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Clinical Biomechanics 17 (2002) 650–659
CLINICAL BIOMECHANICS
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Comparison of scapular kinematics between elevation and lowering of the arm in the scapular plane

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Received 9 August 2001; accepted 16 September 2002

Abstract

Objective. To compare scapular orientation during both the concentric (elevation) and eccentric (lowering) phases of scapular plane abduction in subjects with and without shoulder impingement.

Design. Mixed model analysis of variance with one between-subjects factor (group) and within-subjects factors of phase, humeral angle, and trial.

Background. Abnormal scapular kinematics have been identified in shoulder impingement patients during the concentric phase of arm elevation, and under static conditions. Because abnormal scapular motion is observed clinically during the eccentric phase of arm elevation, analysis of this phase of motion is warranted.

Methods. Twenty-six symptomatic and 26 healthy subjects performed five repetitions of humeral scapular plane abduction. An electromagnetic tracking device described three-dimensional scapular kinematics during arm elevation and lowering. Angular values for scapular anterior/posterior tipping in the sagittal plane, upward/downward rotation in the scapular plane, and internal/external rotation in the transverse plane were calculated. Scapular orientation relative to the thorax at humeral angles of 40°, 60°, 80°, 100°, and 120° was statistically tested for effects of phase and trial, or for interactions of phase with group or humeral angle.

Results. Internal rotation was significantly increased in the eccentric phase for both groups at the 100° angle ($P < 0.05$) and for the symptomatic group only at the 120° angle ($P < 0.05$). Scapular anterior tipping was significantly decreased during the eccentric phase in both groups at the 80° ($P < 0.001$), 100° ($P < 0.0001$), and 120° ($P < 0.0001$) angles.

Conclusions. Small but statistically significant differences in scapular tipping and internal rotation during the eccentric phase of arm elevation were identified at higher humeral angles in both subject groups, while no significant phase differences for scapular upward rotation or for scapular variables at lower humeral angles were found. Averaged across phases, the symptomatic group demonstrated significant reductions in upward rotation at lower humeral elevation angles, and significant increases in anterior tipping at higher elevation angles as compared to the healthy group.

Relevance

Normal and abnormal scapular kinematics during varying types of motion need to be understood in order to optimally design rehabilitation programs for individuals with impingement syndrome.

Keywords: Biomechanics; Three-dimensional movement; Shoulder; Shoulder impingement

1. Introduction

Shoulder impingement is a commonly diagnosed and treated musculoskeletal pathology described as a mechanical compression of the rotator cuff tendons, subacromial bursa, and long head of the biceps tendon against the anterior undersurface of the acromion and coracoacromial ligament [1]. Abnormal scapulothoracic kinematics are thought to play a role in the development or progression of impingement and are often addressed in the clinical management of this condition [2–4]. Factors including muscle weakness or shortening, trauma, repetitive overhead work conditions, or pain are believed to potentially disrupt muscular control and lead to scapular motion abnormalities and subsequent impingement [3].

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PII: S0268-0033(02)00136-5

Recent three-dimensional (3-D) research has expanded Inman et al.'s original description of "scapulohumeral rhythm" to include anterior/posterior tipping (about an axis approximately parallel to the scapular spine) and internal/external rotation (about an approximately vertical axis), in addition to the originally described upward/downward rotation (about an axis perpendicular to the plane of the scapula) [2,3,5–10] (Fig. 1). These 3-D analyses have identified both normal and abnormal patterns of scapular motion on the thorax with elevation of the arm. Although magnitudes of scapular motion vary, with the exception of scapular internal/external rotation, directions of motion during scapular plane abduction are consistent across investigations of healthy subjects. During arm elevation in the scapular plane, scapular upward rotation increases and tipping progresses from anterior to posterior [2,3,6,11]. Scapular internal rotation is more variable, either decreasing, increasing, or staying relatively unchanged [2,3,6,11]. Deviations from this normal pattern of scapular motion have been identified in patients with shoulder impingement under certain conditions. These deviations include decreased scapular posterior tipping, increased internal rotation, and decreased upward rotation [2–4]. The directions of these changes in patients with impingement symptoms are consistent with possible reductions in the available subacromial space and impingement of the subacromial structures [12].

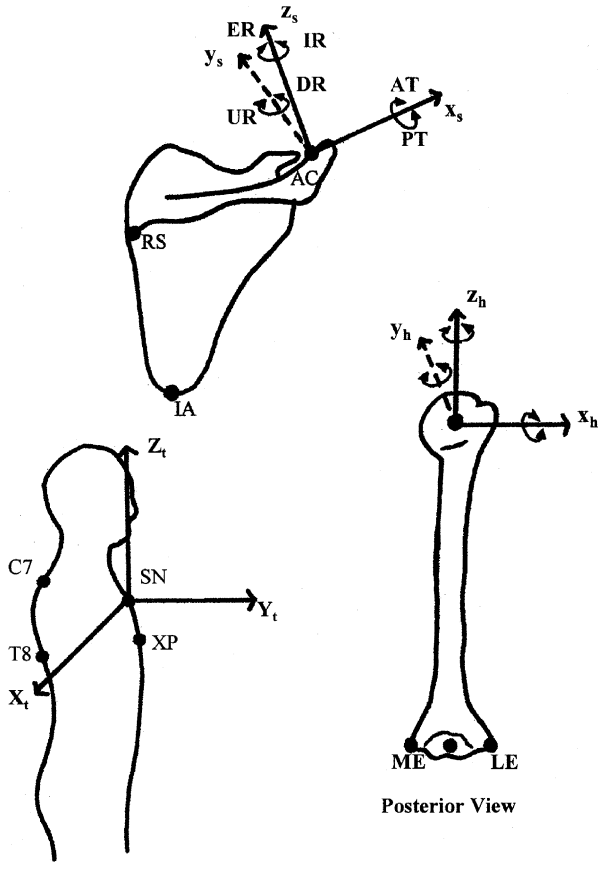

Fig. 1. Local coordinate systems for the trunk, scapula, and humerus. RS: root of scapular spine, AC: posterolateral acromioclavicular joint, IA: inferior angle, x_s: scapular x-axis directed from RS to AC, y_s: scapular y-axis directed anteriorly perpendicular to the scapular plane, z_s: scapular z-axis directed superiorly, ER: external rotation about the scapular z-axis, IR: internal rotation about the scapular z-axis, UR: upward rotation about the scapular y-axis, DR: downward rotation about the scapular y-axis, AT: anterior tipping about the scapular x-axis, PT: posterior tipping about the scapular x-axis; SN: sternal notch, C7: spinous process of seventh cervical vertebrae, T8: spinous process of eighth thoracic vertebrae, XP: xiphoid process, Xt: trunk x-axis directed laterally, Yt: trunk y-axis directed anteriorly, Zt: trunk z-axis directed superiorly; ME: medial epicondyle, LE: lateral epicondyle, x_h: humeral x-axis directed laterally, y_h: humeral y-axis directed anteriorly, z_h: humeral z-axis directed superiorly (Adapted for reprinting from Ludewig PM, Cook TM, Alterations in shoulder kinematics and associated muscle activity in people with symptoms of shoulder impingement, Physical Therapy, 2000;80:276–291, with permission of the American Physical Therapy Association).

Many questions remain regarding the relationship between kinematics and shoulder impingement. One question from a clinical perspective concerns scapular orientation during lowering the arm from an overhead position. It is often during this eccentrically controlled motion that the scapular inferior angle and/or medial border are observed to "wing" or lose contact with the thorax and become more prominent [4,13]. In addition, patients will often describe lowering the arm, particularly at the mid range of motion, to be more painful than raising it. As the inferior angle moves away from the thorax, the superior portion of the scapula tips forward and places the acromion in a position of closer proximity to the humeral head. Should the medial border move off the thorax as well, it is believed there will be a further anterior movement of the acromion as the scapula rotates around a vertical axis. This acromion position is more likely to impinge tissues in the subacromial space. There is currently no literature comparing the orientation of the scapula relative to the thorax between this eccentric phase of arm motion and the concentric phase for subjects with impingement symptoms. An analysis of the eccentric phase of arm elevation is warranted considering the high daily use of the shoulder complex for positioning and stabilizing the upper extremity and hand, and the need to eccentrically lower the arm after attaining elevated positions.

The purpose of this investigation was to compare 3-D scapulothoracic kinematics between the lowering or eccentric phase and the concentric phase of upper extremity elevation in both symptomatic and healthy subjects. We hypothesized that previously identified scapular kinematic deviations in subjects with impingement [3] would be magnified in the eccentric phase as compared to the concentric phase, i.e. there would be an interaction of group and phase with greater effects of phase in the symptomatic group. Specifically, we expected that for subjects with impingement, the scapula

would show a greater degree of both anterior tipping and internal rotation on the eccentric phase as compared to the concentric phase, and also when compared to healthy subjects at the same arm position.

2. Methods

2.1. Subjects

Subjects for this investigation were initially recruited for a larger study [3] of construction workers in the sheet metal and carpentry trades. This population has been shown to be at increased risk for developing shoulder problems due to their occupational exposure to overhead work [14]. Fifty-two volunteers, twenty-six symptomatic and twenty-six asymptomatic, were included in this study. The study was approved by the institutional review board committee on protection of human subjects and informed consent was obtained.

Inclusion criteria for the symptomatic subjects were (1) a history of shoulder pain of greater than 1 week in duration, localized to the proximal anterolateral shoulder region, (2) a positive impingement test [15–18], a painful arc of motion between 60° and 120° [19], and/or tenderness to palpation in the region of the greater tuberosity, acromion, or rotator cuff tendons, and (3) shoulder coronal plane abduction of at least 130° relative to the thorax. The Hawkins/Kennedy and the Neer impingements tests have been shown to be 87%–92% and 89% sensitive, respectfully, and a painful arc test 81% specific to subacromial impingement [18,20]. When used as a comprehensive set of tests, these clinical measures have been shown to be valid diagnostic criteria for shoulder impingement syndrome (86% correct diagnosis) and rotator cuff tears (78% correct diagnosis) as compared to surgical confirmation [17]. There was no attempt to determine impingement subcategories such as partial tears, calcific tendinitis, or acromion morphology because more expensive diagnostic measures may be inconclusive [21] and are not consistently used clinically for diagnosis.

Subjects were excluded if (1) shoulder symptoms were reproduced during a cervical screening examination, (2) they had positive thoracic outlet test results, (3) numbness or tingling in the upper extremity was reported, or (4) there was a history of trauma, surgery, or dislocation of the glenohumeral or acromioclavicular joints. Subjects were further excluded from the healthy group if they (1) were employed for less than 1 year in an occupation with overhead exposure, (2) had less than 150° of glenohumeral abduction or flexion range of motion, or (3) had a history of pain, trauma, or dislocation of the glenohumeral or acromioclavicular joints on the tested shoulder. Inclusion/exclusion criteria were assessed based on patient history and a clinical screening examination prior to kinematic testing. All data were collected and examinations performed by a single investigator.

Using independent groups t tests, no differences were detected between the two groups for any demographic variables (age, height, weight, number of years in the trade, or self-reported percentage of time spent working with arms overhead) (Table 1). Symptomatic subjects reported a mean duration of symptoms of 5.5 years (SD = 3.2), with the majority reporting intermittent episodes of symptoms. All subjects were male. Symptomatic subjects also completed the Shoulder Pain and Disability Index, a functional status scale for the shoulder. The average combined pain and disability subscale scores was 24 (SD = 15) on a 0–100 scale with higher scores equaling greater dysfunction.

2.2. Instrumentation

The FASTRAK electromagnetic motion capture system (Polhemus Inc., Colchester, VT, USA) was used to track 3-D position and orientation of each subject's thorax, scapula, and humerus. A fourth sensor attached to a stylus was used to digitize manually palpated anatomical landmarks. The reported root mean square (RMS) accuracy of this system is 0.3–0.8 mm for position, and 0.15° for orientation when used within a 76 cm source to sensor separation [22].

2.3. Data collection

Surface electromagnetic sensors were attached to the subjects skin overlying the sternum and the flat surface on the superior acromion process using double-sided

Table 1
Subject demographics

Variable	Healthy			Symptomatic		
	Mean	SD	Range	Mean	SD	Range
Age (years)	39.9	13.3	20–71	39.7	12.0	25–68
Height (m)	1.80	0.08	1.67–1.96	1.81	0.06	1.67–1.93
Weight (kg)	85.7	12.7	63.6–122.7	90.9	14.0	61.4–120.5
Exposure (years)	18.1	13.5	2.0–43.5	16.7	12.5	3–42
Time working overhead (%)[a]	37.2	20.6	7.5–80	37.8	20.4	5–75

[a] Subject self-report.

tape. The humeral surface sensor was first attached to a thermoplastic cuff, which was in turn secured to the arm with Velcro straps. Manually palpated landmarks on the subjects' thorax, scapula, and humerus were then digitized using the hand-held stylus [3]. Digitization allowed transformation of the sensor position and orientation into anatomically based position and orientation data [23].

Each subject performed five repetitions of arm elevation and lowering in the scapular plane, considered a plane oriented 40° anterior to the coronal plane. Subjects were kept in the correct plane by a flat vertical surface, and were to complete each elevation and lowering cycle in 4 s. Continuous kinematic data were collected over the five repetitions at 40 Hz per sensor. Reliability of these procedures has been previously described with standard errors of measurement ranging from 1° to 2° for within day and 2° to 4° for between day individual subject values [3]. Validation studies of 3-D scapular kinematics comparing skin sensors to bone-fixed sensors demonstrated maximum RMS errors of 4° for scapular anterior/posterior tipping, 8° for internal/external rotation, and 8° for upward/downward rotation relative to the thorax over the 40°–120° range of humeral scapular plane abduction [24].

2.4. Data reduction

Raw kinematic data were low-pass filtered at a 4.7 Hz cutoff frequency [25]. The data collected from each sensor were transformed using matrix methods into local segment coordinate system position and orientation for the thorax, humerus and scapula [23]. Local coordinate systems were defined using the digitized anatomical landmarks (Table 2). Transformations allowed description of the scapula and humerus relative to the thorax with scapular orientation described using a $ZY'X''$ Cardan sequence [26]. Internal/external rotation was about the superior/inferior thoracic Z-axis followed by upward/downward rotation about the scapular Y'-axis (perpendicular to the scapular plane), followed by anterior/posterior tipping about the scapular X''-axis (directed from the root of the spine of the scapula to the acromioclavicular joint). Humeral orientation relative to the thorax was described using a $ZY'Z''$ Euler sequence including plane of elevation about the thoracic Z-axis, humeral elevation (abduction/adduction) about the humeral Y'-axis, and internal/external rotation about the humeral Z''-axis [27].

2.5. Data analysis

The middle three of the five trials were used for kinematic analysis. Scapular orientation relative to the thorax was analyzed during both humeral elevation in the scapular plane (concentric phase), and on return from elevation (eccentric phase). Humeral angles relative to the thorax of 40°, 60°, 80°, 100°, and 120° were used as positions in the dynamic motions at which to analyze scapular orientation. These angles span the arc of motion where shoulder impingement is likely to occur [12,19] and where differences between scapular motion while raising and lowering of the arm are often observed clinically. A repeated measures analysis of variance (ANOVA) was used to test for main effects of phase (elevation or lowering), group (symptomatic or healthy), and trial, or for interactions of phase and group, or of phase and humeral angle (40°–120°). A criterion level of $P < 0.05$ was considered statistically significant for the overall analysis. In the presence of interactions with humeral angle or group, contrasts compared phase effects at each level of the interacting factor. During elevation of the arm, group effects, angle effects, and group by angle interactions have been previously described [3].

Post-hoc analysis of the distribution of individual scapular tipping angle data at 100° was performed in a manner similar to that of Hebert et al. [28]. Scapular tipping angles of individual subjects from each group were plotted for each phase, as was the 95% confidence limit of the mean for the asymptomatic group. This allowed for visual confirmation of group differences, as well as analysis of subject outliers for any distinguishing

Table 2
Method used for establishment of local coordinate systems based on digitized bony landmarks

Trunk	Z_T: unit vector derived from $(SN + C7)/2 - (XP + T8)/2$ X_T: cross-product of unit vector derived from $(XP - T8)$ and Z_T Y_T: cross-product of Z_T and X_T
Scapula	X_S: unit vector derived from $(AC - RS)$ Y_S: cross-product of unit vector derived from $(RS - IA)$ and X_S Z_S: cross-product of X_S and Y_S
Humerus	Z_H: unit vector derived from $(SC - IC)$ Y_H: cross-product of unit vector derived from $(ME - LE)$ and Z_H X_H: cross-product of Y_H and Z_H

Abbreviations: SN, sternal notch; C7, 7th cervical spinous process; XP, xyphoid process; T8, 8th thoracic spinous process; AC, posterior acromioclavicular joint; RS, root of spine of scapula; IA, inferior angle of scapula; SC, superior humeral cuff; IC, inferior humeral cuff; LE, lateral epicondyle; ME, medial epicondyle.

similarities in terms of demographic or evaluation findings. Scapular tipping at 100° of humeral elevation was selected for this analysis because significant differences were found between phases and groups at this angle, and because both increased anterior tipping and humeral elevation near 90° are considered to be risk factors for impingement.

3. Results

For scapular upward rotation, there were no significant interactions between phase and either group or angle, nor were there significant main effects of phase of motion or trial. Scapular upward rotation was equivalent at a given humeral angle whether raising or lowering the arm regardless of the presence or absence of shoulder symptoms. For scapular internal rotation, however, there was a significant 3-way interaction of both group and humeral angle with phase of motion ($P < 0.01$). When considering the analysis separately for each humeral angle, neither group showed any effects of phase or interactions with phase for the 40°, 60°, or 80° humeral angles (Fig. 2). Scapular internal rotation showed a significant increase (1.2°; within subject standard error of the mean 0.5°; $P < 0.05$) during the eccentric phase at the 100° humeral angle in both groups. There was a significant phase by group interaction ($P < 0.05$) at the 120° humeral angle with internal rotation during the eccentric phase significantly increased (1.8; within subject standard error of the mean 0.5°) in the symptomatic group only (Fig. 2). There were no significant trial-to-trial differences in scapular internal rotation at any humeral angle.

Scapular tipping demonstrated a 2-way interaction of phase and angle ($P < 0.0001$). With further analysis at each humeral angle, neither group showed any effects of phase or interactions with phase for the 40° or 60° humeral angles (Fig. 3). For both groups, scapular anterior tipping was significantly decreased during the eccentric phase at 120° ($P < 0.0001$), 100° ($P < 0.0001$), and 80° ($P < 0.001$). Decreases averaged 2.7°, 2.5°, and 1.3°, with within subject standard errors of the mean of 0.45°, 0.45°, and 0.35° respectively. There were no significant differences between trials at these humeral angles. As with internal rotation, the data tended to show greater differences between groups in the eccentric phase as compared to the concentric phase (Fig. 3), but this tendency was not strong enough to reach statistical significance for a group by phase interaction.

Significant differences between groups for this population have been previously described during concentric elevation of the arm. A summary of the group differences demonstrated includes significant reductions in upward rotation in the symptomatic group at the 40° and 60° humeral angles (mean differences 4°, between subject standard error of the mean 1.2°, $P < 0.05$), and significant increases in anterior tipping in the symptomatic group at the 100° and 120° humeral angles (mean differences 4° and 6°, between subject standard errors of the mean 1.4° and 1.6° respectively, $P < 0.05$). Between group comparison of scapular upward rotation is summarized in Table 3.

Figs. 4 and 5 display the individual scapular tipping angles at 100° humeral elevation of both groups for the eccentric and concentric phases, respectively. During the eccentric phase, 61.5% of symptomatic subject's data values lie outside the 95% confidence interval in the direction of anterior tipping while only 7.7% of

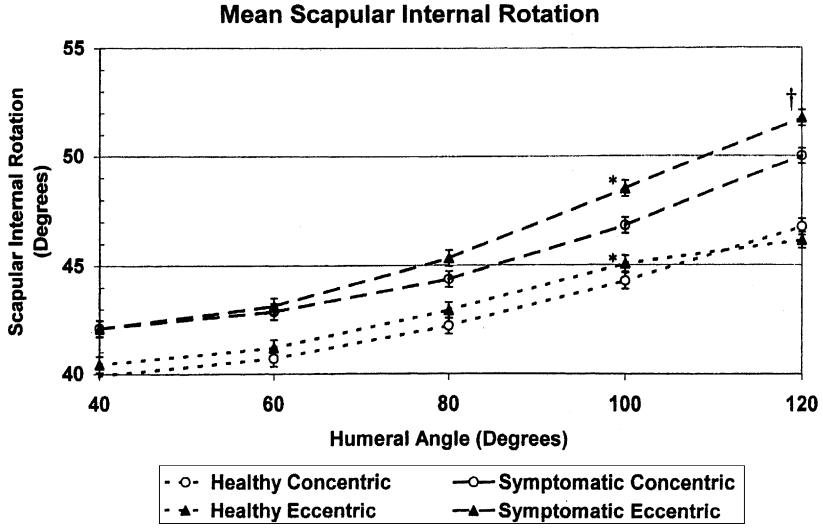

Fig. 2. Mean scapular internal rotation angles relative to the trunk at selected humeral elevation angles. Error bars represent the standard error of the mean. (*) Significant effect of phase in both groups ($P < 0.03$). (†) Significant effect of phase in the symptomatic group ($P < 0.02$).

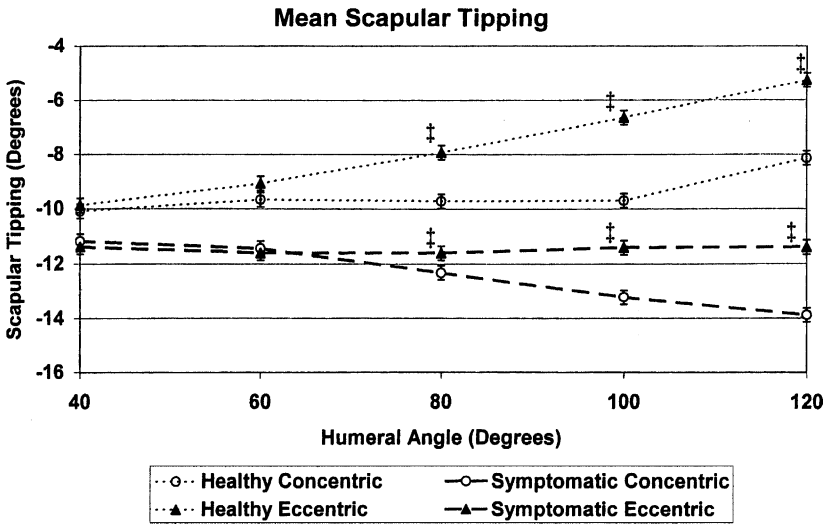

Fig. 3. Mean scapular tipping angles relative to the trunk at selected humeral elevation angles. Negative values indicate anterior tipping. Error bars represent the standard error of the mean. (‡) Significant effect of phase in both groups ($P < 0.001$ at 80°; $P < 0.0001$ at 100° and 120°).

Table 3
Mean scapular upward rotation angular values at each humeral elevation angle by group and phase

Scapular motion	Group	Phase	Humeral angle				
			40°*	60°*	80°	100°	120°
Upward/downward rotation	Healthy	Concentric	−16.7 (0.4)	−22.5 (0.5)	−29.1 (0.6)	−35.3 (0.7)	−40.7 (0.6)
	Healthy	Eccentric	−16.4 (0.4)	−22.7 (0.5)	−29.5 (0.6)	−35.7 (0.7)	−39.2 (0.6)
	Symptomatic	Concentric	−12.9 (0.4)	−19.1 (0.5)	−26.3 (0.6)	−33.7 (0.7)	−40.2 (0.6)
	Symptomatic	Eccentric	−12.4 (0.4)	−18.8 (0.5)	−26.4 (0.6)	−33.5 (0.7)	−39.8 (0.6)

Negative values indicate scapular upward rotation.
Parentheses indicate within subject standard error of the mean.
* Significant differences between the groups at the 40° and 60° humeral angles for both phases ($P < 0.05$).

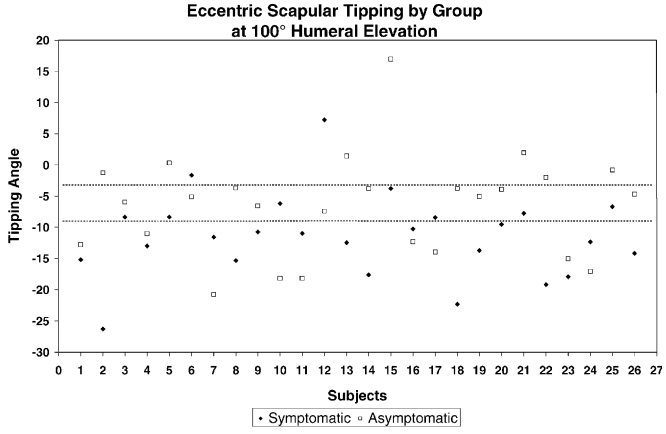

Fig. 4. Eccentric phase scapular tipping by group at 100° of humeral elevation. Negative values indicate anterior tipping. Dotted lines represent upper and lower 95% confidence limits of the mean of the asymptomatic group. Upper limit = −3.508; Lower limit = −9.768 ($n = 26$ subjects per group).

symptomatic subject's data values lie outside the confidence limits in the posterior tipping direction. Data values from the asymptomatic group are more equally distributed above and below the mean. The symptomatic group also demonstrated a greater percentage (57.7%) of subject data values with anterior tipping angles outside

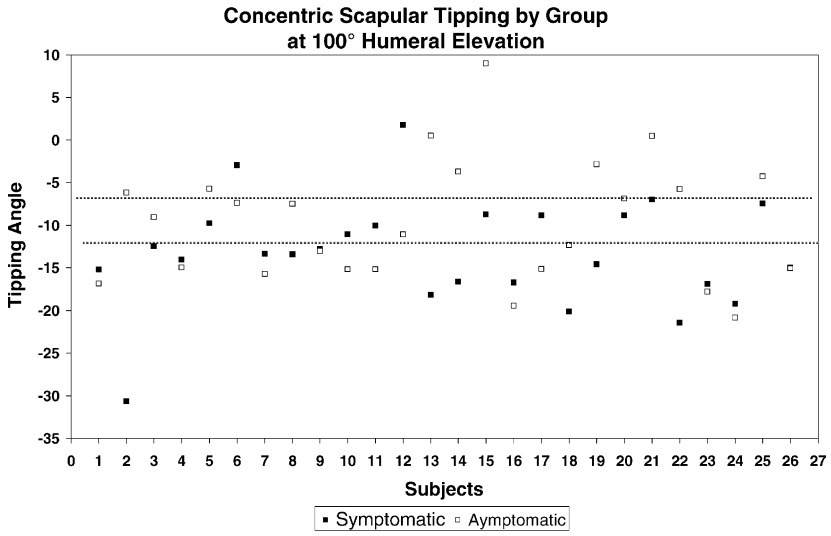

Fig. 5. Concentric phase scapular tipping by group at 100° of humeral elevation. Negative values indicate anterior tipping. Dotted lines represent upper and lower 95% confidence limits of the mean of the asymptomatic group. Upper limit = −6.948; Lower limit = −12.427 ($n = 26$ subjects per group).

the 95% confidence limit during the concentric phase than with posterior tipping angles outside this limit (7.7%) (Fig. 5).

4. Discussion

The results of this analysis show no significant differences in scapular position during the eccentric phase of humeral elevation as compared to the concentric phase for any scapular variable at humeral elevation angles below 80°, for internal rotation below 100°, or for upward rotation at any humeral angle. Where small but statistically significant differences during the eccentric phase were found, these phase effects were not significantly greater in the symptomatic group except at the 120° humeral angle for scapular internal rotation. Tendencies for the group differences to be magnified in the eccentric phase were present in the data (Figs. 2 and 3), but they did not generally reach statistical significance. These findings were minimally supportive of the hypothesis that the symptomatic group would show greater phase effects than the healthy group.

Surprisingly, it was found that scapular anterior tipping actually decreased slightly for all subjects at higher elevation angles during lowering of the arm. In fact, all significant differences discovered in this analysis occurred at higher humeral angles, as opposed to lower humeral angles, where scapular winging is more often observed clinically and where kinematic differences were expected. A recent bone pin based tracking investigation [29] demonstrated similarly small differences in scapular tipping at higher elevation angles during the eccentric phase of scapular plane abduction in eight healthy subjects, although statistical comparisons were not made. There has been no previous 3-D analysis of the eccentric phase of arm elevation in symptomatic subjects for direct comparison of the present findings.

One possible explanation for not finding the expected movement patterns in the symptomatic group may be the chronicity of their condition. Initial onset of symptoms for this group was reported to have been an average of 5.5 years prior to the analysis. All subjects also reported continuing to work overhead with pain, and only one symptomatic subject had less than 150° of active elevation range of motion. Shoulder pain and disability scale scores indicated low levels of pain impairment in symptomatic subjects. It is possible that the modified kinematic motion patterns noted above 80° would not be similar in subjects with more acute pain symptoms, or subjects without routine exposure to overhead work activities.

There is the possibility that due to the consistent use of the upper extremities in elevated positions by both the healthy and symptomatic groups, all subjects analyzed have developed similar types of kinematic patterns. With repeated exposure, similar muscle strength and soft tissue imbalances around the shoulder may develop and lead to altered kinematics by healthy subjects as well as impingement symptom subjects. As this study evaluated scapular motion patterns in male construction workers with a high percentage of time spent working with their hands at or above shoulder level, generalizing the results to other populations is not recommended without data confirming similar motion patterns.

Past studies have demonstrated that glenohumeral motion is altered in both symptomatic and asymptomatic individuals with rotator cuff tears compared to controls [30,31]. These authors discovered a significant increase in superior translation of the humeral head on

the glenoid, and trends toward but no statistically significant glenohumeral to scapulothoracic ratio alterations during active scapular plane abduction. In the current study, it is possible that undiagnosed rotator cuff tears are present in both groups, with resultant kinematic changes occurring in both groups as well. This possibility, as well as the various anatomical and other factors that can contribute to a diagnosis of shoulder impingement, contribute to the between subject variability in our investigation. However, the presence of significant differences between symptomatic and asymptomatic construction workers demonstrated previously [3] suggests that in this sample, symptomatic subjects have differences in kinematics compared to asymptomatic subjects regardless of specific underlying pathologies. The discovery of phase differences in such a sample might therefore lead to more refined rehabilitation strategies.

It is also possible that scapular winging during the eccentric phase, visually observed in some subjects clinically, occurs in a subpopulation of patients not well represented by the sample tested in this investigation. This scapular winging phenomenon is not observed in all clinical patients and no quantification of frequency of occurrence relative to patient characteristics has been presented in the literature. This possibility of subgroups is confounded by the limitations of a clinical examination to classify patients. As mentioned in the patient selection criteria, no attempt was made to group symptomatic subjects into subcategories of impingement, and although clusters of clinical tests can have high sensitivities and specificities, they are not 100% specific. Multiple possible underlying etiologies of subject's shoulder pain add to the between subject variability. Optimally, if precise diagnostic imaging were available, adding these classifications into the analysis may have provided further insight into the type of patient that develops scapular kinematic alterations.

The post-hoc analysis attempted to address the possibility of subgroups with regard to between group differences. However, only one symptomatic individual's data was beyond the limits of the mean plus 2 standard deviations, in the anterior tipping direction (Fig. 4). Conversely, one asymptomatic subject's data was beyond this 2 standard deviation limit in the posterior tipping direction. The same two subjects were noted to be outliers during the concentric phase. There were no obvious demographic or physical examination variables distinguishing the two outliers from the other subjects.

The question that remains, even if subgroups are detectable, is one of cause and effect. We may find that patients with partial rotator cuff tears have the more seriously impaired scapular kinematics, but cannot be certain whether the altered pattern caused the tear, or whether the tear created the need for an altered pattern in order for the individual to remain functional. Although subjects in this analysis experienced minimal pain during shoulder movements without external resistance, this same question of cause and effect arises concerning the impact of shoulder pain on kinematics. Our primary objective, however, was an attempt to discover if differences exist in the phases of arm elevation, and our results indicate that small but statistically significant differences were present for scapular tipping and internal rotation at higher humeral elevation angles.

As with other 3-D analyses using skin sensors to measure underlying bone movement, there is the introduction of measurement error due to skin slippage over the bone [24]. The magnitude of this type of error becomes greater at humeral elevation angles beyond 120° due to increased deltoid encroachment on the scapular sensor. Past investigation indicates skin slip errors create an offset in the data consistent across subjects [24]; for example, average surface sensor values for scapular upward rotation are approximately 6° higher than true values at 80° of humeral elevation. However, these differences occur between two differing measurement techniques. In the current study, the same measurement technique is used to compare subjects to themselves between the elevation and lowering portions of the motion. If skin slip error differed systematically between the elevation and lowering conditions, it could possibly contribute to the phase differences identified. However, there is currently no evidence in the literature of such phase related skin slip differences. Further, our limitation of data analysis to humeral angles at or below 120° reduces the impact of greater errors at higher elevation angles.

Because of the repeated measures component of the study, with subjects compared to themselves under varying test conditions, trial to trial variability is the most relevant source of error in the current investigation. To be meaningful, average differences between conditions need to be greater than the variability between trials. While significant differences between the eccentric and concentric phase were present in our analysis, significant differences were not found between trials. Standard deviations between trials for data from individual subjects ranged from 1° to 2°. If only one subject were tested, phase differences would have to be greater than these standard deviations to be statistically meaningful. However, with a reasonable sample size and random distribution of trial-to-trial error, no difference between trial means results. The within subject standard error of the mean, which averaged 0.5°, indicates the uncertainty associated with the sample mean as an estimate of the true phase specific value.

Between subject variability, which is higher than within subject trial-to-trial variability, relates to the ability to determine between group differences. Group differences were not the focus of the current investigation, however, standard deviations between subjects

ranged from 5° to 11° at specific humeral angles, which resulted in the higher standard errors of the mean for between group comparisons. Figs. 4 and 5 both illustrate the separation between group distributions during the two phases of motion. Generally, the limitation of all of these sources of error and variability is greater difficulty in identifying differences between groups and conditions, rather than creation of systematic differences.

Because the statistically significant differences found in this analysis are small, the question of whether they are clinically meaningful must be considered. Clinical significance of the data is based in part on the magnitude of the differences relative to the magnitude of total motion. The significant differences between phases in this analysis range from 17% to 26% of the total change for internal rotation, to essentially 100% of the total change for tipping. Therefore, although the magnitudes of the differences are small, their clinical significance may be potentially substantial. To ultimately determine if these magnitudes of change are meaningful, analysis of their effect on both the subacromial space and on the development of impingement must be performed.

In a 3-D study comparing the acromiohumeral interval at elevated arm positions between symptomatic and asymptomatic shoulders of subjects with impingement symptoms, Graichen et al. [32] have demonstrated that small position differences can result in substantial percentage reductions in the available subacromial space. A 3 mm smaller average acromiohumeral interval resulted in a 68% average reduction in the available subacromial space. Zuckerman et al. [33] have related 23% reductions in the available supraspinatus outlet to rotator cuff tears in cadaver specimens. It seems likely that even small decreases in the available subacromial space may initiate or exacerbate shoulder impingement symptoms. The change for scapular internal rotation between the concentric and eccentric phase in this investigation was in a direction believed to reduce the available subacromial space. However, the change in scapular tipping between phases was in a direction believed to increase the available subacromial space. Therefore any net effect on the subacromial space in the eccentric phase identified in these subjects was likely inconsequential.

Future investigations analyzing lower humeral elevation angles or larger magnitudes of group differences may not require consideration of the lowering phase of humeral motion. However, we believe that the results of this analysis support consideration of both the raising and lowering phases in some cases where complete analyses of scapular kinematics in shoulder impingement patients where higher elevation angles are of primary interest. For instance, comparison of scapular tipping between groups at the 100° humeral angle demonstrated kinematic group differences of 3.5° for the concentric phase only, but 4.8° for the eccentric phase, with symptomatic subjects showing greater anterior tipping, thus negatively impacting the available subacromial space.

A final limitation in interpreting the results of this analysis is a lack of clavicular data during the motion. The present analysis demonstrated scapular angular orientation changes relative to the thorax during the eccentric phase at higher humeral angles. Scapular patterns of motion and clavicular patterns of motion are intimately related. Observations of altered scapular kinematics may indicate altered clavicular motion, possibly resulting from changes in sternoclavicular joint, acromioclavicular joint, or combined SC/AC joint motion. These potential influences on scapular kinematics and clinical management of shoulder pathology cannot be addressed without accurate clavicular kinematic data.

5. Conclusion

We conclude that there are subtle yet statistically significant differences in scapular kinematics between the eccentric and concentric phases of scapular plane abduction when considering scapular tipping and internal rotation at angles above 80° of humeral elevation only. There were no differences in scapular upward/downward rotation between the two phases, or significant phase effects for any scapular variables at lower elevation angels. Contrary to our hypothesis, with the exception of scapular internal rotation at the 120° humeral angle, no consistent differential effects of phase were observed when analyzing subjects with shoulder impingement symptoms versus those without impingement. Depending on the goals of the investigation, scapular kinematics during both the concentric and eccentric phases may be beneficial to consider for a complete description of shoulder kinematics during humeral motion. Given the previously noted clinical observations and subjective reports from subjects, we believe that the kinematics of the shoulder complex during lowering of the arm deserve further analysis in other subject populations in order to optimize shoulder rehabilitation strategies.

Acknowledgements

This research was supported in part by the Center to Protect Worker's Rights, the Public Health Service and the University of Iowa under Public Health Service Grant no. U60/CCU317202. Its contents are solely the responsibility of the authors and do not necessarily represent the official view of the Center to Protect Worker's Rights, the Public Health Service, or The University of Iowa.

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