subsequent scapular stabilizer fatigue.

Fatigue was monitored using a modified Borg CR10 Rate of Perceived Exertion (RPE) scale (Borg, 1982). RPE was verbally expressed by the participants prior to and every 30 s during the fatiguing protocol. Participants continued the protocol until either exhaustion (RPE of 10) was verbally indicated or they were unable to maintain repetitions at 42 bpm.

2.3.4. Post-fatigue trials

Post-fatigue trials were collected using an identical protocol to that described in Section 2.3.2. To prevent fatigue recovery confounding the data, post-fatigue trials were measured within one minute of the completion of the fatiguing protocol.

2.4. Data analysis

2.4.1. Motion processing

Kinematic data were processed using Vicon software (Vicon, Oxford, UK) and MATLAB (The Mathworks, Inc., Natick, MA, USA). Missing markers in the original data were interpolated using the Pattern Fill algorithm (Vicon, Oxford, UK). Filled marker data were low-pass filtered at 4 Hz with a second-order dual-pass Butterworth filter in MATLAB (The Mathworks, Inc., Natick, MA, USA). Scapular angles were calculated using the local coordinate system of each segment using the Grood and Suntay approach (1983) as recommended by ISB (Wu et al., 2005). The scapular angles measured in the calibration trial were defined as the neutral scapular orientation. The scapular orientation following the fatiguing protocol was expressed relative to this neutral scapular orientation to account for anatomical differences in absolute scapular angles among participants (Picco et al., 2010). Scapular upward rotation was defined as lateral rotation of the inferior border of the scapula; scapular posterior tilting was defined as anterior movement of the inferior border of the scapula; and scapular retraction was defined as posterior movement of the lateral border of the scapula (Ebaugh et al., 2006; Michener et al., 2003; Solem-Bertoft et al., 1993; Chopp et al., 2010).

2.4.2. Frequency and time domain EMG processing

EMG data were processed in the frequency and time domain. In the frequency domain, the data were analyzed using a Fourier Transform. Signals were first high-pass filtered at 30 Hz to eliminate the heart rate contamination (Drake and Callaghan, 2006). Mean power frequency (MPF) was calculated from the average of 500 msec intervals. The MPF values from the pre-fatigue reference exertions were compared to the post-fatigue reference exertions to test for fatigue (Mannion and Dolan, 1996). In the time domain, the data were full-wave rectified and low pass filtered at 4 Hz using a second-order dual-pass Butterworth filter (Mathiassen et al., 1995). A 500 ms moving window was applied. The EMG data obtained during isometric holds were normalized to the peak value (maximum amplitude) obtained from the MVC trials to allow comparison across participants (Knutson et al., 1994). Muscles were considered fatigued when all of the following criteria were satisfied: (1) a significant decrease in MPF and (2) a significant increase in EMG amplitude.

2.4.3. Statistical analysis

A Shapiro–Wilk test revealed that the data were not normally distributed; therefore, three non-parametric two-way repeated measures ANOVAs were used to identify the effects of fatigue (pre- and post-fatigue) and arm angle (0° , 45° , 90°) on scapular rotation, tilt, and protraction/retraction. Two one-way repeated measures ANOVAs were used to identify the effects of fatigue (pre and post fatigue) on MPF and EMG amplitude. In the analysis, a *p*-value of 0.05 was used to determine the significance. Interactions were examined using the post hoc Tukey test with Bonferroni adjustments to accurately assess the *p*-value (*p*), and angle and fatigue effects were examined using the Wilcoxon Signed rank test.



Fig. 1. Fatiguing protocol - prone rowing with 5%MVC weight bottle: 90° shoulder flexion with 0° elbow flexion (left) and 0° shoulder flexion with 90° elbow flexion (right).

Table 1

Change in mean power frequency (MPF) for each of the seven muscles following the fatiguing protocol; p < 0.05 indicates statistical significance.

Muscles	MPF change (%) (p-value)
Supraspinatus	-9.83 (<0.05)
Infraspinatus	-19.78 (<0.05)
Upper trapezius	-14.82 (<0.05)
Middle trapezius	-7.37 (<0.05)
Lower trapezius	-11.36 (0.21)
Serratus anterior	-38.77 (0.22)
Latissimus dorsi	-11.20 (<0.05)



Fig. 2. Pre-fatigue (light grey) and post-fatigue (dark grey) scapular orientation: (A) scapular rotation, (B) tilt, and (C) protraction/retraction. Significant arm angle effect is indicated by a single star (*) (p < 0.05). There were no fatigue nor fatigue-related interaction effects.

Cohen's *d* test was done to calculate the effect size (*d*) (Cohen, 1988). Statistical analyses were performed using R12.1 (R Development Core Team, Vienna, Austria).

3. Results

The prone rowing fatiguing protocol fatigued all of the scapula stabilizer muscles, excluding the lower trapezius and serratus anterior. It also fatigued the measured rotator cuff muscles (supraspinatus and infraspinatus). Fatiguing this combination of muscles did not significantly alter any of the three-dimensional scapular orientation compared to the pre-fatigue trials.

3.1. Fatigue quantification

All muscles except the lower trapezius and serratus anterior were fatigued following the protocol, as identified through increases in EMG amplitude and decreases in MPF (Table 1). Amplitude increases occurred in all muscles except the lower trapezius, while MPF decreases occurred in all muscles except the lower trapezius and serratus anterior. All muscles had a reduction in MPF of at least 8%, which has been previously used as a muscle fatigue anchor (Oberg et al., 1990). The average time to fatigue was 9.59 (SD 4.93) minutes, and all participants reached 10 ("extremely strong" exertions) on the Borg CR10 scale prior to the post-fatigue trials.

3.2. Scapular orientation

Scapular orientation changes following the fatiguing protocol were not significant, as indicated by the absence of both main and interaction fatigue effects (Fig. 2). Fatigue did not affect rotation (p = 0.58, d = 0.08), tilt (p = 0.17, d = 0.50), or protraction/retraction (p = 0.34, d = 0.24). Interaction effects between arm angle and fatigue did not influence rotation (p = 0.76, d = 0.05), tilt (p = 0.29, d = 0.32), and protraction/retraction (p = 0.31, d = 0.31). Humeral elevation angle influenced scapula rotation (p < 0.0001) and tilt (p < 0.0001) (Fig. 2). Upward scapula rotation was higher at 90° arm elevation than for lower angles (d = 6.72 - 38.36). Posterior tilt increased as the humeral angle increased from 0° to 45° to 90° (d = 1.59 - 9.37). For protraction and retraction, the humeral elevation angle did not influence the results, as confirmed by a small to medium effect size (d = 0.01 - 0.56).

4. Discussion

Significant three-dimensional scapular kinematic changes were absent following the experimental fatigue protocol. The anticipated ability of a prone rowing task to isolate and fatigue the scapula stabilizer muscles without fatiguing the rotator cuff was unsubstantiated. Indeed, performing this task to exhaustion caused fatigue of both the rotator cuff muscles (supraspinatus and infraspinatus) and three of the five scapula stabilizers examined (upper and middle trapezius, and latissimus dorsi). This suggests that rotator cuff fatigue may be concomitant with any repetitive or prolonged arm movement. Additionally, the inability of this task to fatigue the lower trapezius and serratus anterior muscles may limit its clinical use for strengthening the scapular stabilizing muscles, as these muscles are critical in maintaining normal scapular kinematics (Michener et al., 2003; Phadke et al., 2009). Globally fatiguing the upper extremity musculature has been reported to orient the scapula in such a way to increase the subacromial space (upwardly rotate and posteriorly tilt) (Chopp et al., 2011; Ebaugh et al., 2006; McQuade et al., 1998); however, these changes primarily exist at mid to higher elevation angles.

Prior to selecting the prone rowing task for the fatiguing protocol, many other exertions were evaluated for their ability to locally fatigue the scapular stabilizing muscles. These tasks included: seated mid-rowing, in which a participant pulled a resistive exercise band from a 90° shoulder flexion angle into the midline of their body while flexing their elbows and reducing their shoulder angle (similar to the prone rowing task); scapular punches, in which the scapula was moved anteriorly and posteriorly with resistance provided by an exercise band while maintaining a stationary torso; and the push-up plus, as documented by Borstad et al. (2009) and Szucs et al. (2009). Subjective indication of fatigue and post hoc EMG analysis revealed that all tasks caused both scapular stabilizer and rotator cuff fatigue. The prone rowing task was the only task that locally fatigued only the scapular stabilizers for a sub-set of participants. However, even in these participants, no changes in scapular orientation occurred.

Several aspects of the study should be considered when assessing the results. First, skin motion artefacts may have existed. Karduna et al. (2001) demonstrated that the RMS errors using a similar acromion tracking method could range from 2.0° to 9.4°, depending on angle considered. The repeated measures structure of the study should reduce these potential errors substantially. Second, the fatiguing exertion may have caused perspiration or changes in skin temperature, which may have decreased the adhesiveness of the electrodes and/or skin markers. Finally, the healthy male student participants in this study may not fully represent a more diverse population.

5. Conclusion

Two major findings which have applications in fundamental injury mechanisms and practical considerations for prevention:

- Scapular orientation is minimally affected by the upper extremity muscle fatigue pattern induced from a prone rowing exercise in healthy subjects, implying that scapular dyskinesis is not likely the predominant fatigue-induced mechanism reducing the subacromial space width.
- Prone rowing or similar exertions intended to highly activate the scapular stabilizing muscles, while minimally activating the rotator cuff, failed to do so, suggesting that the rotator cuff contributes to maintain healthy glenohumeral and scapulothoracic kinematics across a wide range of exertion types.

The inability of repetitive or prolonged tasks to solely fatigue the scapular stabilizing muscles provides reinforcement for the importance of strengthening the rotator cuff muscles as they are ubiquitous in arm function. As upper extremity fatigue generally does not cause scapular orientation changes indicative of subacromial space reduction, it can be assumed that it is not the predominant mechanism of fatigue-induced impingement.

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