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Fatigue-induced glenohumeral and scapulothoracic kinematic variability: Implications for subacromial space reduction

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ABSTRACT

Superior humeral head translation and scapula reorientation can reduce the subacromial space. While these kinematic abnormalities exist in injured populations, the effect of muscle fatigue is unclear. Additionally, these mechanisms were typically studied independently, thereby neglecting potential covariance. This research evaluated the influence of upper extremity muscle fatigue on glenohumeral and scapulothoracic kinematics and defined their relationship. Radiography and motion tracking systems captured these kinematic relationships, during scapula plane elevation, both before and after fatigue. Fatigue-induced changes in humeral head position, scapular orientation and the minimum subacromial space width were measured. High inter-subject variability existed for each measure which precluded identification of mean differences at the population level. However, significant scapular upward rotation occurred following fatigue ($p = 0.0002$). Despite similar population mean results, between 39% and 57% of participants exhibited fatigue-related changes in disadvantageous orientations. Additionally, correlations between measures were generally fair (0.21–0.40) and highly dependent on elevation, likely attributed to the variable fatigue responses. Overall, the data confirms that fatigue-induced changes in kinematics poses highly variable risk of subacromial impingement syndrome across individuals. Thus, solely considering the "average" or mean population response likely underestimates potentially injurious fatigue consequences.

1. Introduction

Glenohumeral (GH) and scapulothoracic (ST) kinematic variation can influence the healthy geometry of the shoulder by altering the relative relationship between the humerus and scapula. A predominant focus in shoulder biomechanics research has targeted the quantification of these kinematic differences in populations suffering from rotator cuff pathology and/or subacromial impingement syndrome (SAIS) to determine whether a causal relationship can be identified (Endo et al., 2001; Ludewig and Cook, 2000; Ludewig and Reynolds, 2009; McClure et al., 2006; Poppen and Walker, 1976). SAIS results from compression of the tissues, notably the supraspinatus tendon of the rotator cuff, residing between the superior humerus and inferior acromion in an area termed the subacromial space (Michener et al., 2003). Debilitating pain, decreased quality of life, lack of independence and compromised function, all accompany rotator cuff pathology (Milgrom et al., 1995). Thus, the prevention of SAIS in society is critical.

While GH and ST kinematic trends have been identified in injured populations, the development of SAIS in healthy individuals is less studied. Different exposures, such as posture, force and repetitive activity historically relate to shoulder pain and injury, with SAIS the predominant diagnosis (Frost and Andersen, 1999; Svendsen et al., 2004; van Rijn et al., 2010). Upper extremity muscle fatigue is a possible intermediary step that relates these work-related task characteristics to SAIS development (Michener et al., 2003; Dickerson et al., 2011). Specifically, humeral head position and scapular upward–downward rotation, anterior–posterior tilt and internal–external rotation, demonstrably change as a function of muscular exposure and accompanying fatigue, as the surrounding muscles act to stabilize these bones in a healthy individual (Borstad et al., 2009; Chen et al., 1999; Chopp et al., 2010, 2011; Cote et al., 2009; Ebaugh et al., 2006; McQuade et al., 1998; Teyhen et al., 2008; Tsai et al., 2003). The rotator cuff muscles

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(supraspinatus, infraspinatus, subscapularis and teres minor) are predominantly responsible for maintaining a stable glenohumeral position. These muscles act to compress the humeral head in the glenoid cavity and resist the superior destabilizing shear force of the deltoid muscle, particularly during early arm elevation (Poppen and Walker, 1978; Yanagawa et al., 2008). The scapula remains stable with respect to the thorax by means of periscapular stabilizing musculature, primarily the upper and lower trapezius and serratus anterior (Michener et al., 2003; Phadke et al., 2009). Thus, simultaneously fatiguing these GH and ST stabilizing muscles may initiate kinematic changes that reduce the subacromial space and subsequently elevate the risk of SAIS.

This research evaluated the effect of upper extremity muscle fatigue on GH and ST relationships at several scapular plane arm elevations. Additionally, by simultaneous capturing both kinematic relationships from the same population, the covariance between kinematic variable was examined. It was hypothesized that fatigue would induce changes that reduced the subacromial space, thereby increasing SAIS risk. These changes consist of superior humeral translation and scapular downward rotation, anterior tilting and internal rotation. It was also hypothesized that these subacromial space reducing mechanisms would be correlated with one another and with the size of the space.

2. Methods

2.1. Participants

Twenty-eight healthy right-hand dominant male participants with a mean age of 24.9 ± 3.6 years and height and weight of 1.8 ± 0.8 m and 84.1 ± 14.2 kg, participated in this research. Health status was confirmed based on self-reports of pain and current/previous injury, pain-free active range of motion and clinical impingement tests, as well as with a full shoulder ultrasound exam (Toshiba Aplio XU, Toshiba Medical Systems Corporation, Japan). This study was approved by both the Office of Research Ethics at the University of Waterloo and the Hamilton Integrated Research Ethics Board. Prior to commencing the study, participants provided their informed consent.

2.2. Instrumentation

2.2.1. Glenohumeral and scapulothoracic kinematics

Digital radiography and optical motion tracking were used to measure GH and ST kinematics. Ten anterior–posterior digital radiographs of the glenohumeral joint were captured for each participant on their right side using the Discovery XR656 Digital Radiography System (GE Healthcare, UK) with technical factors of 70 kV and 320 mA. Lead shielding protected against radiation. The X-ray beam was positioned perpendicular to the imaging plate with no caudal angulation. Six Vicon MX20 motion capture cameras (Vicon, Oxford, UK) were used to track rotations of the scapula with respect to the torso. Kinematic data was measured at 50 Hz. Seven reflective markers were placed on anatomical landmarks of the upper limb as per International Society of Biomechanics recommendations (Wu et al., 2005). Additionally, a marker cluster secured on a rigid plate was positioned over the posterior–lateral acromion (van Andel et al., 2009) to track scapula movement during the trials.

2.2.2. Electromyography

Electromyography (EMG) was used to measure muscle activity from six GH and ST stabilizing muscles. Surface electrodes were used to collect activity from the scapula stabilizer muscles: the serratus anterior muscle and the upper and lower portions of the trapezius muscle (Michener et al., 2003). Intramuscular electrodes were used to collect activity from three of the four rotator cuff muscles: supraspinatus, infraspinatus, and subscapularis. Activity collected from the teres minor muscle using intramuscular electrodes often contains significant motion artifacts and was therefore not included (Brookham and Dickerson, 2013). Additionally, surface electrodes were placed on the supraspinatus and infraspinatus muscles (surrounding the wire).

Bipolar Ag–AgCl Noraxon dual surface electrodes (Noraxon, Arizona) with a fixed 2 cm spacing were placed over the muscle belly of each muscle on the right side of the body using published placements (Cram and Kasman, 1998). Prior to placement, the skin overlying the muscle was shaved with a disposable razor and cleaned with isopropyl alcohol to minimize impedance. Hypodermic needles, each containing two sterilized fine-wires with hooked ends (Motion Lab Systems, Inc., Louisiana), were inserted into the rotator cuff muscles on the right side of the body. Electrodes were gamma radiation sterilized and each was contained within its own sterilized packaging. Prior to insertion, the area overlying the muscle was shaved with a disposable razor and cleaned with isopropyl alcohol. The insertions were performed in accordance with previously published instructions (Geiringer, 1999; Nemeth et al., 1990). After each needle was inserted to the appropriate depth into the muscle (using visual feedback) it was removed and safely disposed in a sharps biohazardous waste container. The pair of wires remained inserted into the muscle where they were used to measure muscle activity.

All EMG signals were collected at 3000 Hz using the Noraxon Telemyo 2400 T G2 wireless system. Raw signals were band pass filtered from 10 to 1000 Hz and differentially amplified with a common-mode rejection ratio >100 dB and an input impedance of 100 MΩ. Analog signals were converted to digital using a 16 bit A/D card with a ±3.5 V range.

2.3. Experimental protocol

2.3.1. Strength scaling

Strength scaling procedures were performed to determine the individualized load lifted during the fatiguing protocol (Chopp et al., 2010). With the arm abducted to 90° and the humerus externally rotated (palm facing forward), participants exerted a maximal posterior force and anterior force against an ErgoFet 300™ hand dynamometer (Hoggan Health Industries, Utah). These specific internal (anterior force) and external (posterior force) exertions above shoulder height were selected as they directly relate to rotator cuff muscle demands, while also requiring scapular stabilization. Each exertion was performed twice unless directional exertions differ by ±5 N, in which case a third exertion was performed. The average of these four exertions (two anterior and two posterior) were defined as participants' "maximal force".

2.3.2. Kinematic measurement

Five randomized kinematic trials and a static calibration trial were collected. Participants were positioned at 30° to the plane of the X-ray beam; their arm was elevated to five elevation angles (0°, 30°, 60°, 90° and 120°) in neutral axial rotation. A digital radiograph and five-second motion capture trial were simultaneously collected for each posture. Participants held a 1 kg weight during each trial, consistent with previous research (Chen et al., 1999; Chopp et al., 2010; Cote et al., 2009; Teyhen et al., 2008).

2.3.3. Electromyographic measurement

Following kinematic trials, participants were instrumented with EMG and completed five-second static reference exertions in two postures. Specifically, lying prone on a clinical bench, participants elevated their arm to 60° and 120° in the coronal plane