Scapulothoracic and Glenohumeral Kinematics Following an External Rotation Fatigue Protocol

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Study Design: Repeated-measures experimental design.

Objective: To determine the effects of shoulder external rotator muscle fatigue on 3-dimensional scapulothoracic and glenohumeral kinematics.

Background: The external rotator muscles of the shoulder are important for normal shoulder function. Impaired performance of these muscles has been observed in subjects with impingement syndrome and it is possible that external rotator muscle fatigue leads to altered kinematics of the shoulder girdle.

Methods and Measures: Twenty subjects without a history of shoulder pathology 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 external rotation fatigue protocol.

Results: After completing the fatigue protocol subjects demonstrated less external rotation of the humerus. Additionally, they had less posterior tilt of the scapula in the beginning phase of arm elevation, and more scapular upward rotation and clavicular retraction in the mid ranges of arm elevation.

Conclusions: Performance of an external rotation fatigue protocol results in altered scapulothoracic and glenohumeral kinematics. Further studies are needed to investigate the effects of external rotator muscle fatigue on scapulothoracic and glenohumeral kinematics in subjects with shoulder pathology. *J Orthop Sports Phys Ther 2006;36(8):557-571.* doi:10.2519/jospt.2006.2189

Key Words: *muscle endurance, shoulder biomechanics, 3-dimensional scapular motion*

Coordinated motion of the humerus, clavicle, and scapula is essential for normal function of the shoulder girdle and has been studied with 2-dimensional[15,21,57] and 3-dimensional techniques.[27,35,36,38-40] The generally accepted pattern of motion during arm elevation is as follows: humeral elevation and external rotation,[35,65] clavicular elevation and retraction,[34,39] and scapular upward rotation, posterior tilt, and external rotation.[36,39]

This motion is produced and controlled by the neuromuscular and capsulo-ligamentous systems associated with the shoulder girdle. Impairments in either one of these systems could result in altered kinematics of the humerus, clavicle, and/or scapula, which could lead to the development of abnormal stresses and strains on the tissues of the shoulder girdle. Associations between altered scapulothoracic kinematic patterns and shoulder pathology have been identified in impingement syndrome,[35,38,72] rotator cuff tears,[52] and glenohumeral instability.[51,52,72]

The infraspinatus and teres minor muscles contribute to the formation of the rotator cuff and are collectively referred to as the external rotators of the shoulder. The primary action attributed to these muscles in anatomy texts is that of shoulder external rotation. However, these muscles have also been shown to contribute to arm elevation,[33,50,62] stability of the glenohumeral joint,[7,9,30,61,74] and the production of normal glenohumeral kinematics.[8,46,52] The multiple roles of the external rotators illustrate their importance for production of normal shoulder motion. Impairments in the external rotator muscles have been reported in subjects with shoulder impingement syndrome.[3,71]

Shoulder muscle fatigue is a common sequela of repetitive arm use and this has been proposed as a possible link to explain the association between repetitive arm use and the development of shoulder pain.[1,11,28] Previous studies have shown that fatigue of the shoulder girdle musculature results in altered scapulothoracic kinematics.[41,40,66] Recently, we demonstrated that shoulder girdle muscle fatigue following the performance of a repetitive elevation task resulted in altered scapulothoracic and glenohumeral kinematics.[17] While electromyographic (EMG) signs of local muscle fatigue were apparent for several shoulder girdle muscles, we found that the infraspinatus muscle demonstrated the greatest change, which suggested that this muscle was fatigued to a greater extent than any of the other muscles.[17] This may indicate that infraspinatus muscle fatigue played a significant role in the kinematic changes reported in that study. To the best of our knowledge, a study by Tsai et al[66] is the only one that has investigated the effects of infraspinatus muscle fatigue on scapular kinematics. In that study, healthy subjects performed shoulder external rotation against the resistance of a green Thera-Band until they could no longer perform the task. Shoulder external rotation force measurements were taken before and after the task and subjects performed the task until their force measurements decreased by at least 25% from their baseline measurement. They reported decreased amounts of scapular posterior tilt, upward rotation, and external rotation during arm elevation after the external rotator muscles were fatigued.[66]

Given the multiple roles that the external rotator muscles have in shoulder motion and the fact that reductions in external rotator muscle strength and endurance have been identified in subjects with shoulder impingement syndrome, we believe that further studies designed to investigate the effects of external rotator muscle fatigue are warranted. Therefore, the primary purpose of this study was to determine the effects of shoulder external rotator muscle fatigue on scapulothoracic and glenohumeral kinematics. A secondary purpose of this study was to compare the results of this study to those from a previous study[17] that used a shoulder elevation fatigue protocol to fatigue several different shoulder girdle muscles. Our hypothesis was that external rotator muscle fatigue would result in altered scapulothoracic and glenohumeral kinematics, and that the pattern of change would be similar to that noted following the performance of a general fatigue protocol.

METHODS

Subjects

Twenty subjects (10 male and 10 female) without a history of shoulder pathology or pain in at least 1 shoulder voluntarily participated in the study (mean age, 22.5 [range, 18-30 years]; mean height, 166.5 cm [range, 150-182.5 cm]; mean mass, 66.4 kg [range, 47-100 kg]). Subjects were required to be at least 18 years of age and have a minimum of 120° of humeral elevation. The dominant arm (the arm the subject used to write with) was tested in 11 subjects and the nondominant arm was tested in 9 subjects. Two subjects had a history of shoulder injury on their nondominant arm; therefore, their dominant arm was tested. We elected to test both dominant and nondominant arms to increase the generalizability of our findings. Approval for this study was obtained from the Internal Review Board at Drexel University. Each subject read and signed a consent form prior to participation in the study. These subjects were also part of a previously reported study related to muscle fatigue associated with repetitive elevation tasks.[17] Briefly, the elevation tasks consisted of 1 static task and 2 dynamic tasks. During the static task, subjects were asked to maintain their shoulders in 45° of elevation for 2 minutes. The dynamic tasks required the subjects to lift a weight overhead in the sagittal plane and through a diagonal pattern of motion.[17] Subjects' performance of the external rotator fatigue protocol or elevation fatigue protocol was determined randomly, and testing sessions were separated by at least 48 hours to minimize the effects of muscle fatigue and soreness. Upon arrival at the lab for the second testing session, none of the subjects reported any muscle soreness or fatigue.

Procedure

Overview of Experimental Procedure The overall flow of the experiment was as follows. First, EMG surface electrodes were applied to the subjects and baseline measures of median power frequency (MPF) were collected during isometric contractions. Second, kinematic sensors were attached to the subjects and baseline kinematic measures were collected during elevation trials. These baseline measures represented the prefatigue condition. Next, subjects performed the fatigue protocol and upon completion MPF and kinematic measures were collected. These measures represented the postfatigue condition.

Electromyography The Noraxon MyoSystem 1200 (Noraxon USA, Inc, Scottsdale, AZ) was used to collect raw surface EMG data. This unit provides signal amplification (1000×), band pass filtering (10-500 Hz), a common-mode rejection ratio greater than 100 dB, and an input impedance greater that 10 MΩ. Output from the Noraxon was linked to an 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 were placed over the upper and lower trapezius, serratus
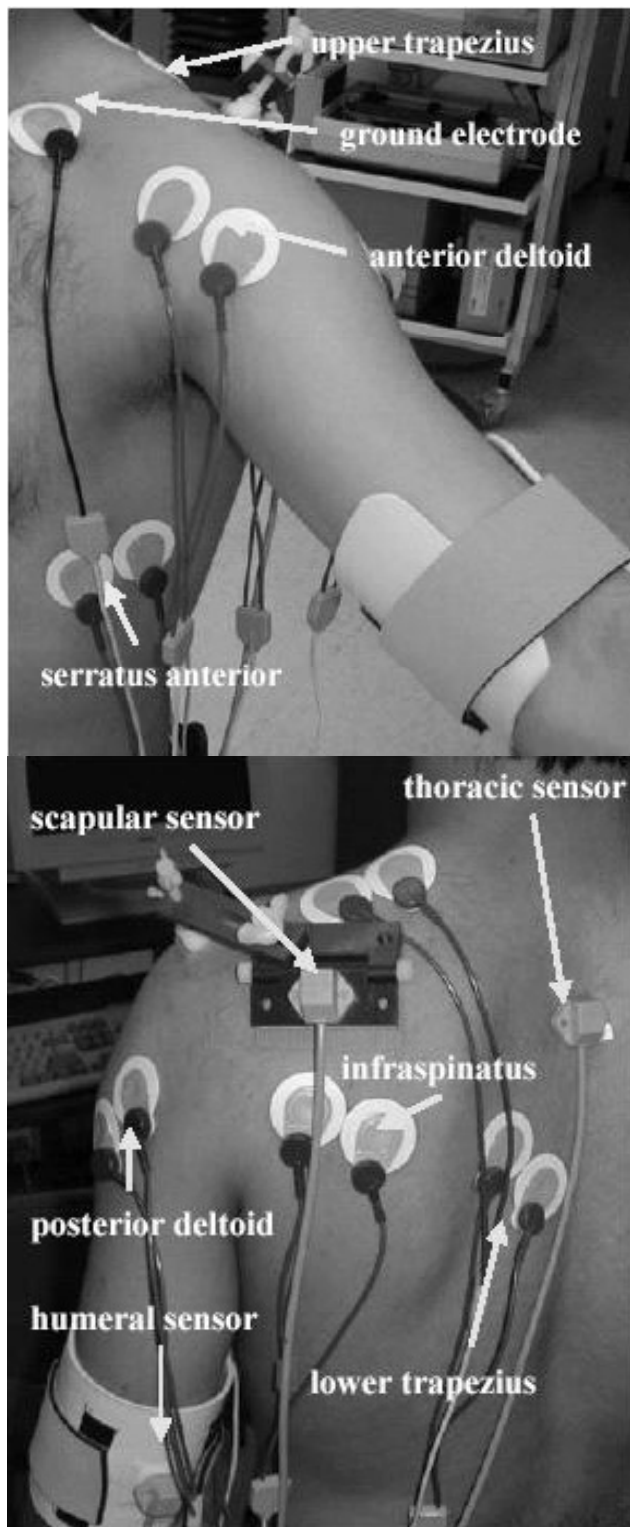
FIGURE 1. Anterior and posterior view of EMG surface electrodes and Polhemus sensor placement.

anterior, anterior deltoid, posterior deltoid, and infraspinatus muscles, on either side of the ideal needle insertion site, as described by Perotto et al (Figure 1).[56] Correct electrode placements were confirmed through observation of all EMG signals on an oscilloscope during resisted contractions of each muscle. The skin was prepared by scrubbing the area with alcohol pads and the electrodes were applied in a direction that was parallel with the muscle fibers. A ground electrode was placed over the ipsilateral clavicle.

Median Power Frequency and Muscle Strength A load cell (MLP-50; Transducer Technique, Temecula, CA) was used to record the force generated during an isometric contraction of the shoulder external rotator 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 the external rotator muscles. 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, an upright 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 in a sidelying position. Subjects were asked to lie on their nontested side, with their tested shoulders in 30° to 40° of abduction and 0° of external rotation. Shoulder abduction was maintained with the use of a towel roll placed between the subjects' waists and elbows, and the lever arm of the positioning unit was adjusted so that the force pad was 2.5 cm proximal to the radial styloid process (Figure 2). Subjects performed a maximum voluntary isometric contraction (MVIC) by pushing against the force pad into the direction of external rotation for 5 seconds. This was repeated 3 times, with a 30-second rest between trials. External rotator muscle strength production was determined by averaging the mean value from a 1-second period (3.5-4.5 seconds) from

FIGURE 2. Setup used for obtaining measures of strength and median power frequency.

each trial. This period was selected to capture the greatest amount of EMG activity during the isometric contractions. In viewing the EMG activity from all of the subjects, this was a period where the EMG activity appeared to be at its highest level.

MPF measures were used as indicators of local muscle fatigue.[12,13,32,43,45] To acquire MPF measures, subjects were placed in the same position that was used to collect strength measures (on their side with their tested shoulders in 30° to 40° of abduction, and 0° of external rotation), and were instructed to push up into the force pad with 60%[53,59] of their previously determined strength measure for 5 seconds. The computer was configured so that subjects had a visual target to help them maintain the 60% (±5%) level. This step was performed prior to and immediately following the fatigue protocol.

Kinematics Three-dimensional kinematic data from the scapula, humerus, and trunk were collected at 40 Hz with the Polhemus 3Space Fastrak (Polhemus, Colchester, VT). The manufacturer has reported an accuracy of 0.8 mm and 0.15° for this device, and we have verified this accuracy under controlled laboratory conditions. This magnetic tracking device consists of a transmitter, 3 receivers, and a digitizing stylus, all of which are hardwired to a systems electronic unit. The transmitter emits electromagnetic fields that are detected by the digitizer and receivers. The system's electronic unit determines the relative orientation and position of the receivers, and this information is sent to a computer where the data are collected. This system has been used in a number of studies that have investigated shoulder girdle motion.[27,35,42,40] The accuracy of using surface-mounted receivers to measure scapular and humeral motion has been validated and maximal root-mean-square errors for scapular plane motion have been reported to be less than 5° for scapular motions and 6° for humeral motions.[27,37]

Three Polhemus receivers were attached to each subject (Figure 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.[37] The scapular receiver was mounted to a scapular tracker device.[27] The base of the scapular tracker was attached to Velcro strips placed above and below the scapular spine, and the footpad of the tracker was attached to the 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 to allow the arbitrary axis system, defined by the Polhemus, to be converted to a meaningful anatomical axis system.[27] The anatomical axis system was determined from 3 points on the thorax, scapula, and humerus.[26,27,39,73] For the purpose of this study, the body segments and their corresponding digitization points were the thorax (T1, T7, sternal notch), scapula (acromioclavicular joint, root of the scapular spine, inferior angle of the scapula), and 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.[23] As this study was conducted prior to the recently published standardization document for shoulder motion,[73] our trunk coordinate system did not follow the International Society of Biomechanics recommendation, and for the scapula system we used the previously recommended acromioclavicular landmark.[68]

Arm Elevation Trials Following the digitization process, kinematic data were collected during trials of maximal scapular plane arm elevation. This step was performed before and after subjects completed the fatigue protocol. For the motion 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 their backs against the chair back. 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. Arm elevation took place in the scapular plane, which was defined as 40° (±10°) anterior to the frontal plane. A plastic pole was positioned along the lateral aspect of the subjects' arms and acted as a guide to maintain the plane of elevation. Subjects were told to raise and lower their hands over their heads with their thumbs pointing up, while maintaining light contact with the plastic pole. Each trial of arm elevation was performed to a count of 8 seconds: 4 seconds to raise the arm and 4 seconds to lower it.

External Rotation Fatigue Protocol To fatigue the shoulder external rotator muscles, subjects performed 2 activities. For both activities subjects were asked to lie on their nontested sides with their shoulders supported by a towel roll in 10° to 20° of abduction in the frontal plane. A sidelying position was chosen, as we felt that this position was best for minimizing unwanted trunk and scapular motion, thereby limiting the motion to the glenohumeral joint, which would isolate (as best as possible) the external rotator muscles. In the first activity, subjects were asked to maintain their shoulders in 0° of external rotation for 2 minutes while they identified small objects with their hands. Second, subjects were asked to perform 20 repetitions of shoulder external rotation against resistance. This motion began with a subject's hand resting across their abdomen. From

there, the hand was raised up until their forearm was parallel to the floor, and then lowered. For the second activity, subjects were instructed to reach a target each time they performed the motion. To determine target placement, subjects raised their forearms until they were parallel to the floor and the target was placed so that it made contact with the back of their forearms. The amount of weight that subjects lifted for the second activity was targeted at 20% of the force that was recorded when they performed their sidelying MVIC. Upon completion of the second activity, subjects immediately returned to the first activity and rotated through the 2 activities until 1 of 2 criteria for determining task fatigue was met: (1) the subjects reported that they were unable to continue to perform the required activities, or (2) the subjects failed to correctly perform both activities. Failure for the first activity was defined as follows: an inability to keep forearms parallel to the floor despite verbal feedback from the investigator. Failure for the second activity was defined as follows: missed the target more than 2 times, and/or altered posture (more than 2 times) by protracting and/or retracting the scapulae or rolling the trunk while raising the forearms. If subjects altered their postures, the investigator provided them with verbal feedback to remind them that they were to maintain their posture.

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 minutes elapsed from when the subjects reached fatigue to when they repeated the trials of arm elevation. Throughout the entire experiment every effort was made to ensure that the EMG and kinematic cables did not pull on either the electrodes or Polhemus sensors.

Data Reduction

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-second intervals that were entered into the algorithm to establish a power density spectrum.[22] The power density spectrum was used to determine the MPF for each 1-second interval over a 5-second period. The MPF from the second, third, and fourth seconds were then averaged. Changes in MPF were determined by subtracting the averaged postfatigue MPF values from the averaged prefatigue values. These new values (MPF change) were expressed as a percentage of the

prefatigue MPF values. A reduction in MPF has been used as an indicator of local muscle fatigue.[12,13,32,43,45]

The kinematic data for scapular orientation and position were described using 3 scapular rotations and 2 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 (x_s axis) (Figure 3). Two clavicular rotations, protraction/retraction, and elevation/depression were used to describe scapular position. The basis and details of this approach have been described previously.[27,39]

A globe-based system was used to describe humeral motion relative to the trunk.[16,54] 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 3 trials were averaged.

Data Analysis

Primary Study Reliability statistics for within- and between-day kinematic measurements included intraclass correlation coefficients ($ICC_{3,1}$) and the standard error of the measurement (SEM). These statistics were performed on the full sample for the prefatigue condition. A 2-factor analysis of variance (ANOVA) with 2 repeated factors, condition (prefatigue and postfatigue) and arm elevation (minimum, 60°, 90°, and 120°), was performed on each dependent variable. The dependent variables of interest were scapular external/internal rotation, scapular upward/downward rotation, scapular posterior/anterior tilting, clavicular protraction/retraction, clavicular elevation/depression, and humeral external rotation relative to the trunk. For the 2-factor analyses, a significance level of .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.

Secondary Study To compare changes after the performance of the external rotation fatigue protocol with data from our previous study on shoulder elevation fatigue,[17] a 2-factor analysis of variance
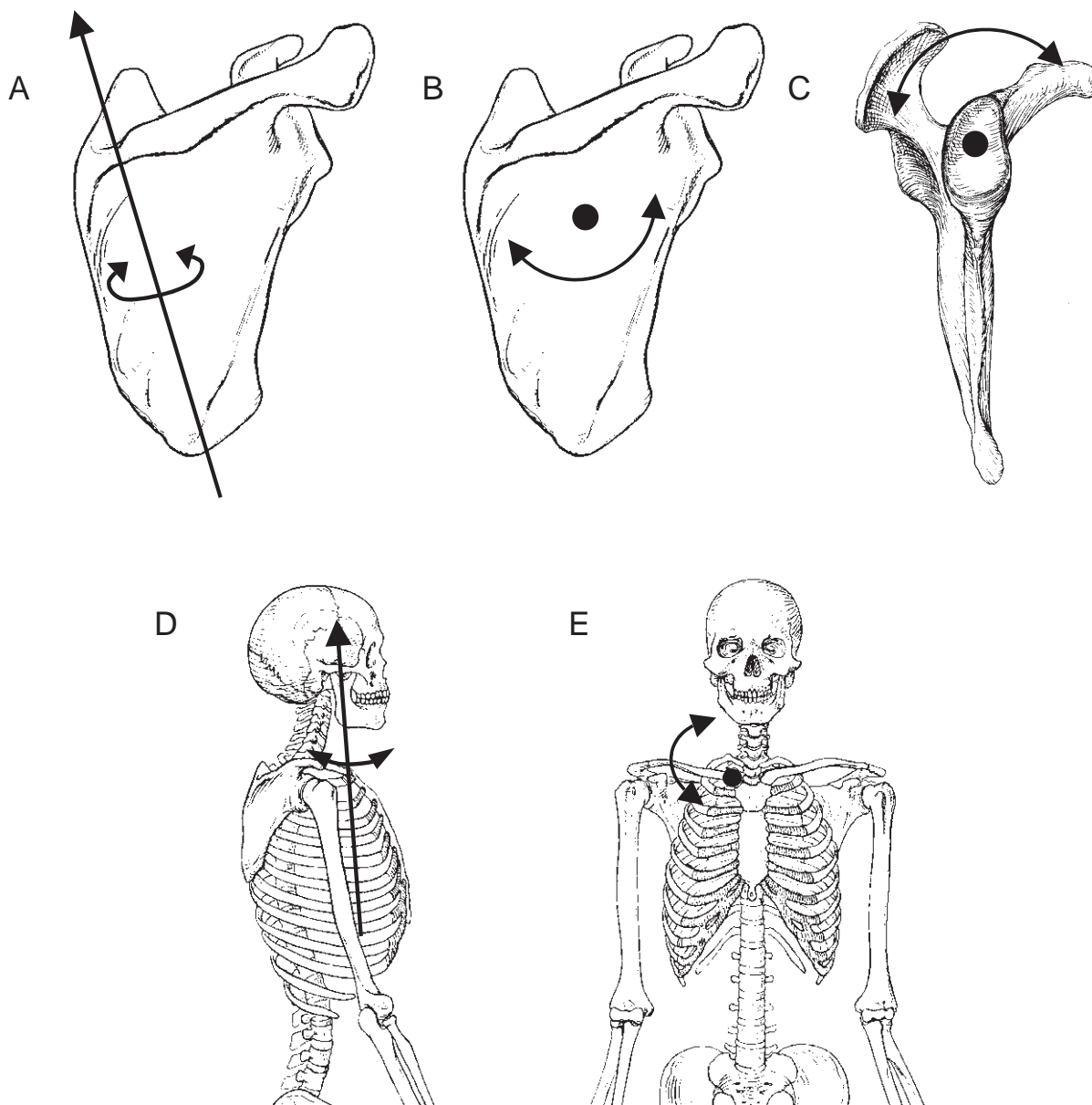
FIGURE 3. Axes and rotations for scapular and clavicular rotations. (A) Scapular external/internal rotation. (B) Scapular upward/downward rotation. (C) Scapular posterior/anterior tilt. (D) Clavicular protraction/retraction. (E) Clavicular elevation/depression.

(ANOVA) with 2 repeated factors—fatigue protocol (shoulder elevation and external rotation) and arm elevation (minimum, 60°, 90°, and 120°)—was performed on each dependent variable. We did not compare the kinematic changes between the 2 protocols at the maximal elevation position because this position was different between the shoulder elevation and external rotation fatigue protocols. The dependent variables for this part of the study were the change scores (postfatigue – prefatigue) for scapular posterior/anterior tilting, scapular upward/downward rotation, scapular external/internal rotation, clavicular protraction/retraction, clavicular elevation/depression, and humeral external rotation. For the 2-factor analyses, a significance level of .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 .01.

RESULTS

Primary Study

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° (Table 1). Between-day ICC values for scapular, clavicular, and

TABLE 1. Trial-to-trial and between-day intraclass correlation coefficient values (and SEM) for scapular, clavicular, and humeral rotations across arm elevation angles.

| | Scapular Rotations | | | Clavicular Rotations | | Humeral Rotation |
	Posterior Tilt	Upward Rotation	External Rotation	Protraction	Elevation	External Rotation
30° TT	0.97 (1.3°)	0.92 (2.6°)	0.95 (1.8°)	0.95 (1.2°)	0.98 (1.1°)	0.92 (4.2°)
BD	0.45 (4.9°)	0.63 (5.2°)	0.59 (4.1°)	0.60 (2.8°)	0.75 (3.0°)	0.76 (7.2°)
60° TT	0.98 (1.0°)	0.92 (1.9°)	0.96 (1.4°)	0.96 (1.0°)	0.99 (0.7°)	0.78 (4.0°)
BD	0.16 (5.4°)	0.63 (5.1°)	0.70 (4.0°)	0.69 (2.6°)	0.79 (2.7°)	0.59 (5.1°)
90° TT	0.98 (1.0°)	0.96 (1.9°)	0.97 (1.5°)	0.96 (1.0°)	0.97 (0.7°)	0.81 (3.3°)
BD	0.04 (6.2°)	0.63 (4.7°)	0.70 (4.5°)	0.70 (2.5°)	0.80 (2.4°)	0.52 (5.4°)
120° TT	0.96 (1.7°)	0.94 (2.1°)	0.96 (2.2°)	0.92 (1.4°)	0.98 (0.8°)	0.86 (3.2°)
BD	0.19 (7.5°)	0.63 (4.1°)	0.62 (6.4°)	0.70 (2.5°)	0.87 (1.9°)	0.51 (6.4°)

Abbreviations: BD, between day; TT, trial to trial.

humeral rotations ranged from 0.04 to 0.87, indicating poor to good reliability,[58] and the standard error of the measurement ranged from 2.2° to 11.3° (Table 1). Prior to beginning the external rotator fatigue protocol, the averaged RPE score was 6.4 (no exertion at all). The average length of time that subjects performed the fatigue protocol was 14 minutes and 45 seconds, after which the average RPE score increased to 19.6 (extremely hard to maximal exertion). Percent change in MPF for this study and our previously reported study[17] are provided in Table 2.

The ANOVA results for the primary and secondary studies are based upon the Greenhouse-Geisser correction factor due to a violation of the sphericity assumption associated with repeated-measures testing. This was done to prevent biasing of our tests in the direction of a type I error.

TABLE 2. Averaged (SD) (range) for percent change in median power frequency (MPF) for each muscle. Negative values represent an increase in MPF after fatigue.

Muscle	External Rotation Fatigue (% Change)	Shoulder Elevation Fatigue (% Change)
Upper trapezius	2.5 (16.3) (–21.3 to 56.6)	9.3 (6.2) (–1.2 to 21.4)
Lower trapezius	–5.1 (6.6) (–15.3 to 7.4)	0.7 (9.8) (–16.6 to 24.1)
Serratus anterior	–6.4 (44.9) (–156.3 to 56.1)	12.9 (21.9) (–28.7 to 68.5)
Anterior deltoid	2.6 (13.3) (–31.4 to 24.4)	12.2 (7.4) (–3.8 to 25.0)
Posterior deltoid	3.4 (7.1) (–18.2 to 13.1)	13.6 (11.0) (–17.8 to 39.1)
Infraspinatus	8.6 (10.2) (–9.7 to 31.1)	21.5 (10.5) (8.5 to 45.3)

Findings from the primary study are presented in Tables 3 and 4, and Figure 4. For scapular upward rotation, scapular external rotation, and clavicular retraction, there were differences between the prefatigue and postfatigue conditions that were not consistent across angles of arm elevation. Subsequently, the differences between prefatigue and postfatigue conditions were investigated at all angles of arm elevation. Following completion of the fatigue protocol, subjects demonstrated 2.8° and 3.3° more scapular upward rotation at 60° (df = 19, t = –3.29, $P<.01$) and 90° (df = 19, t = –4.14, $P<.01$) of arm elevation, respectively, compared with the prefatigue condition. For the postfatigue condition, subjects demonstrated 1.6° (df = 19, t = 3.67, $P<.01$) and 1.4° (df = 19, t = 3.40, $P<.01$) more clavicular retraction at 90° and 120° of arm elevation, respectively, compared with the prefatigue condition. Although findings from the ANOVA test for scapular external rotation were statistically significant, statistical significance was not reached on the follow-up paired t tests with an adjusted alpha level of .01.

For scapular posterior tilt, differences between prefatigue and postfatigue conditions were not consistent across arm elevation angles. Subsequently, the differences between prefatigue and postfatigue conditions were investigated at all angles of arm elevation. Follow-up paired t tests revealed 2.5° (df = 19, t = 4.23, $P<.01$) and 1.6° (df = 19, t = 2.84, P = .01) less posterior tilt of the scapula at the beginning and 60° of arm elevation, respectively, after completion of the fatigue protocol. Although the amount of clavicular elevation changed across arm elevation angles, there were no differences between the prefatigue and postfatigue conditions. Finally, there were differences in humeral external rotation between the prefatigue and postfatigue conditions, as well as between different positions of arm elevation. Collapsed across all levels of arm elevation, subjects demonstrated 4.7° less humeral external rotation following the fatigue protocol.

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TABLE 3. Means (SD) for scapular, clavicular, and humeral rotations across arm elevation angles for prefatigue and postfatigue conditions. For scapular rotations, negative values indicate less posterior tilt, and external rotation. Negative clavicular retraction values indicate more clavicular retraction.

| | Scapular Rotations (°) | | | Clavicular Rotations (°) | | Humeral Rotation (°) |
	Posterior Tilt	Upward Rotation	External Rotation	Retraction	Elevation	External Rotation
Min prefatigue	0.0 (7.4)	24.7 (7.9)	–46.6 (6.3)	–20.3 (3.9)	5.5 (5.7)	28.5 (24.1)
Postfatigue	–2.5 (6.9)	25.4 (7.3)	–46.3 (5.6)	–20.6 (3.6)	4.8 (5.1)	24.9 (22.0)
60° prefatigue	1.0 (6.7)	37.8 (8.2)	–46.4 (7.1)	–23.5 (3.9)	10.8 (5.6)	42.4 (8.2)
Postfatigue	–0.6 (6.5)	40.5 (8.0)	–45.1 (6.8)	–24.4 (4.0)	11.0 (5.3)	37.0 (9.3)
90° prefatigue	–0.1 (7.2)	51.2 (7.7)	–45.5 (7.6)	–28.0 (3.8)	15.9 (5.3)	41.2 (7.5)
Postfatigue	–0.5 (7.3)	54.5 (8.8)	–43.1 (7.9)	–29.6 (4.5)	16.1 (5.5)	35.7 (9.6)
120° prefatigue	–1.2 (9.0)	64.7 (7.0)	–43.2 (9.0)	–34.5 (4.2)	20.5 (5.0)	40.1 (9.6)
Postfatigue	–0.9 (9.5)	66.6 (8.2)	–40 (10.3)	–35.9 (5.1)	20.0 (5.3)	35.9 (10.3)

TABLE 4. Summary of 2-factor ANOVAs for scapulothoracic and humeral kinematic changes with repeated measures on condition and arm elevation.

Dependent Variable	Source	*df*	F Ratio	Probability Level
Scapular UR	Pre-post (PP)	1.0, 19.0	9.32	0.007
	Humeral elevation (HE)	1.8, 34.1	454.12	0.001
	PP × HE	1.5, 29.1	5.30	0.017
Clavicular retraction	Pre-post (PP)	1.0, 19.0	8.62	0.008
	Humeral elevation (HE)	1.5, 29.1	255.28	0.001
	PP × HE	1.7, 31.9	6.07	0.008
Scapular ER	Pre-post (PP)	1.0, 19.0	5.11	0.036
	Humeral elevation (HE)	1.4, 26.3	9.42	0.002
	PP × HE	1.5, 28.6	7.68	0.004
Scapular posterior tilt	Pre-post (PP)	1.0, 19.0	3.09	0.095
	Humeral elevation (HE)	1.4, 25.8	1.25	0.289
	PP × HE	1.3, 24.4	11.29	0.001
Clavicular elevation	Pre-post (PP)	1.0, 19.0	0.10	0.757
	Humeral elevation (HE)	1.6, 30.3	333.74	0.001
	PP × HE	1.5, 28.8	3.59	0.052
Humeral ER	Pre-post (PP)	1.0, 19.0	13.62	0.002
	Humeral elevation (HE)	1.1, 21.0	9.50	0.005
	PP × HE	1.2, 22.4	0.413	0.056

Abbreviations: ER, external rotation; UR, upward rotation.

Secondary Study

Differences were noted when the change scores from the shoulder elevation fatigue protocol were compared to the change scores from the external rotation fatigue protocol (Figure 5). For scapular upward rotation, scapular external rotation, and clavicular retraction, there were differences between the prefatigue and postfatigue conditions that were not consistent across angles of arm elevation. Therefore, the differences between protocols were investigated at all angles of arm elevation. Follow-up paired t tests revealed a larger change score for scapular upward rotation at 90° (df = 19, t = –3.1, $P<.01$) and 120° (df = 19, t = –3.68, $P<.01$) of arm elevation for the shoulder elevation fatigue protocol. The change score for scapular external rotation was larger for the shoulder elevation fatigue protocol at 90° (df = 19, t = –2.93, $P<.01$) and 120° (df = 19, t = –3.05, $P<.01$) of arm elevation compared to the external rotation fatigue protocol. For clavicular retraction, the change score for the shoulder elevation fatigue protocol was larger than that of the external rotation fatigue protocol at 90° (df = 19, t = 4.381, $P<.01$) and 120° (df = 19, t = 5.28, $P<.01$) of arm elevation. Although the change score for scapular posterior tilt and clavicular elevation varied across angles of arm elevation, there were no differences between the fatigue
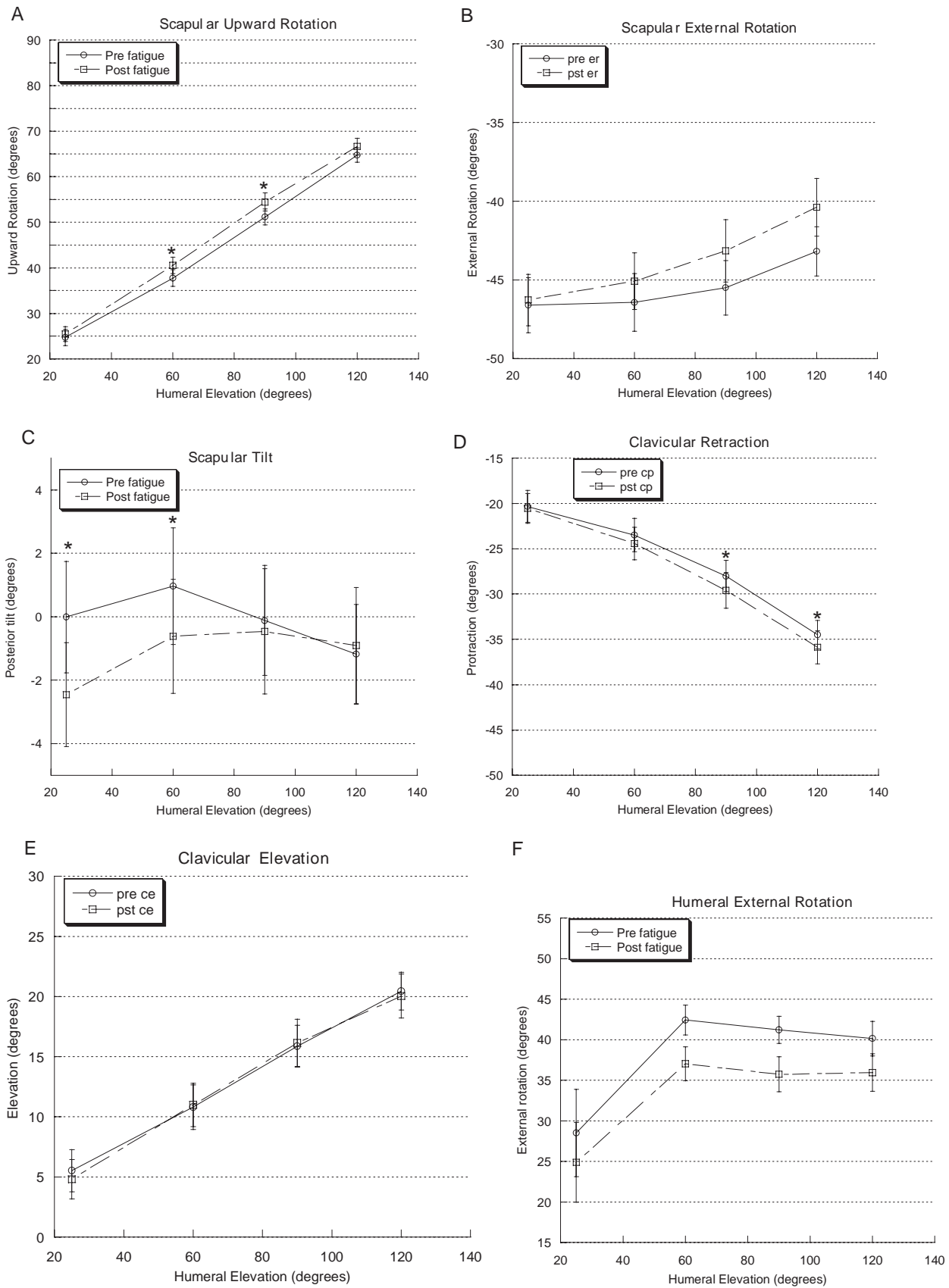
FIGURE 4. Averaged scapular and humeral kinematics and standard error of the mean. (A) Scapular upward rotation (positive values = upward rotation). (B) Scapular external rotation (positive values = external rotation). (C) Scapular tilt (positive values = posterior tilt). (D) Clavicular retraction (negative values = retraction). (E) Clavicular elevation (positive values = elevation). (F) Humeral external rotation (positive values = external rotation). Asterisk (*) indicates significant difference between prefatigue and postfatigue conditions (paired *t* tests).
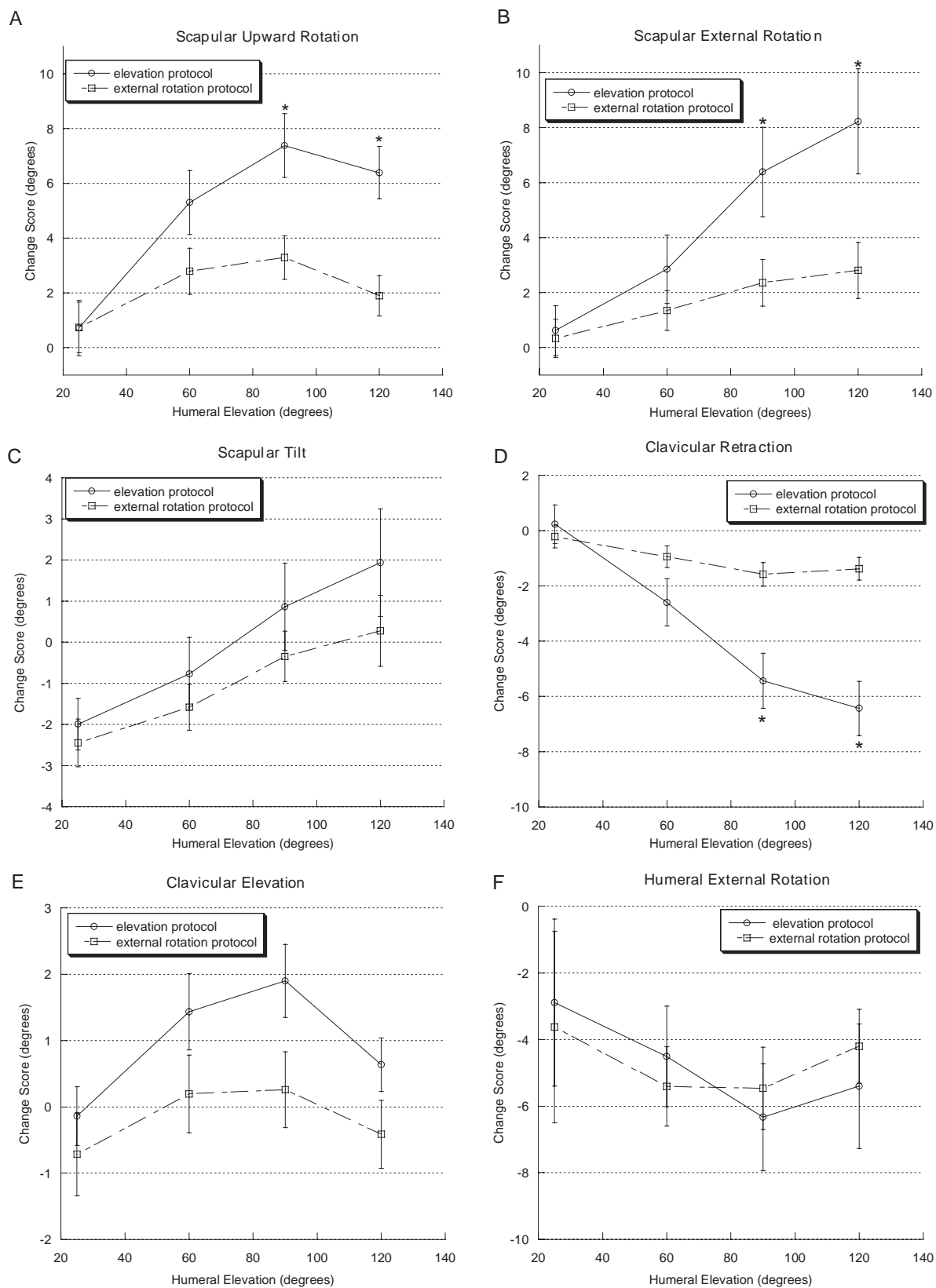
FIGURE 5. Averaged change scores and standard error of the mean for shoulder elevation fatigue and shoulder external rotation fatigue protocols. (A) Scapular upward rotation (fatigue protocol × arm elevation interaction: *df* = 2.2, 41.4; F = 8.7; *P*<.001). (B) Scapular external rotation (fatigue protocol × arm elevation interaction: *df* = 1.5, 27.9; F = 11.7; *P*<.001). (C) Scapular tilt (arm elevation effect). (D) Clavicular retraction (fatigue protocol × arm elevation interaction: *df* = 1.6, 31.1; F = 27.3; *P*<.001). (E) Clavicular elevation (arm elevation effect). (F) Humeral external rotation. Asterisk (*) indicates significant difference between fatigue protocols (paired *t* tests).

protocols. Finally, there were no differences in humeral external rotation between fatigue protocols or across arm elevation angles.

DISCUSSION

The findings from this study demonstrate that performance of an external rotation fatigue protocol results in altered scapulothoracic and glenohumeral kinematics. Although the results of a number of tests performed in this study achieved statistical significance, many of the reported differences were small ($<3°$) and the clinical importance of these findings is unknown. Whether or not an individual who demonstrates these small changes over a period of time would develop shoulder pain is unknown at this time.

Posterior tilting of the scapula decreased from the beginning of the motion up to approximately $60°$ of arm elevation after subjects completed the fatigue protocol. This finding is consistent with that of a similar study by Tsai et al.[66] Decreased amounts of scapular posterior tilt have been identified in subjects with shoulder impingement syndrome and it has been suggested that this may reduce the size of the subacromial space, thereby subjecting the rotator cuff tendons to greater compressive forces.[35] In the prefatigued condition our subjects demonstrated a pattern of posterior tilt from the beginning of the motion to $60°$ of humeral elevation, and then anterior tilting from $60°$ to $120°$. This pattern of motion is in contrast to the majority of the past literature in healthy subjects. It is interesting to note that of the 20 subjects tested, 9 demonstrated a pattern of anterior tilt, 8 demonstrated a pattern of posterior tilt, and in 3 subjects there was no clearly identifiable pattern. Of the 9 subjects who demonstrated an anterior tilt 6 were female, while only 1 female subject demonstrated a pattern of posterior tilt. This suggests that tilting patterns may be influenced by gender.

The reported changes in scapular upward rotation and scapular external rotation in this study differ from those reported by Tsai et al.[66] We noted increased scapular upward rotation at $60°$ and $90°$ of arm elevation after the external rotator muscles had been fatigued, while Tsai et al[66] noted decreased scapular upward rotation from the beginning of arm elevation up to $60°$ of elevation. Although statistical significance was not achieved for our findings related to scapular external rotation, the scapula tended to demonstrate more external rotation in the postfatigue condition. In contrast, Tsai et al[66] reported more scapular internal rotation following fatigue of the external rotator muscles. These differences may, in part, be explained by the methods used to fatigue the external rotator muscles and/or the criteria used to determine when the subjects stopped performing the fatigue protocol. It may be that the

subjects in this study experienced different levels of fatigue than subjects in the study by Tsai et al.[66] A direct comparison of the level of fatigue between studies is not possible, as Tsai et al[66] did not measure the length of time subjects performed the fatigue protocol nor did they measure subjects' ratings of fatigue or EMG values of local muscle fatigue.

We noted more clavicular retraction and less humeral external rotation following completion of the fatigue protocol. It should be noted that differences in humeral external rotation were on the order of our reported trial-to-trial measurement error. Increased clavicular retraction may be a compensatory motion to help prevent narrowing of the subacromial space that occurs with shoulder protraction.[63] External rotation of the humerus is believed to be important for clearing the greater tuberosity from underneath the acromion and preventing excessive compression of the soft tissues located in the suprahumeral space.[2,6,35,65] The overall decreased amount of humeral external rotation noted in this study may expose the soft tissues in the suprahumeral space to greater compressive forces, thereby increasing their risk for injury. Decreased humeral external rotation has been proposed as one mechanism that contributes to the development of shoulder impingement syndrome.[44,48,55]

Taken collectively, it is possible that the increases noted in scapular upward rotation and clavicular retraction were compensatory motions in response to decreased amounts of scapular posterior tilt and humeral external rotation. Increased scapular upward rotation and clavicular retraction may prevent narrowing of the subacromial space and subsequent increase in compressive forces within 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.[25] It is important to understand that this finding was noted in cadavers with the arm positioned at $90°$ of elevation and maximal internal rotation.[25] At this time there is inadequate evidence to strongly support either one of these contentions and additional studies are needed to explore the effects of altered scapulothoracic and humeral kinematics on the size of the subacromial space and forces.

The mechanisms by which fatigue resulted in altered scapulothoracic and glenohumeral kinematics are unknown. Fatigue of the shoulder muscles has been shown to result in altered shoulder proprioception.[10,29,47,69] It is possible that muscle fatigue results in changes in muscle spindle sensitivity/activity, which then leads to altered feedback to the central nervous system.[10,47] This altered feedback may result in altered muscle coordination with subsequent alterations in shoulder kinematics.[41] As indicated in Table 2, the infraspinatus muscle demonstrated the largest

averaged reduction in MPF, which suggests that this muscle was fatigued to a greater degree than the other muscles investigated in this study. Given the important role that the infraspinatus muscle plays in glenohumeral stability, it may be that the altered scapulothoracic kinematics are due to compensatory activity of the scapulothoracic muscles in an attempt to help maintain glenohumeral stability. Finally, the decreased amounts of humeral external rotation may be explained by a reduction in the force output of the shoulder external rotator muscles. Although premaximal and postmaximal force measurements were not a part of this study, the infraspinatus muscle did demonstrate EMG signs of fatigue (reduced MPF values) and decreased force output is a common sequel to muscle fatigue.[4,64,70]

As mentioned previously, the participants in this study were part of a larger study designed to assess the effects of muscle fatigue on shoulder girdle kinematics. All subjects performed the 2 fatigue protocols (shoulder elevation and shoulder external rotation) on 2 separate days. The fatigue protocol described in this study was designed to target the shoulder external rotator muscles (external rotation fatigue protocol), while the shoulder elevation fatigue protocol described in a previous study[17] was designed to target multiple muscles of the shoulder girdle, including the trapezius, serratus anterior, deltoid, and infraspinatus muscles. The subjects' performance of the shoulder elevation or external rotation fatigue protocol on their first visit was randomly determined and the subjects were retested with a minimum of 2 days between test sessions. None of the subjects reported any shoulder muscle soreness or fatigue upon their arrival to the lab for the second test session.

Given that all subjects performed both fatigue protocols it is reasonable to compare the changes in scapulothoracic and glenohumeral kinematics between the 2 fatigue protocols. We found that patterns of kinematic change were similar for both fatigue protocols. However, the magnitude of change was less for the external rotation fatigue protocol. Although differences in change scores were noted for a number of variables, the majority of these were small ($<5°$) and on the order or our reported between day measurement error. Therefore, the meaningfulness of these differences is questionable.

For both fatigue protocols approximately 2 minutes elapsed between the time the subjects completed the fatigue protocol and the postfatigue arm elevation task. Partial recovery from the fatigue task may have occurred during this time frame, which may have impacted the kinematic results. It is possible that recovery occurred to a greater extent in the shoulder external rotation fatigue protocol because the mean change in MPF values was less than that noted in the shoulder elevation fatigue protocol. This may, in part,

explain the differences in the magnitude of the kinematic changes between the 2 fatigue protocols.

Changes in MPF values following the external rotation fatigue protocol varied widely amongst the subjects, which may indicate that subjects used different muscle recruitment strategies to perform the fatigue tasks. Decreased MPF values have been suggested to be an indicator of local muscle fatigue and this has been attributed to several factors, including synchronization of motor units, changing motor unit recruitment patterns, and a slowing in the conduction velocity of the action potential across the sarcolemma.[31,32,43,45] Despite the fact that 9 of the subjects did not demonstrate EMG signs of infraspinatus muscle fatigue, other signs of fatigue were noted. First, all of the subjects showed evidence of fatigue by the inability to continue performing the external rotation tasks. Secondly, at the completion of the external rotation fatigue protocol, all subjects' ratings of perceived exertion were at the "extremely hard" maximal exertion levels. This inconsistency in the findings between fatigue measures reinforces the notion that fatigue is a complex phenomenon and may be best assessed by a variety of measures.[18,19]

We believe that the differences in the magnitude of change scores may have been secondary to the degree to which the shoulder muscles were fatigued. Oberg et al[49] have suggested that a reduction in trapezius muscle MPF that exceeds 8% of the initial value can be used as an indicator of muscle fatigue. While application of this value to muscles other than the upper trapezius muscle should be made with caution, we used this value to help us gauge the different levels of muscle fatigue between the 2 fatigue protocols. In the shoulder elevation fatigue protocol, EMG signs of local muscle fatigue were present in all of the muscles except the lower trapezius, while only the infraspinatus muscle demonstrated EMG signs of fatigue following the external rotation fatigue protocol. Furthermore, EMG signs of infraspinatus muscle fatigue were much larger in the shoulder elevation fatigue protocol compared to the external rotation fatigue protocol, which may indicate a greater degree of infraspinatus muscle fatigue.[24,60,67] This is not surprising, given the fact that the elevation tasks performed in the shoulder elevation fatigue protocol required the external rotator muscles to contribute to shoulder elevation and external rotation, thereby placing greater demands on them.[33,50,62]

The similar pattern of kinematic change noted in these 2 fatigue studies suggests that infraspinatus muscle fatigue may play a significant role in altering shoulder kinematics and there may be a common pattern of scapulothoracic and glenohumeral kinematic change secondary to shoulder muscle fatigue, regardless of how muscle fatigue is induced. It is interesting to note that the findings related to

scapular upward rotation in the external rotation fatigue study are similar to those in studies that have investigated scapulothoracic motion in subjects with rotator cuff tears.[14,20,52,75] This suggests that there may be an inherent compensatory mechanism whereby scapulothoracic motion is altered in response to impairments of the rotator cuff muscles. If altered scapulothoracic motion leads to harmful effects on the soft tissues of the shoulder girdle, then therapeutic exercises designed to enhance the strength and endurance of the rotator cuff muscles would be an important part of a rehabilitation program for individuals with impairments in the rotator cuff muscles. Furthermore, if overhead motions are included in a therapeutic exercise program, it may be important to have the subject perform these exercises when they are not fatigued to avoid the potential for altered shoulder kinematics during the performance of the exercise.

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 external rotator muscles were fatigued. 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. Third, MPF measures were not collected from the supraspinatus and subscapularis muscles. It is possible that these muscles may have become fatigued during the performance of the fatigue protocol. Additional studies designed to investigate the effect of supraspinatus and or subscapularis muscle fatigue on shoulder girdle kinematics are warranted. Furthermore, the use of MPF as a measure of fatigue is limited to studying 1 aspect of local muscle fatigue, caused in part by metabolite accumulation at the sarcolemma, with a subsequent decrease in action potential conduction velocity. Mechanisms other than metabolite accumulation are believed to play an important role in muscle fatigue and include subject motivation and task dependency.[18] Fourth, the use of surface electrodes to record EMG activity from the infraspinatus muscle is controversial and some of the EMG signal from this muscle may have been contaminated by lower trapezius or posterior deltoid muscle activity. Finally, the tasks used to fatigue the shoulder external rotator muscles did not resemble functional tasks typically performed by the subjects in this study. The results may be different for a group of subjects whose work activities require them to perform repetitive external rotation motions.

CONCLUSION

The findings from this study demonstrate that performance of an external rotation fatigue protocol results in altered scapulothoracic and glenohumeral kinematics. Although the differences were small, they could potentially be significant relative to muscle mechanics, size of the subacromial space, and glenohumeral kinematics. Further studies designed to address these issues are warranted. Additional studies are also needed to investigate the effect of shoulder external rotator muscle fatigue on scapulothoracic and glenohumeral kinematics in subjects with shoulder pathology. Finally, patterns of scapulothoracic and glenohumeral kinematic changes were similar between a shoulder elevation and external rotation fatigue protocol, which suggests an inherent mechanism whereby motion of the shoulder girdle is altered regardless of which shoulder muscles are fatigued.

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