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Alterations in Upper Extremity Motion After Scapular-Muscle Fatigue

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Objective: To determine the effect of scapular fatigue on shoulder and elbow kinematics and accuracy. ***Design:*** Pretest–posttest. ***Setting:*** Laboratory. ***Participants:*** 30 healthy men. ***Interventions:*** Subjects performed seated overhead throws into a target before and after a standardized scapular-muscle-fatigue protocol. ***Main Outcome Measurements:*** Shoulder and elbow kinematic data were analyzed during throwing. Scapular upward rotation was measured (0°, 45°, and 90° humeral elevation in scaption) with an inclinometer. Throwing accuracy was measured as mean error distance from the target (cm). ***Results:*** After fatigue, there was a significant increase in total elbow motion (12 % more in cocking phase, $P < .05$) and elbow velocity in the follow-through phase (average and maximum into flexion, $P < .05$). Throwing accuracy decreased 26% after fatigue ($P < .05$). ***Conclusions:*** Scapular-muscle fatigue results in compensatory motions at the elbow that might affect performance and contribute to elbow pathologies. ***Key Words:*** dynamic stability, neuromuscular control, kinetic chain, throwing mechanics

Understanding the relationship, as well as the individual contributions, of glenohumeral and scapulothoracic movements is important for achieving optimal shoulder function. Shoulder-complex fatigue has been linked to alterations in gross movement patterns (ie, throwing mechanics) that disrupt the synchrony between the glenohumeral and scapulothoracic articulations.[1-4] Changes in scapular position[5-7] and movements[8-11] or strength imbalance[3,5,11-17] have been identified in patients with overuse injuries in the shoulder. For this reason, examining specific outcomes that result from scapular fatigue and its effect on the kinetic chain is important.

The kinetic chain defines the body as a linked system that delivers force from proximal to distal segments.[12,13,18] Hirashima et al[18] confirmed a proximal-to-distal sequence of muscle firing as the scapular protractors (ie, serratus anterior) were activated first followed by the shoulder horizontal flexors (ie, anterior deltoid and pectoralis major) and elbow extensors (ie, triceps brachii). This demonstrates the

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importance of the scapula serving as a stable base for subsequent distal extremity movements and how adaptations resulting from muscle fatigue might directly affect motions at the elbow.[18-20] Because the scapula has been identified as the site where the exchange of energy from the trunk to the upper extremity ensues, the importance of scapular position and function becomes critical.

During overhead tasks the scapula is required to work as a pivot to transfer energy from the legs and trunk to the arm, allowing for efficient and precise movements.[4,12,13,20] Some suggest that the repetitive demands placed on the shoulder complex cause alterations to scapular function, particularly during arm elevation, when the scapula upwardly rotates.[11-13,21-23] Warner et al[11] found that changes to scapular positioning or motion were evident in 68% to 100% of patients with shoulder impairments. These scapular adaptations might result in compensatory motions at distal segments that diminish dynamic restraint, particularly in controlling humeral-head deceleration, and might subsequently lead to shoulder and elbow pathologies.[3,4,8-13,23-28] For this reason, the effects of scapular fatigue warrant further research. The purpose of this study was threefold. First, our goal was to determine the role of scapular-muscle fatigue (ie, upper, middle, and lower trapezius; rhomboid major and minor; levator scapulae; serratus anterior; and pectoralis minor) on shoulder and elbow kinematics. Second, we wanted to determine whether scapular fatigue affects scapular upward rotation and, last, its effect on throwing accuracy.

Methods

Subjects

Thirty male subjects (age 21.4 ± 2.7 years, height 178.4 ± 7.4 cm, mass 86.3 ± 13.3 kg) volunteered for the study. All subjects were right-arm dominant, which was determined by the hand used to throw a ball.[3] Subjects were healthy individuals and were excluded if they had had head, neck, upper back, shoulder, elbow, or wrist injuries in the preceding 6 months or a history of upper extremity surgery or neuropathology. In addition, individuals currently involved in upper extremity sports (ie, volleyball and baseball) were excluded from study participation. Before testing, subjects completed and signed informed consent and a physical activity and health-history questionnaire approved by the university's institutional review board.

Instrumentation

Kinematic data were collected using the Peak Motus® motion-analysis system (Peak Performance Technologies, Inc, Englewood, Col) while subjects performed overhead throws. All trials were recorded using 2 color cameras (JVC Model # TK-C138OU) and VHS tapes. The video cameras that collected data at 60 Hz with shutter speed set to 1/500 s were positioned approximately 70º from one another with respect to the field of view.[29] A 24-point calibration unit (Peak Performance Technologies) was videotaped simultaneously by the cameras and used to calibrate the test area. The marker set used has been previously reported and was selected to minimize encumbrance yet enable tracking during the throwing task.[30] Reflective markers were automatically digitized in each frame to approximate joint centers using the direct linear-transformation method to obtain 3-dimensional coordinate data. Kinematic data were autodigitized, filtered (fourth-order, zero-lag Butterworth filter with 6-Hz cutoff), and analyzed with Peak motion-analysis software.

For analyses, the throwing motion was divided into cocking, acceleration, and follow-through phases during visual frame-by-frame analysis of the motion.[31] The cocking phase was defined as the period between windup and maximum shoulder external rotation. The acceleration phase was the time between maximum shoulder external rotation and ball release. Follow-through started at ball release and ended in the termination of the throwing motion. The termination of the throwing motion in this study was when the subject's arm began to move from follow-through (adduction/flexion) into abduction/extension. Kinematic data analyzed within each throwing phase at the shoulder and elbow included displacement and velocity-dependent variables. Shoulder rotation angle was defined as the combined actions between glenohumeral, scapulothoracic, and trunk articulations. It was calculated as the angle formed between the forearm and the horizontal plane with the shoulder abducted 90° and elbow flexed 90°.[30-32] Shoulder abduction was defined as the intersection between the arm and trunk segments. The elbow (humeroulnar) joint was defined as the angle between the forearm and arm segments. Angular velocities were calculated as the first derivative of the time-dependent angular displacements.[30,31] At the shoulder, abduction joint angles (maximum, minimum, and total range of shoulder-abduction motion) and velocity during abduction (minimum, maximum, and average) were measured. In the cocking phase, the maximum shoulder external-rotation angle was used for analysis. Elbow motion measured in the sagittal plane (flexion/extension) included joint angles (maximum extension angle, maximum flexion angle, and total range of motion) and velocity (maximum velocity into extension, maximum velocity into flexion, and average velocity). Intratester measurement reliability of this instrument has been reported to have an intraclass correlation coefficient ($ICC_{2,1}$) of .98.[33]

An ATEC Pitchers' Practice Screen (Athletic Training Equipment Co Inc, Sparks, Nev) was used as the target to measure throwing accuracy (Figure 1). The screen has a 48- × 38-cm strike-zone target trimmed in high-visibility orange located on a 153- (height) × 132-cm (width) backdrop made of a black heavy-duty nylon tarpaulin material. A 4-cm orange circle was placed in the middle of the target to represent the center. The shape and color of the target center have been shown to produce high reliability for throwing accuracy.[34] The target was placed ~6 m away from the subject and ~91.5 cm above the ground. After each throw, a black mark was placed where the ball had hit the target. This location was identified visually and confirmed by the indentation from the ball's impact. After testing, means and standard deviations for prefatigue and postfatigue accuracy were calculated using the absolute radial error distance (cm) of each black mark.[34,35]

Maximum voluntary isometric contraction (MVIC) of the scapular muscles was measured using a MicroFet handheld dynamometer (HHD; Hoggan Health Industries, West Draper, Utah), and percentages of the MVIC values were used to standardize load during the fatigue protocol. The HHD is a battery-operated, microprocessor-controlled transducer used to measure force application. The handheld transducer weighs less than 0.5 kg and fits into the palm of the examiner's hand. It has a cantilevered arm with 3 strain gauges arranged to measure multiple force vectors simultaneously. The MicroFet was set at the low threshold setting, which detects values in 0.09-kg (0.2-lb) increments. The MicroFet has a test range

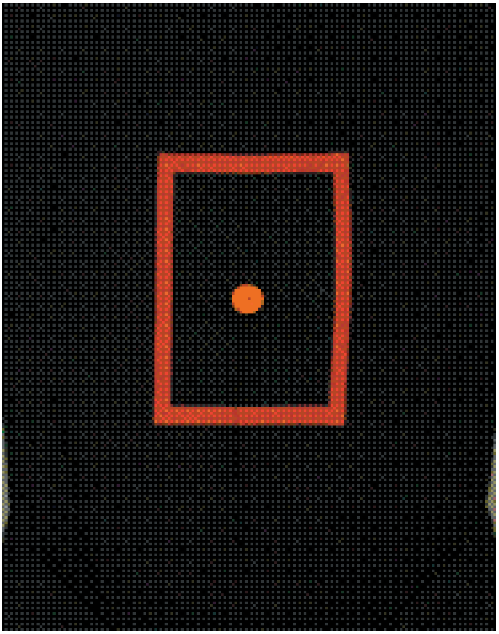

Figure 1 — Pitching screen used as target for the throwing task.

of 0.36 to 45.36 kg (0.8 to 100 lb) and a liquid-crystal display that shows force being applied, peak force applied during a test, and the time of force application to the 0.1 second.

Scapular upward rotation was measured using a digital inclinometer (Saunders Group Inc, Chaska, Minn). The inclinometer was modified using wooden locator rods attached to the bottom of the instrument so that it rested evenly on the scapular spine.[36,37] The digital inclinometer measures angles in a 360° range with a manufacturer-reported accuracy of 0.1°. Validity (r = .74 to .92) and intratester reliability (ICC = .89 to .96) of this instrument while measuring scapular upward rotation with humeral elevation angles of rest, 60°, 90°, and 120° abduction in the scapular plane have previously been established as good to excellent.[37]

Testing Procedures

Data were collected during a single test session. The study was explained and subjects completed informed-consent and health-history forms. Subjects removed their shirts to adequately expose the upper extremity for scapular-inclination and -motion analysis. Before data collection, all subjects underwent a standardized active stretching protocol (2 sets × 30 seconds each) that included shoulder horizontal adduction/abduction, flexion/extension, elbow flexion/extension, and circumduction (10 clockwise and counterclockwise). Scapular upward rotation was then assessed, followed by practice trials for throwing accuracy. Next, kinematic data were collected on 10 repetitions during the throwing-accuracy trials. Subjects were then instructed to perform the fatigue protocol, immediately followed by scapular-position assessment and throwing-accuracy testing.

Scapular upward rotation of the test arm was measured with the subject in a standing position before and immediately after fatigue using a digital inclinometer. The digital inclinometer was held in a plane perpendicular to horizontal, using a bubble level, with the medial locator arm over the spine of the scapula at its root and the lateral locator arm over the posterolateral acromion (Figure 2).[36,37] When the inclinometer had been positioned, the examiner measured the static scapular position (degrees). Two measurements were taken with the subject in each test position: resting posture (standing, facing forward with arms at side) and 45º and 90º glenohumeral abduction in the scapular plane (30° anterior to the frontal plane). Humeral positions were determined using a goniometer, and a guide pole was used for the subsequent repetition.

Before throwing accuracy was assessed, reflective markers (Peak Performance Technologies) were placed on the following bony landmarks: intersternal notch, xiphoid process, acromion process, olecranon process, radial styloid process, and ulnar styloid process. Subjects completed 10 practice throws toward the target for familiarization and warm-up. Testing was performed from a seated position[6] approximately 6 m away from the target. This position was selected to reduce contributions from distal segments in the kinetic chain so that the role of the scapular muscles could be identified. Pilot testing determined a throwing distance that was challenging yet attainable from the test position. The throwing-accuracy test included 10 repetitions of throwing the ball and was videotaped for kinematic analysis. Subjects were instructed to throw a baseball toward the target's center as fast and accurately as possible for each trial.[18] A throwing motion was selected so comparisons could be made with related literature, as well as because it was

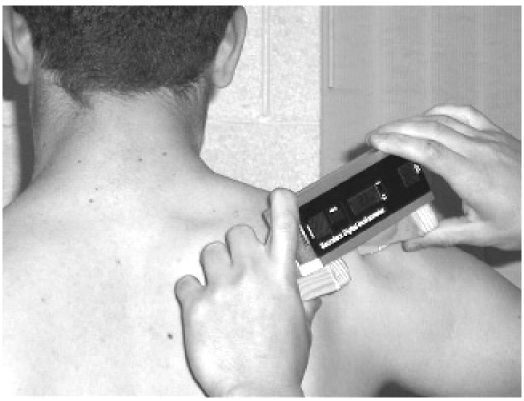

Figure 2 — Scapular upward rotation measurement using a digital inclinometer.

a familiar task. Data were collected in the same fashion for both prefatigue and postfatigue testing.

After the pretest, a standardized circuit of exercises (Table 1) was performed by all subjects to induce scapular-muscle fatigue. The protocol required subjects to perform a circuit of exercises against a set load until fatigued, which was determined visually when subjects were unable to maintain exercise workload (ie, tempo, complete full arc of motion, or movement without compensation) for 3 consecutive repetitions. On average, fatigue was achieved within 10 minutes. No more than 30 seconds separated individual exercises in the circuit, and 1 minute, between reaching fatigue and posttesting, minimizing the opportunity for recovery. The exercises included were the shoulder shrug, neck extension, modified push-up plus, scapular retraction, scapular protraction/retraction proprioceptive neuromuscular facilitation (PNF), 90° arm raise overhead, and 120° arm raise overhead. These exercises were used to target and elicit maximum recruitment of the trapezius (upper, middle, and lower), rhomboids (major and minor), serratus anterior, pectoralis minor, and levator scapulae.[38-41] Although it should be recognized that contributions from the glenohumeral muscles could not be eliminated while these exercises were performed, we attempted to minimize activity of those muscles and focus on the scapular muscles through body positioning and also by subjects performing the tasks through small arcs of motion.[38-40,42] In addition, extensive pilot testing was performed to ensure that both the exercises and the exercise circuit were effective in emphasizing fatigue of the scapular muscles.

To determine and standardize the amount of resistance used during the exercises, scapular-muscle strength was measured using the HHD. The examiner provided manual resistance (with the HHD in hand) against each subject in positions related to each fatigue exercise for 5 seconds, and the average of 3 MVICs

Table 1 Exercise Circuit Used to Induce Isolated Scapular-Muscle Fatigue*

Exercises (in order)	Resistance
Shoulder shrug	70% MVIC
Prone neck extension	Manual resistance
Modified push-up plus	40 beats/min (cadence)
Shoulder shrug	80% MVIC
Prone scapular retraction	70% MVIC
Modified push-up plus	40 beats/min (cadence)
Shoulder shrug	80% MVIC
Scapular retraction/protraction PNF	Manual resistance, above 60% MVIC
Prone arm raise overhead to 90°	30% MVIC
Shoulder shrug	80% MVIC
Modified push-up plus	40 beats/min (cadence)
Prone arm raise overhead to 120°	30% MVIC

*MVIC indicates maximal voluntary isometric contraction, and PNF, proprioceptive neuromuscular facilitation.

was used to calculate 30%, 60%, 70%, and 80% of maximum. These values were determined through pilot testing. Five positions were used to measure strength of scapular elevation, retraction, and protraction. The examiner stabilized the subject's thorax and provided verbal feedback on body position during all MVIC measures. Scapular elevation (upper trapezius and levator scapulae) was assessed with the subject in a seated position. Subjects were instructed to elevate the scapula while the examiner applied resistance on the acromion process in an inferior direction.[41] Scapular-retraction strength (middle trapezius, rhomboid major and minor) was evaluated in 3 positions. First, the subject was prone at the edge of the table with the test arm free to hang toward the floor. The subject maintained scapular retraction against the examiner's resistance, which was applied in a downward (anterior) direction with the HHD on the subject's posterior deltoid/acromion process.[41] For the second and third scapular-retraction positions the subject was prone with the test arm raised overhead, free of the table. Scapular retraction was measured while the subject maintained 90° abduction with a neutral hand position and 120° abduction in the scapular plane with the thumb facing upward.[38] The examiner applied resistance on the distal forearm in a downward (anterior) direction. Scapular-protraction (serratus anterior and pectoralis minor) MVICs were measured with the subject side-lying (nontest arm against table). The test arm was placed behind the subject's back, and scapular protraction was maintained against the examiner's inferoposteriorly directed force on the acromion process. Subjects were instructed to protract the scapula. Once load values were calculated, subjects were instructed to perform the exercises described as follows.

Shoulder Shrug. For the shoulder shrug, each subject was seated at the edge of a table with the arm hanging free over the edge (Figure 3). The subject was instructed

Figure 3 — Shoulder shrug.

to elevate and depress the scapula as many times as possible. Once concentric failure (inability to elevate shoulder) occurred, the examiner assisted with shoulder elevation so that the eccentric portion of the exercise could continue. Assisted shoulder shrugs were performed until eccentric failure (inability to lower shoulder and resistance in controlled manner). During this exercise, the subject's uninvolved hand was on his knee to prevent it from holding the table. The resistance during shoulder-shrug exercise was distributed between a dumbbell and cuff weights.

Neck Extension. Neck extension was performed using manual resistance. Subjects were prone with their head extended beyond the edge of the table and hands placed on their back (Figure 4). The examiner provided resistance with one hand on a subject's external occipital tubercle and used the other hand to stabilize the subject's trunk. The subject was instructed to resist neck extension concentrically and flexion eccentrically. The criterion of fatigue was when the subject was unable to extend his neck against resistance for 3 continuous repetitions.

Modified Push-Up Plus. The modified push-up plus was performed in push-up position (90° shoulder flexion and elbow extension). Subjects' feet were elevated on a 36-cm box to elicit more scapular-muscle activity (Figure 5).[39] In this position, subjects were instructed to perform scapular protraction (the plus phase of the push-up-plus exercise). Repetitions of the "plus" were maintained with a metronome set at a rate of 40 beats/min. Subjects repeated the exercise until they were unable to properly perform the movement or sustain the set rate for 3 consecutive repetitions.

Scapular Retraction. Scapular retraction was performed in prone position. Subjects began this exercise with their arm off the table in 90° shoulder flexion and 0° of elbow extension (Figure 6). The nontest hand was positioned on the back to eliminate accessory movements. Subjects were instructed to retract the scapula while maintaining arm position and continue until they could not control

Figure 4 — Neck extension.

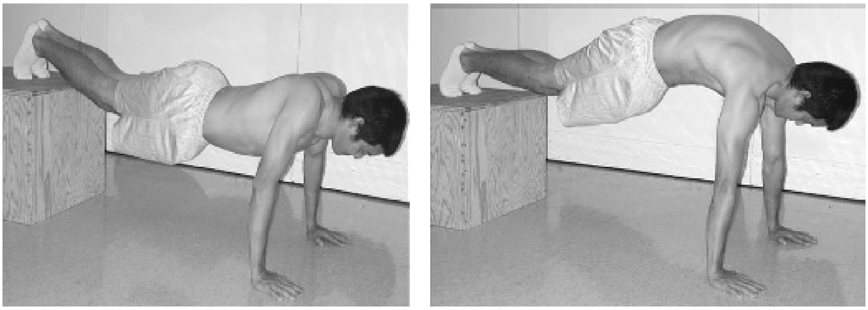

Figure 5 — Push-up plus.

Figure 6 — Prone scapular retraction.

shoulder protraction and compensatory movements were visible for 3 consecutive repetitions.

Scapular PNF. Scapular protraction/retraction PNF was performed against manual resistance.[43] Subjects were side-lying with the test hand against the low back in shoulder internal rotation (Figure 7). Subjects performed shoulder retraction/depression and protraction/elevation against the examiner's manual resistance. The examiner placed one hand (with HHD) on the subjects' acromion process, and

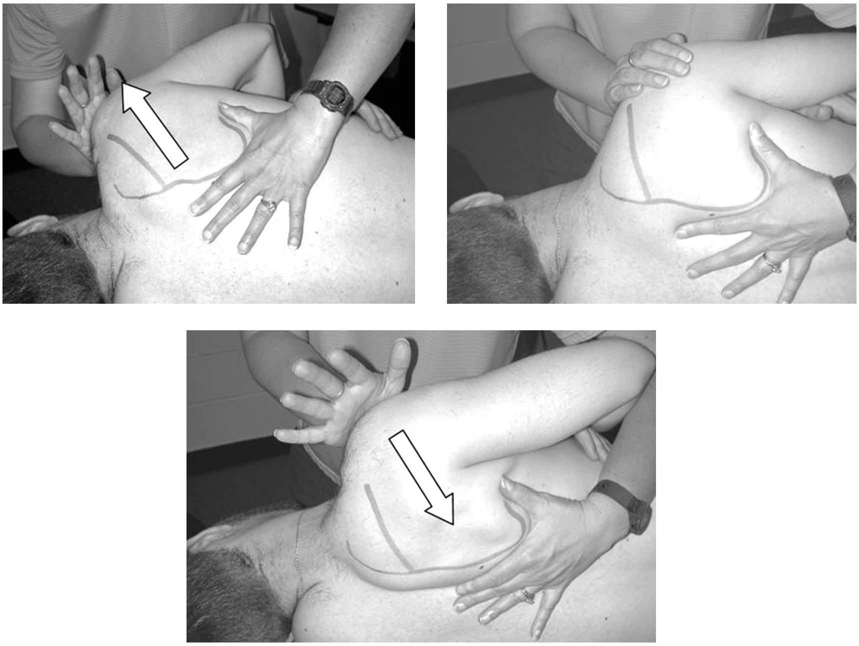

Figure 7 — Scapular proprioceptive neuromuscular facilitation.

the other hand grasped the inferior angle of scapula. The fatigue criterion was when the HHD registered a value below 60% of MVIC for 3 consecutive repetitions.

Overhead Arm Raise. Ninety-degree and 120° overhead arm-raise (Figure 8) exercises were performed with a load placed around the wrist (cuff weight) that was equivalent to 30% of MVIC. The 90° overhead arm raise required subjects to maintain 90° shoulder abduction and retract the scapula. Figure 6 illustrates the same body positioning for the 90° exercise, but the arm was placed perpendicular to the trunk (90° shoulder abduction). The 120° overhead arm raise required subjects to lift their arm within a 160° to 200° arc of motion. Both exercises were performed at 60 beats/min as many times as possible until the subject was unable to complete the movement or maintain speed.[10] The examiner stabilized the subject's thorax during the exercise to prevent compensatory motion.

Feedback and encouragement on the quality of exercise were provided by the examiner to prevent compensating movements such as shoulder shrugging, arm swinging, elbow flexion, and arm rotation. Once fatigued, subjects immediately performed 10 throws that were analyzed and compared with prefatigue data.

Statistical Analysis

Descriptive and inferential statistics were derived from the data. The average of 4 throwing trials was used to analyze kinematic and accuracy data for each subject

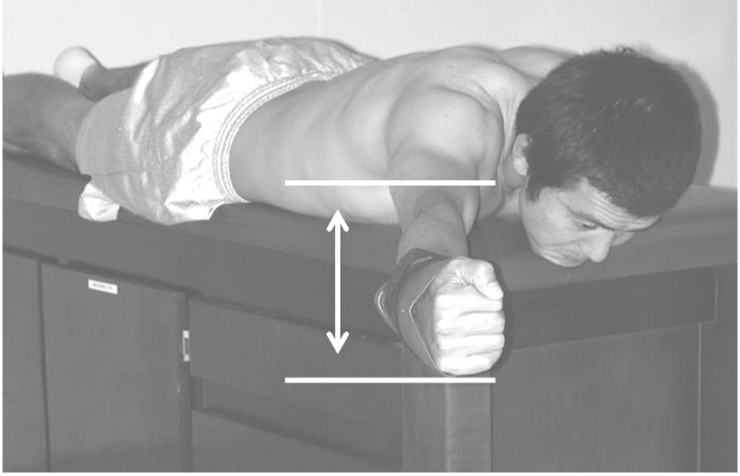

Figure 8 — Overhead arm raise to 120°.

prefatigue and postfatigue. Thirty subjects were tested, but only 23 and 26 subjects were included in elbow and shoulder analyses, respectively, as a result of poor video quality during data processing.

Two 2 (pretest–posttest) × 3 (throwing phase) multivariate analyses of variance (MANOVAs) with repeated measures were performed to evaluate shoulder-abduction and elbow-flexion variables. Dependent variables used in the MANOVA to evaluate shoulder-abduction motion included joint angles (maximum, minimum, and total range of motion) and velocity (maximum, minimum, and average). Dependent variables to evaluate elbow flexion/extension motion included joint angles (maximum flexion, minimum flexion, and range of motion) and velocity (maximum into flexion, maximum into extension, and average). When significant differences were found at the univariate level, post hoc tests were performed on each dependent variable. A paired-samples *t* test was used to determine differences in maximum shoulder external rotation between prefatigue and postfatigue conditions. To evaluate throwing accuracy prefatigue–postfatigue, a paired-samples *t* test was used. A 2 (prefatigue–postfatigue) × 3 (humeral elevation) analysis of variance (ANOVA) with repeated measures was used to analyze scapular upward rotation. All analyses were performed using Statistical Package for Social Science Version 12.0 software (SPSS, Inc, Chicago, Ill). An alpha level of .05 probability was set a priori to be considered statistically significant.

Results

No significant differences were found in shoulder-abduction or external-rotation displacement and velocity after fatigue. The results of the 2 × 3 MANOVA for shoulder abduction revealed a significant Time × Phase interaction ($F_{11,12} = 32.9$,

$P < .001$) and significant main effects for time ($F_{6,17} = 38.4$, $P < .001$) and phase ($F_{11,12} = 23.3$, $P < .001$). Post hoc analyses were not able to detect significant differences, however, when separating displacement and velocity variables prefatigue and postfatigue ($P > .05$). Paired-samples t tests revealed no significant differences ($t_{21} = 1.6$, $P = .13$) in maximum external rotation between prefatigue and postfatigue.

Significant differences were found in elbow range of motion and velocity (flexion) between prefatigue and postfatigue (Table 2). The results of the 2 × 3 MANOVA for elbow displacement and velocity revealed a significant increase in total elbow motion in the cocking phase between prefatigue and postfatigue trials ($F_{10, 13} = 89.2$, $P < .001$). Although the difference was insignificant, the elbow was more extended (maximum displacement) in postfatigue trials (prefatigue = 35.6° ± 15.1°, postfatigue = 40.3° ± 17.5°). Average ($F_{11,12} = 32.9$, $P < .001$) and maximum ($F_{11,12} = 4.7$, $P = .02$) elbow-flexion velocity were significantly greater in the postfatigue follow-through phase. As the elbow moved into a flexed position, the average velocity was approximately 7 times faster than in the prefatigue follow-through phase.

The Time × Position ANOVA for scapular upward rotation revealed a statistically significant main effect for position ($F_{1,29} = 191.9$, $P < .001$). There was significantly more upward rotation in the 90° humeral-elevation test position (27.3° ± 7.5°) than in the rest position and 45° humeral-elevation position (7.5° ± 3.6° and 7.9° ± 3.6°, respectively). No significant differences were detected in scapular inclination prefatigue to postfatigue ($F_{1,29} = 2.4$, $P = .131$) or Time × Position interaction ($F_{1,29} = .51$, $P = .60$).

A paired-samples t test for throwing accuracy revealed a significant decrease in scores between prefatigue and postfatigue ($t_{29} = -2.9$, $P = .01$). Subjects threw the ball less accurately, or farther from the center of target (prefatigue = 30.12 ± 11.7 cm, postfatigue = 40.77 ± 9.9 cm), after the fatigue protocol.

Comments

With this study, we attempted to provide information regarding some of the alterations that might occur as a result of scapular-muscle fatigue. The results revealed that scapular-muscle fatigue altered elbow kinematics and throwing accuracy in healthy men throwing from a seated position. Our findings revealed a significant increase in total motion at the elbow during the cocking phase. In addition, a significant increase in both maximum flexion and average elbow velocity was demonstrated during the follow-through phase in postfatigue trials as the elbow moved into a flexed position. Finally, no changes were found in shoulder kinematics or scapular upward rotation as a result of fatigue.

Scapular position and function depend on the surrounding muscles (upper, middle, and lower trapezius; rhomboid major and minor; levator scapulae; serratus anterior; and pectoralis minor), particularly during overhead activities. These dynamic contributions have been well documented in research involving baseball, and it was for this reason that we chose a baseball throw as the functional task.[4,14,44] Previous studies have found that alterations caused by fatigue were evident during each phase of throwing.[4,14,44] Emphasis on scapula position and movement is particularly important, however, during both ball-release and follow-through

Table 2 Elbow-Joint Kinematics During Overhead Throwing

	Cocking Phase		Acceleration Phase		Follow-Through Phase	
Variable	**Prefatigue**	**Postfatigue**	**Prefatigue**	**Postfatigue**	**Prefatigue**	**Postfatigue**
Displacement (°)						
minimum (flexion)	50.8 ± 11.5	50.2 ± 13.1	67.3 ± 12.3	70.8 ± 12.6	114.3 ± 13.8	111.7 ± 15.7
maximum (extension)	86.4 ± 16.6	90.6 ± 12.3	123.5 ± 12.4	123.7 ± 15.8	137.1 ± 8.6	137.6 ± 9.3
total range of motion	35.6 ± 15.1	40.3 ± 17.5*	56.2 ± 16.0	52.9 ± 13.8	22.8 ± 9.4	25.9 ± 11.3
Velocity (m/s)						
maximum (extension)	307.5 ± 158.5	331.2 ± 198.3	1137.8 ± 330.5	1200.4 ± 310.2	779.9 ± 309.6	743.0 ± 358.7
maximum (flexion)	–219.6 ± 169.0	–199.6 ± 185.1	–230.3 ± 236.9	–266.0 ± 230.5	–311.4 ± 135.0	–371.5 ± 171.6*
average	13.6 ± 42.5	20.5 ± 42.7	485.3 ± 232.7	476.1 ± 182.4	–6.3 ± 104.4	–42.7 ± 90.2*

*Denotes statistical significance ($P < .05$) between prefatigue and postfatigue trials.

phases, when the muscles are required to contract eccentrically to assist the posterior rotator cuff in decelerating the arm.[4,44,45] These muscles also function to dissipate and absorb forces throughout the distal segment.[21,44,45]

The kinetic-chain concept is based on activation of segments beginning at the ground and moving in a proximal-to-distal manner.[12,21] This concept directly applies to overhead throwing, as demonstrated by Hirashima et al,[18] who documented a sequential segment specific to upper extremity muscle activation using electromyography and found that in the presence of optimal muscle length–tension relationships, activity first occurred in the scapular muscles (specifically protractors), followed by shoulder (horizontal flexors) then elbow (extensors) during the throwing motion. Our findings support the important role of the scapular muscles in transferring energy along the kinetic chain from proximal to distal segments.[12,13,20,44,46] In this study, alterations in length–tension relationship caused by scapular-muscle fatigue were evident at the elbow and not at the shoulder as expected.

Scapular-muscle weakness has been identified as a leading risk factor for elbow injuries and pain in youth sports.[25-27] Werner et al[17] found that altered throwing mechanics accounted for 97% of elbow-valgus forces in pitchers, suggesting that fatigue of proximal muscles and repetitive overload directly affect elbow function. Alterations that result in elbow pain and injury often produce sensations of diminished control, particularly during follow-through.[15,47] In our study, the significant increase in total elbow motion during the cocking phase after scapular fatigue supports findings in the literature regarding the role of scapular function.[13,21] In addition, both maximum and average velocity significantly increased for elbow flexion during the follow-through phase after our scapular-fatigue protocol. Although we did not test overhead athletes, these findings support the importance of dynamic contributions from the scapula in maintaining distal-segment function.[13,14,17,21,26,28,45]

Accuracy is the product of a coordinated and sequentially activated kinetic-chain system.[34] Our results demonstrated that isolated scapular-muscle fatigue and resulting kinematic changes caused a disruption in kinetic energy transfer that led to a 26% decrease in accuracy (30.12 cm prefatigue vs 40.77 cm postfatigue). The reduction in accuracy after fatigue was found to be more horizontal (x axis) error (30%) than vertical (y axis) error (20%) compared with prefatigue values. The decreased accuracy in our study was expected and supports the effectiveness of our fatigue protocol. Clinically, decreased accuracy might be an indicator of altered mechanics and predisposition to injury.[48]

Our findings revealed that shoulder-complex kinematics (abduction and external-rotation angle and velocity) do not change as a result of scapular fatigue, which contrasts with previous research. One explanation for these differences might involve the muscles targeted for fatigue. Others have determined that shoulder-complex fatigue, compared with a more isolated scapular-muscle fatigue protocol, resulted in changes in scapulohumeral rhythm and muscle activity.[6,8-10] In addition, after glenohumeral fatigue, Tsai et al[49] identified significant changes in scapular position (decreased upward rotation, posterior tilting, and external rotation). These protocols used fatigue exercises that induced scapular, as well as glenohumeral, muscle fatigue, so including more segments and muscles might have led to greater kinematic changes at these joints. The lack of significant findings at the shoulder after our scapular-fatigue protocol was surprising, but it could suggest that alterations in motion might have occurred elsewhere within shoulder complex or at the trunk. MacWilliams et al[32] studied mechanics (ie, motion and ground-reaction forces) and demonstrated the importance of the lower extremity in maintaining the throwing motion. Our testing attempted to rule out lower extremity contributions to specifically examine the scapular muscles by having subjects throw from a seated position; however, trunk motion was not restricted, and therefore the trunk muscles might have compensated for decreased scapular motion caused by fatigue. For this reason, we are limited in comparing our results with those from baseball players.

Scapular upward rotation is important during overhead activities because it provides a stable base for the glenohumeral joint. The scapula also assists with acromial elevation to increase subacromial space for underlying soft tissues.[12,13,45] For this reason, changes in scapular position are important. After our isolated scapular fatigue there were no changes in upward rotation. Su et al[7] and Birkelo et al[5] also found no significant changes in upward rotation with arm abduction after fatigue in healthy swimmers and baseball pitchers. Nonetheless, several researchers have identified decreased scapular upward rotation in both healthy subjects and subjects with shoulder pathologies.[7,23,50] Lack of agreement in the findings might be explained by the nature of measurements used, which differ between static and dynamic movements, as well as instrumentation. Future research is needed to determine the effects of muscle fatigue on scapular motion during dynamic movements. Clinicians often incorporate static measures into shoulder evaluation. It was for this reason that we attempted to measure changes using the inclinometer after fatigue. The inclinometer might not be sensitive enough to detect potentially minute but important changes in static scapular position.

Several limitations might have influenced the results of this study. The test population consisted of healthy college-age men, so comparisons with an athletic (eg, baseball or swimming), adolescent, or pathologic population should not be made. Second, the intent of this study was to exclude as many kinetic-chain contributions to throwing as possible in an effort to isolate the scapula and determine its effect on arm movements. We think that if subjects had thrown from a standing position, different results might have occurred. For example, contributions from the latissimus dorsi, a prime mover during throwing, might have been affected because it was fixed distally when subjects were seated. Finally, our 2-dimensional kinematic measurements were based on a model of the shoulder complex and did not examine individual joints or components (ie, scapulothoracic, glenohumeral, trunk, etc). Based on previous research, we expected alterations to occur at the shoulder instead of the elbow, so specific forearm movements (ie, supination/pronation) were not included in analyses. We recognize that more sensitive instruments, 3-dimensional kinematics, and the inclusion of more scapular measures (ie, protraction/retraction and anteroposterior tilt) might have enabled us to detect further alterations caused by fatigue.

Conclusions

Scapular-muscle function is imperative to maintaining coordinated movements involving the upper extremity. This study investigated how scapular-muscle fatigue affects elbow motion and throwing accuracy. Our findings demonstrated that scapular-muscle fatigue results in decreased accuracy during goal-directed tasks. These findings also suggest that scapular-muscle fatigue might contribute to elbow pathology. Clinically, emphasis on scapular-muscle endurance exercises should be incorporated in prevention and rehabilitation protocols for elbow injuries.

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