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Effects of shoulder muscle fatigue caused by repetitive overhead activities on scapulothoracic and glenohumeral kinematics

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Abstract

The purpose of this study was to determine the effects of shoulder muscle fatigue on three dimensional scapulothoracic and glenohumeral kinematics.

Twenty healthy subjects participated in this study. Three-dimensional scapulothoracic and glenohumeral kinematics were determined from electromagnetic sensors attached to the scapula, humerus, and thorax. Surface electromyographic (EMG) data were collected from the upper and lower trapezius, serratus anterior, anterior and posterior deltoid, and infraspinatus muscles. Median power frequency (MPF) values were derived from the raw EMG data and were used to indicate the degree of local muscle fatigue. Kinematic and EMG measures were collected prior to and immediately following the performance of a shoulder elevation fatigue protocol. Following the performance of the fatigue protocol subjects demonstrated more upward and external rotation of the scapula, more clavicular retraction, and less humeral external rotation during arm elevation. All muscles with the exception of the lower trapezius showed EMG signs of fatigue, the most notable being the infraspinatus and deltoid muscles. In general, greater scapulothoracic motion and less glenohumeral motion was observed following muscle fatigue. Further studies are needed to determine what effects these changes have on the soft tissues and mechanics of the shoulder complex.

Keywords: Shoulder; Scapula; Biomechanics; Fatigue

1. Introduction

Shoulder girdle motion is complex and involves synchronous movement of the scapula, clavicle, and humerus. Two dimensional (2D) [11,15,57] and more recently three dimensional (3D) [26,32,35,37,38,41–43] measurement techniques have been used to describe this motion. As the arm is raised, the generally accepted pattern of motion at the shoulder is as follows; the scapula upwardly rotates, posteriorly tilts, and externally rotates [35,38]; the clavicle elevates and retracts [33,38]; and the humerus elevates and externally rotates [32,65]. This coordinated motion is important for normal function of the shoulder girdle and is dependent upon capsuloligamentous structures and neuromuscular control [27,64]. Due to the important role that the shoulder musculature has in producing and controlling shoulder motion, impairments of these muscles could alter the motion of the scapula, clavicle, and/or humerus. Altered scapular kinematics have been identified in individuals with impingement syndrome [32,37,71], rotator cuff tears [51], and glenohumeral instability [50,51,71].

Shoulder pain is frequently reported in individuals who use their arms in a repetitive manner during work or recreational activities [4,8,20,28,31,39,40,45,59,

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70,72]. Several variables have been identified as risk factors for the development of shoulder pain and include highly repetitive use of the arm, work with the arm in an elevated position, and heavy work loads [2,3,16,56,63,68]. Although there is evidence to support an association between repetitive use of the arm and the development of shoulder pain, there is a gap in the evidence that addresses the issue of how repetitive use of the arm contributes to shoulder pain. One of the potential biomechanical mechanisms that may explain this association is altered scapular and humeral kinematics secondary to shoulder girdle muscle fatigue.

Shoulder girdle muscle fatigue has been shown to alter scapulothoracic kinematics [42,43,66]. However, it is not clear whether muscle fatigue results in increased [43] or decreased scapular upward rotation [42,66], and only Tsai et al. [66] reported the effects of muscle fatigue on scapular tilt and external rotation where they found decreased posterior tilt, and external rotation after the external rotator muscles were fatigued. Furthermore, we are not aware of any study that has reported the effect of muscle fatigue on clavicular or humeral kinematics. A more complete understanding of the effects that muscle fatigue has on scapulothoracic and glenohumeral kinematics could provide insight into underlying mechanisms of shoulder injuries. It could also provide a basis for research in subjects with shoulder injuries, and lead to improved examination and treatment procedures. Therefore, the purpose of this study was to determine the effects of shoulder girdle muscle fatigue on three dimensional scapulothoracic and glenohumeral kinematics. Our hypothesis was that shoulder girdle muscle fatigue would result in increased amounts of scapulothoracic motion and decreased amount of glenohumeral motion.

2. Material and methods

2.1. Subjects

Twenty subjects (10 male and 10 female) without a history of shoulder pathology or pain in at least one shoulder voluntarily participated in the study. Subjects were required to be at least 18 years of age (mean age = 22 years, SD 3.4 years) and have a minimum of 120° of humeral elevation. The height of the subjects varied from 150 to 182.5 cm (mean 166.5 cm, SD 8.3 cm) and mass varied from 47.2 to 99.9 kg (mean 66.4 kg, SD 13.4 kg). The dominant arm (arm used for writing) was tested in eleven subjects and the non-dominant arm was tested in nine subjects. In all subjects except two, the arm to be tested was determined randomly. Two subjects had a history of shoulder injury on their non-dominant arm; therefore their dominant arm was tested. Approval for this study was obtained from the institutional review board at Drexel University. Each subject read and signed a consent form prior to participation in the study.

2.2. Experimental procedures and instrumentation

2.2.1. Overview of experimental procedure

The overall flow of the experiment was as follows. First, electromyographic (EMG) surface electrodes were applied to the subjects and baseline measures of median power frequency (MPF) were collected. Second, kinematic sensors were attached to the subjects and baseline kinematic measures were collected. These baseline measures represented the pre fatigue condition. Next, the subjects performed a fatigue protocol. Upon completing the fatigue protocol MPF and kinematic measures were collected. These measures represented the post fatigue condition.

2.2.2. Electromyography

The Noraxon MyoSystem 1200 (Noraxon, USA, Inc., Scottsdale, AZ) was used to collect raw surface electromyographic (EMG) data. This unit provides differential signal amplification (1000×), band pass filtering of 10–500 Hz (fourth-order Butterworth filter), input impedance > 10 MΩ, and a common mode rejection ratio greater than 100 dB at 50/60 Hz. Output from the Noraxon was linked to a 16 bit analog to digital board in a personal computer and raw data were monitored and collected in LabView (National Instruments, Austin, TX) at a frequency of 1024 Hz. Disposable bipolar Ag–AgCL surface electrodes with a sensor area of 13.2 mm^2 were placed over the upper and lower trapezius, serratus anterior, anterior deltoid, posterior deltoid, and infraspinatus muscles following previously described techniques [22,43,52] (Fig. 1). The electrodes were applied to the skin in a direction that was parallel with the muscle fibers and the inter-electrode distance was 2.5 cm. The skin was prepared by scrubbing the area with alcohol pads and a ground electrode was placed over the ipsilateral clavicle.

2.2.3. Median power frequency and muscle strength

A load cell (MLP-50, Transducer Technique, Temecula, CA, range 0–23 kg, linearity 0.1%) was used to record the resistive force generated during an isometric contraction of the shoulder muscles. The resistive force represented a measure of muscle strength, and was used as a basis for establishing the intensity of an isometric contraction that would be used for determining the MPF for each muscle. Additionally, this measure was used to determine the amount of weight each subject would lift during the fatigue protocol.

The load cell was mounted on a thermoplastic cuff that was attached to the adjustable arm of a positioning unit which consisted of a base with wheels, an upright

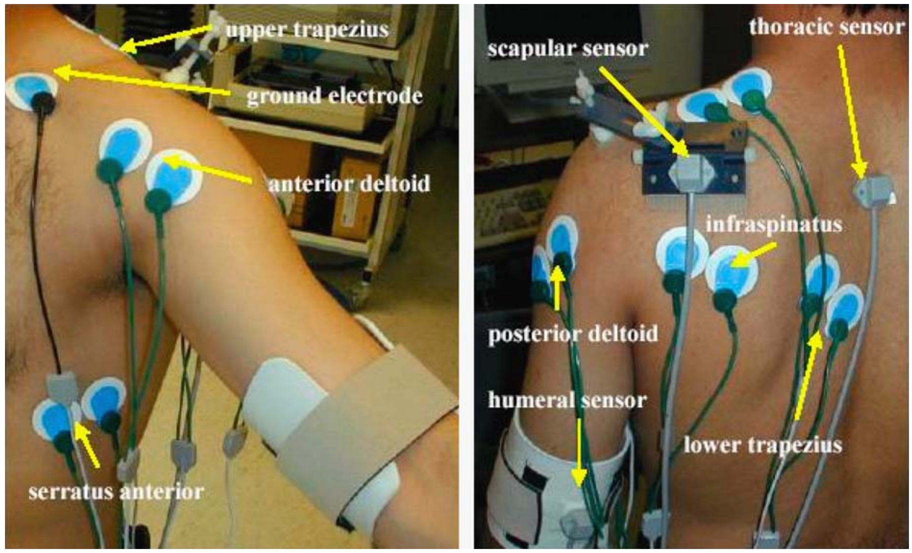

Fig. 1. Anterior and posterior view of EMG surface electrode and Polhemus sensor placement.

pole, and an adjustable arm. The output from the load cell was fed into a signal conditioner (DMD-465WB Bridgesensor, Omega Engineering Inc, Stamford, CT) and then to an analog to digital board in a personal computer where it was collected at a frequency of 1024 Hz in LabView. Strength measurements were obtained with subjects seated in an upright position, elbows extended and their arms elevated to 90° in the scapular plane. Subjects performed a maximal voluntary isometric contraction (MVIC) by pushing up against the cuff/load cell for 5 s. This was repeated three times with a 30 s rest between trials. Shoulder muscle strength was determined by averaging the mean resistive force from a 1 s time period (3.5–4.5 s) from each trial.

Median power frequency measures were used as indicators of local muscle fatigue [9,10,30,44,46]. In order to acquire MPF measures subjects were seated with their arm elevated to 90° in the scapular plane, and were instructed to push up into the cuff/load cell with 60% [54,60] of their previously determined force for 5 s. The computer was configured so that subjects had a visual target to help them maintain the 60% (±5%) force level. This step was performed prior to and immediately following the fatigue protocol.

2.2.4. Kinematics

Three-dimensional kinematic data from the scapula, humerus, and trunk were collected at 40 Hz with the Polhemus 3Space Fastrak (Colchester, VT). This magnetic tracking device consists of a transmitter, three receivers, and a digitizing stylus, all of which are hard-wired to a systems electronic unit. The manufacturer has reported an accuracy of 0.15° for orientation and 0.8 mm for position [13] and it has been used in a number of studies that have investigated shoulder girdle motion [26,32,41,43].

Three Polhemus receivers were attached to each subject (Fig. 1). The thoracic receiver was attached, by double-sided tape, to the skin overlying the third thoracic spinous process. The humeral receiver was attached to a thermoplastic cuff which was placed distally on the humerus just proximal to the epicondyles and was held in place with an elastic strap [36]. The scapular receiver was mounted to a scapular tracker device [26]. The base of the scapular tracker was attached to adhesive-backed Velcro strips placed on the skin above and below the scapular spine, and the footpad of the tracker was attached to Velcro on the superior aspect of the acromion. The transmitter was attached to an upright plastic pole, and acted as the global reference frame. The coordinate axes of the transmitter were aligned with the cardinal planes of the body.

With subjects in a seated position, several bony landmarks on the thorax, humerus and scapula were palpated and digitized in order to allow the arbitrary axis system defined by the Polhemus to be converted to a meaningful anatomical axis system. The anatomical axis system has been described previously and was determined from three points on the thorax, scapula and humerus [25,26,38]. For the purpose of this study, the body segments and their corresponding digitization points are: Thorax: T1, T7, sternal notch; Scapula: acromioclavicular joint, root of the scapular spine, inferior angle of the scapula; Humerus: medial epicondyle, lateral epicondyle, humeral head. The center of the humeral head was calculated using a least squares algorithm and was defined as the point that moved the least during several small arcs of motion [21].

2.2.5. Arm elevation trials

Kinematic and EMG data were simultaneously collected during trials of maximal scapular plane arm elevation. For these trials females held a 1.4 kg weight and males held a 2.3 kg weight in their hands. Subjects were instructed to sit upright in a low-back chair with their feet flat on the floor and raise their arm in the scapular plane which was defined as 40° (±10°) anterior to the frontal plane. The top of the chair back reached the lower thoracic/upper lumbar level in all subjects and did not contact the scapula during any of the tests. A plastic pole was positioned along the lateral aspect of the subjects arm and acted as a guide to maintain the plane of elevation. Subjects were told to raise and lower their hand over their head with their thumb pointing up while maintaining light contact with the plastic pole. Each trial of arm elevation was performed to a count of 8 s; 4 s to raise the arm and 4 s to lower it.

2.2.6. Shoulder elevation fatigue protocol

In order to fatigue the shoulder girdle muscles, subjects were asked to perform three tasks. First, subjects stood with their arms elevated to 45° and manipulated small objects for 2 min (Fig. 2). Second, subjects were asked to raise and lower their tested arm against resistance (Fig. 3). A weighted cable and pulley system was used to provide the resistance and the amount of weight that subjects lifted for this task and the third task was targeted at 20% of the force that was recorded during the MVIC. With their elbow in full extension, subjects performed 20 repetitions of arm elevation in the plane of the scapula. Third, subjects were asked to raise and lower their arm through a diagonal pattern against resistance (Fig. 3). The diagonal pattern began with the hand of the tested arm in front of the contralateral hip. With their elbow in full extension, subjects raised their hand up and over the ipsilateral shoulder, and then lowered their arm back down to the starting position and repeated this twenty times. Upon completion of the third activity, subjects immediately returned to the first activity and rotated through the three activities until one of two criteria was met:

1. The subjects reported that they were unable to continue to perform the required tasks, or
2. The subjects failed to correctly perform two tasks in a row. Failure for the first task was defined as follows: an inability to maintain their arms in 45° of elevation despite verbal feedback from the investigator. Failure for the second and third tasks was defined as follows: an inability to move through the required motion more than two times, and/or altering their posture (more than two times) by leaning the trunk to the contralateral side while elevating the arm. If subjects altered their posture, the investigator provided them with verbal feedback to remind them that they are to maintain an upright posture.

A flow chart of the shoulder elevation fatigue protocol is presented in Fig. 4. Prior to and immediately following the completion of the fatigue protocol subjects were asked to rate their level of perceived exertion (RPE) using the Borg Scale[5]. This is an interval scale with anchor points at 6 (no exertion at all) and 20 (maximal exertion). Upon completing the fatigue protocol, subjects repeated the procedures for obtaining EMG measures of fatigue and kinematic and EMG measures during arm elevation. Approximately 2 min elapsed from when subjects' reached fatigue to when they repeated the trials of arm elevation.

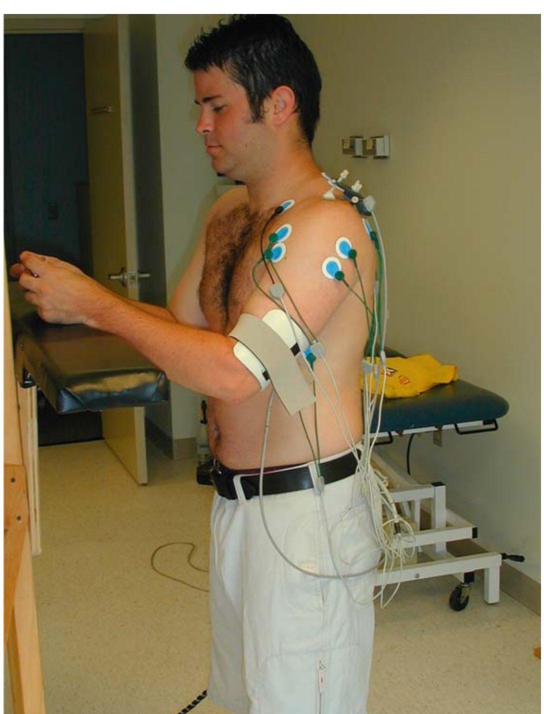

Fig. 2. Static elevation task.

2.3. Data reduction

2.3.1. EMG – median power frequency (MPF)

The MPF was derived from the raw EMG with the use of a Fast Fourier Transformation (FFT) algorithm. The EMG data were separated into 1-s intervals which were entered into the algorithm in order to establish a power density spectrum [17]. The power density spectrum was used to determine the MPF for each 1-s interval over a 5 s time period. The MPF from the 2nd, 3rd, and 4th s were then averaged. Changes in MPF were determined by subtracting the averaged post fatigue MPF values from the averaged pre fatigue values. These new values (MPF change) were expressed as a percentage of the pre fatigue MPF. A minimum reduction of 8% in the MPF value was considered to be an indication of local muscle fatigue [49].

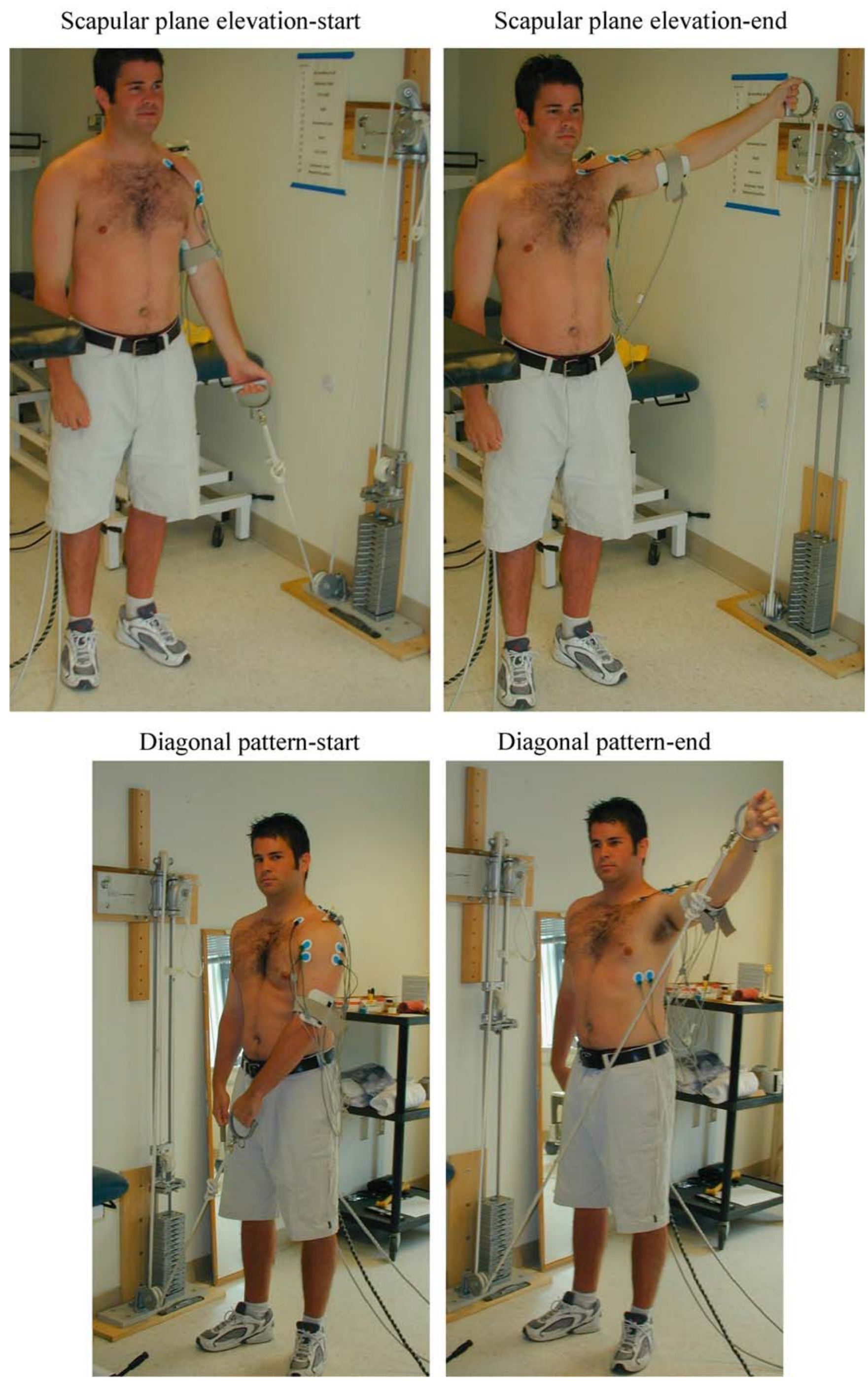

Fig. 3. Dynamic elevation tasks.

One Cycle	Task	Parameter
↻	Manipulation of small objects	2 minutes
	Repetitive elevation in scapular plane	20 reps (20% MVIC)
	Repetitive elevation in D2 flexion pattern	20 reps (20% MVIC)

Fig. 4. Flow chart for shoulder elevation fatigue protocol.

2.3.2. Kinematics

The kinematic data for scapular orientation and position were described using three scapular rotations and two clavicular rotations as dependent variables that were plotted against humeral elevation as the independent variable. The orientation of the scapula relative to the trunk was described using an Euler angle sequence of external/internal rotation (Z_S axis), upward/downward rotation (Y_S axis), and posterior/anterior tilt

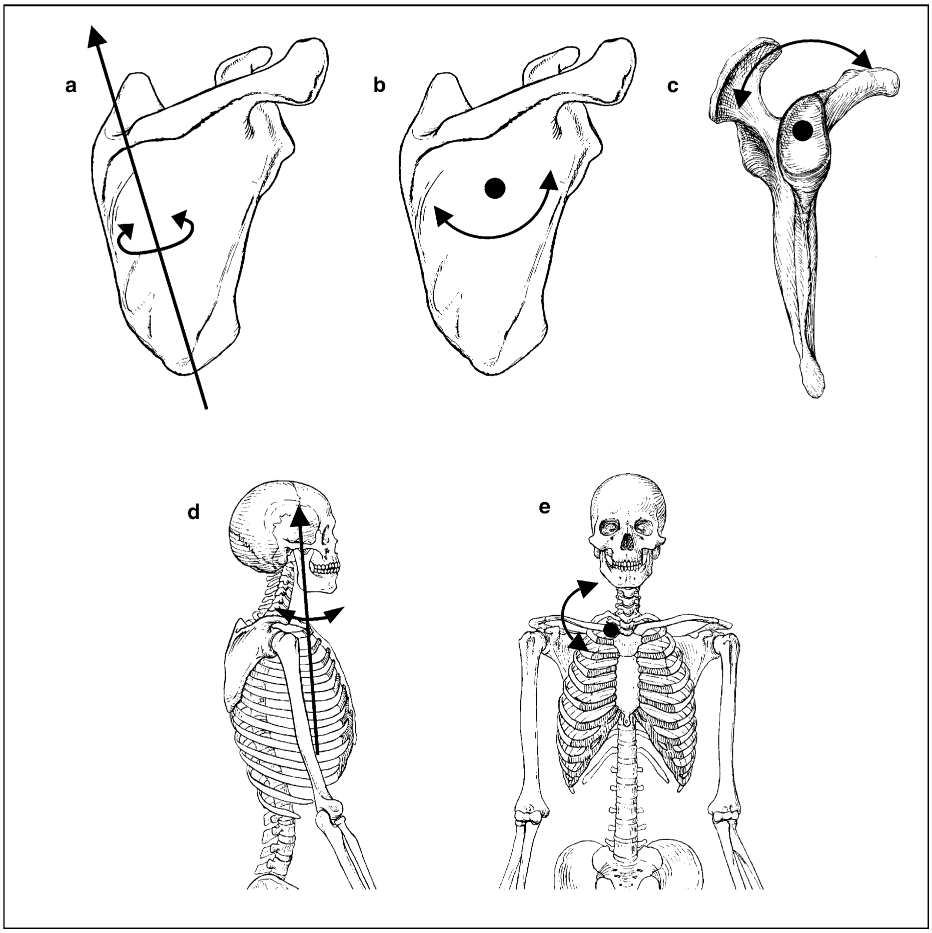

Fig. 5. Axes and rotations for scapular and clavicular rotations: (a) scapular external/internal rotation; (b) scapular upward/downward rotation; (c) scapular posterior/anterior tilt; (d) clavicular protraction/retraction and (e) clavicular elevation/depression.

(X_S axis) (Fig. 5). Two clavicular rotations, protraction/retraction and elevation/depression were used to describe scapular position (Fig. 5). The basis and details of this approach have been described previously [26,38].

A globe based system was used to describe humeral motion relative to the trunk [12,55]. In this system humeral rotations are described in terms of longitude and latitude along a globe that has its center aligned with the center of rotation at the shoulder. Using an Euler angle sequence, the first rotation described the plane of elevation (longitude), the second rotation described the amount of elevation (latitude), and the third rotation described the amount of external/internal rotation that occurred along the long axis of the humerus. Following collection of scapular and humeral kinematic data, a linear interpolation program was used to obtain data in 5° increments and data from the three trials were averaged.

2.4. Data analysis

Reliability statistics for trial to trial kinematic measurements included intraclass correlation coefficients (ICC 3,1) and the standard error of the measurement (SEM). A 2-factor analysis of variance (ANOVA) with two repeated factors, condition (pre- and post-fatigue) and arm elevation (minimum, 60°, 90°, 120°, and maximum), was performed on each dependent variable. The dependent variables of interest in this study were scapular external/internal rotation, upward/downward rotation, posterior/anterior tilting, clavicular protraction/retraction, elevation/depression, and humeral external rotation. For the two-factor analyses, a significance level of 0.05 was used for each dependent variable. Paired t-tests were used for follow up analyses where appropriate. A Bonferonni factor was used to correct for multiple comparisons and the significance level for the paired t-tests was set at 0.01.

3. Results

Trial to trial ICC values for scapular, clavicular, and humeral rotations ranged from 0.78 to 0.99 indicating good reliability [58], and the standard error of the measurement ranged from 0.7° to 4.8°. Prior to beginning the shoulder elevation fatigue protocol all subjects

RPE scores were 6 (no exertion at all). The average length of time that subjects performed the fatigue protocol was 10 min and 44 s after which the average RPE score increased to 19.25 (extremely hard – maximal exertion). Based on our criteria of an 8% reduction in MPF as a sign of local muscle fatigue, all muscles demonstrated signs of fatigue with the exception of the lower trapezius muscle (Table 1).

The results from the ANOVA tests for all dependent variables are presented in Table 2. For scapular upward rotation, scapular external rotation, and clavicular retraction, differences were found between the pre and post fatigue conditions as well as across the different arm elevation angles. Additionally, the pre and post fatigue conditions varied across different positions of arm elevation (Fig. 6). Therefore, differences between pre and post fatigue conditions were investigated at all angles of arm elevation. After completing the fatigue protocol subjects demonstrated the following: (1) more scapular upward rotation at 60° (5.3°), 90° (7.4°), 120° (6.4°), and maximum elevation (2.9°); (2) more scapular external rotation at 90° (6.4°), 120° (8.2°), and maximum elevation (5.2°); and (3) more clavicular retraction at 60° (2.6°), 90° (5.4°), 120° (6.4°), and maximum elevation (3.3°) (Fig. 6).

Scapular posterior tilt differences between pre and post fatigue conditions varied across arm elevation angles. Subsequently the differences between pre and post fatigue conditions were investigated at all angles of arm elevation. Subjects demonstrated decreased amounts of scapular posterior tilt (1.9°) at the minimum elevation position (Fig. 6). Clavicular elevation differed across arm elevation angles and this difference was not consistent between the pre and post fatigue conditions. Subjects demonstrated more clavicular elevation at the 90° (1.9) position after they completed the fatigue protocol (Fig. 6). Finally, there were differences in humeral external rotation between the pre and post fatigue conditions as well as between different positions of arm elevation. Collapsed across all levels of arm elevation subjects demonstrated less humeral external rotation (5.8°) following the fatigue protocol (Fig. 6).

Table 1
Changes in median power frequency

Muscle	% Change
Upper Trapezius	9.3 (6.2)
Lower Trapezius	0.7 (9.8)
Serratus Anterior	10.0 (18.4)
Anterior Deltoid	12.2 (7.4)
Posterior Deltoid	13.5 (11.3)
Infraspinatus	21.5 (10.5)

4. Discussion

The findings from this study demonstrate that fatigue of the shoulder girdle musculature results in altered scapulothoracic and glenohumeral kinematics. Although the results of a number of tests performed in this study achieved statistical significance, some of the reported differences were small (<3°) and the importance of these findings is unknown. Whether an individual who exhibits these small changes over a sustained period

Table 2
Results of the ANOVA tests

Dependent variable	Source	df	F Ratio	Probability level
Scapular posterior tilt	Pre–post (PP)	1	0.140	0.713
	Humeral elevation (HE)	1.157	0.751	0.414
	PP × HE	2.092	6.293	0.004
Scapular UR	Pre–post (PP)	1	26.128	0.000
	Humeral elevation (HE)	2.425	707.136	0.000
	PP × HE	2.369	21.693	0.000
Scapular ER	Pre-Post (PP)	1	10.621	0.004
	Humeral elevation (HE)	1.287	23.446	0.000
	PP × HE	2.210	18.827	0.000
Clavicular Protraction	Pre-Post (PP)	1	19.006	0.000
	Humeral elevation (HE)	2.107	359.983	0.000
	PP × HE	2.129	49.932	0.000
Clavicular Elevation	Pre-Post (PP)	1	2.890	0.105
	Humeral elevation (HE)	1.867	496.491	0.000
	PP × HE	2.435	11.016	0.000
Humeral ER	Pre-Post (PP)	1	12.822	0.002
	Humeral elevation (HE)	2.098	7.087	0.000
	PP × HE	1.865	2.205	0.128

UR, upward rotation and ER, external rotation.

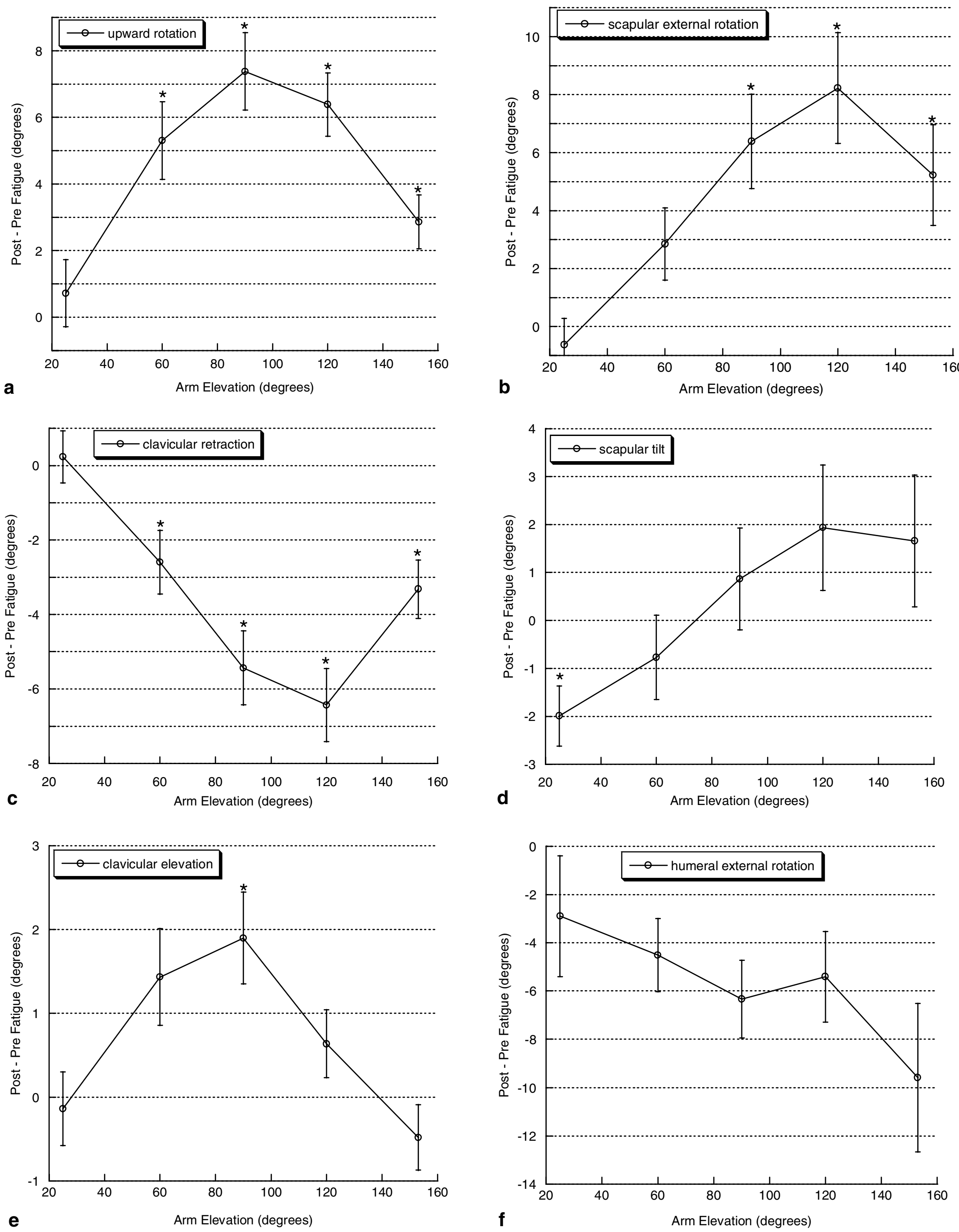

Fig. 6. Averaged kinematic differences (post-muscle fatigue minus pre muscle fatigue) and standard error of the mean. Asterisk (*) indicates significant difference between post and pre fatigue conditions (paired *t*-tests, $p < 0.01$): (a) scapular upward rotation. (+) values = more upward rotation post fatigue; (b) scapular external rotation. (+) values = more external rotation post fatigue; (c) clavicular retraction. (−) values = more retraction post fatigue; (d) scapular tilt. (−) values = less posterior tilt post fatigue; (e) clavicular elevation. (+) values = more elevation post fatigue; (F) humeral external rotation. (−) values = less external rotation post fatigue. Because the subjects varied in their range of humeral elevation motion, the minimum and maximum values represent the average of the 20 subjects. The standard error of the mean for these values were 1.6° and 2.7°, respectively.

of time would develop shoulder pathology is unknown at this time.

Our finding that shoulder muscle fatigue resulted in increased upward rotation of the scapula is in agreement with that of the 1998 McQuade et al.'s study [43]. Averaged across the range of arm elevation the changes in upward rotation in our study were more than twice those reported in their study [43]. This may be due to the fact that our fatigue protocol consisted of three tasks whereas the fatigue protocol in their study consisted of only one [43]. The brief periods of rest taken by our subjects as they moved from one task to the next may have provided them with enough of a rest period that they were able to perform the fatigue protocol longer than the subjects in the McQuade et al.'s [43] study which then resulted in greater amounts of muscle fatigue and subsequently larger changes in scapular upward rotation. On average our subjects performed the fatigue protocol for approximately 11 min while the subjects' in the McQuade et al.'s [43] study performed for 1.5–2 min. A direct comparison of local muscle fatigue (MPF values) between the two studies is not meaningful as the MPF values in the McQuade et al. [43] study were obtained under dynamic conditions while those in this study were obtained under static conditions.

Although our finding related to scapular upward rotation is in agreement with that of the 1998 McQuade et al. study [43], the direction of change is opposite to that reported in their 1995 study [42] and a recent study by Tsai et al. [66]. Both of these studies [42,66] reported less upward rotation of the scapula after the shoulder muscles had been fatigued. A possible explanation for the different findings between this study and the 1995 McQuade et al. study [43] is that only four male subjects were involved in the latter study. With such a small homogenous sample the findings do not represent the population of interest as well as a larger more heterogeneous sample. In the Tsai et al. study [66], the fatigue protocol was designed to selectively fatigue the external rotator muscles of the shoulder rather than global shoulder muscle fatigue in the present study. Perhaps fatigue of additional glenohumeral muscles (i.e. deltoid) noted in the current study results in increased scapular upward rotation in an attempt to help elevate the arm to an overhead position.

Our finding that shoulder muscle fatigue resulted in increased amounts of scapular external rotation is different from that in the Tsai et al. study [66] where they reported decreased amounts of scapular external rotation. Additionally, our overall finding that scapular tilting was not influenced by muscle fatigue does not agree with the reduced amount of posterior tilt reported by Tsai et al. [66]. These differences could largely be due to the fact that the fatigue protocol in the Tsai et al. [66] study was designed to target the shoulder external rotator muscles whereas our fatigue protocol was designed to fatigue several muscles of the shoulder girdle including the shoulder external rotators. It may be that patterns of altered scapular kinematics are dependent upon the group or groups of muscles that are fatigued.

We are unaware of any investigators that have studied the effects of muscle fatigue on humeral external rotation. Knowing how muscle fatigue influences humeral external rotation is important since this motion is believed to clear the greater tuberosity from underneath the acromion thereby preventing excessive compression of the soft tissues located within the subacromial space [1,6,32,65]. Between 60° and 120° of elevation, the average decreased humeral external rotation was between 4° and 7°. This reduced external rotation may prevent adequate clearance of the greater tuberosity and subsequently place the soft tissues in the subacromial space at risk for injury. This range of humeral elevation (60–120°) is associated with a decrease in the width of the subacromial space [14,18,19] and high subacromial pressures [48,53].

The scapulothoracic kinematic changes noted in this study may be viewed as compensatory motions in an attempt to offset the effects of decreased humeral external rotation. Upward rotation and external rotation of the scapula are believed to play an important role in maintaining an optimal relationship between the humeral head and glenoid fossa as well as maintaining the size of the subacromial space [27,34,43]. The increased upward and external rotation of the scapula noted in this study after performance of the fatiguing protocol may act to rotate the acromion up and back away from the greater tuberosity [43]. Furthermore, the increased amount of clavicular retraction could be an attempt to prevent a reduction in the size of the subacromial space [62]. In individuals who use their hands in a repetitive overhead manner these compensatory motions may prevent narrowing of the subacromial space thereby reducing potentially harmful forces in the subacromial space. It should be noted that recent work from our lab suggests that an increase in upward rotation of the scapula may be detrimental in that it leads to a reduction in subacromial space [24]. It is important to understand that this finding was noted in cadavers with the arm positioned at 90° of elevation and maximal internal rotation [24]. There is not enough evidence to strongly support either one of these contentions and further studies are needed to explore the effects of altered scapulothoracic and humeral kinematics on subacromial forces.

Although the results of this study indicate that muscle fatigue influences scapulothoracic motion, the mechanisms for how this occurs are unknown. Fatigue of the shoulder muscles has been shown to result in altered shoulder proprioception [7,29,47,69]. It is possible that muscle fatigue results in changes in muscle spindle sensitivity/activity [47] which then leads to altered feedback to the central nervous system [7,47]. This altered feedback may result in altered muscle coordination [7] with subsequent alterations in shoulder kinematics. The MPF changes for the infraspinatus and deltoid muscles were much larger than the upper and lower trapezius and serratus anterior muscles indicating that these muscles were fatigued to a greater degree [23,61,67]. The greater amount of fatigue in these muscles could have resulted in a compensatory response in the scapulothoracic musculature which resulted in increased amounts of scapulothoracic motion. Another possible explanation for the observed changes in scapulothoracic motion could be the decreased amount of humeral external rotation. Perhaps altered glenohumeral motion in and of itself was the primary mechanism for increased scapulothoracic motion. While this could be the case, we believe that in this study the changes in scapulothoracic motion were a direct result of fatigue in the external rotator muscles. Further research to explore the influence of altered glenohumeral motion on scapulothoracic motion in the absence of muscle fatigue is needed.

There are several limitations of our study that should be acknowledged. First, it is important to note that our findings represent changes that occurred immediately after the shoulder muscles were fatigued. Whether or not these patterns change with repeated bouts of muscle fatigue, or how long these changes persist are not known at this time and are areas for future research. Second, all of the subjects in this study were young and did not have a history of shoulder injury on their tested side. Research studies that investigate the effects of muscle fatigue on scapulothoracic and humeral kinematics in an elderly and injured population are needed. However, these findings are relevant to individuals who experience shoulder muscle fatigue secondary to vocational or recreational activities and may be predisposed to shoulder injuries. Third, the majority of subjects (18/20) in our study did not use their arms in a repetitive overhead manner on a regular basis. Alterations in scapulothoracic and humeral kinematics may differ in individual's who use their arms in a repetitive overhead manner on a regular basis.

5. Conclusions

This study has shown that fatigue of the shoulder girdle muscles results in increased amounts of scapulothoracic motion and decreased amounts of humeral external rotation. These changes were noted throughout the range of motion with the largest differences occurring in the mid ranges of arm elevation. Further studies are needed to determine what effects these kinematic changes have on the soft tissues of the shoulder complex. Additional studies are also needed to determine the effects of muscle fatigue on scapulothoracic and humeral motion in subjects with shoulder pathology.

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