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Research Report

Alterations in Shoulder Kinematics and Associated Muscle Activity in People With Symptoms of Shoulder Impingement

Background and Purpose. Treatment of patients with impingement symptoms commonly includes exercises intended to restore "normal" movement patterns. Evidence that indicates the existence of abnormal patterns in people with shoulder pain is limited. The purpose of this investigation was to analyze glenohumeral and scapulothoracic kinematics and associated scapulothoracic muscle activity in a group of subjects with symptoms of shoulder impingement relative to a group of subjects without symptoms of shoulder impingement matched for occupational exposure to overhead work. Subjects. Fifty-two subjects were recruited from a population of construction workers with routine exposure to overhead work. Methods. Surface electromyographic data were collected from the upper and lower parts of the trapezius muscle and from the serratus anterior muscle. Electromagnetic sensors simultaneously tracked 3-dimensional motion of the trunk, scapula, and humerus during humeral elevation in the scapular plane in 3 hand-held load conditions: (1) no load, (2) 2.3-kg load, and (3) 4.6-kg load. An analysis of variance model was used to test for group and load effects for 3 phases of motion (31°–60°, 61°–90°, and 91°–120°). Results. Relative to the group without impingement, the group with impingement showed decreased scapular upward rotation at the end of the first of the 3 phases of interest, increased anterior tipping at the end of the third phase of interest, and increased scapular medial rotation under the load conditions. At the same time, upper and lower trapezius muscle electromyographic activity increased in the group with impingement as compared with the group without impingement in the final 2 phases, although the upper trapezius muscle changes were apparent only during the 4.6-kg load condition. The serratus anterior muscle demonstrated decreased activity in the group with impingement across all loads and phases. Conclusion and Discussion. Scapular tipping (rotation about a medial to lateral axis) and serratus anterior muscle function are important to consider in the rehabilitation of patients with symptoms of shoulder impingement related to occupational exposure to overhead work. [Ludewig PM, Cook TM. Alterations in shoulder kinematics and associated muscle activity in people with symptoms of shoulder impingement. *Phys Ther.* 2000;80:276–291.]

Key Words: *Biomechanics, Electromyography, Shoulder impingement, Shoulder kinematics.*

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Shoulder impingement has been defined as compression and mechanical abrasion of the rotator cuff structures as they pass beneath the coracoacromial arch during elevation of the arm.[1,2] Rotator cuff problems are thought to account for nearly one third of physician visits for shoulder pain complaints.[1] The vast majority of people with impingement syndrome who are younger than 60 years of age relate their symptoms to occupational or athletic activities that involve frequent overhead use of the arm.[1] Epidemiologic investigations[3–7] have revealed a high prevalence (16%–40%) of shoulder complaints consistent with impingement in certain occupations, including assembly-line workers, welders, steelworkers, and construction workers. Frequent or sustained shoulder elevation at or above 60 degrees in any plane during occupational tasks has been identified as a risk factor for the development of shoulder tendinitis or nonspecific shoulder pain.[3,8,9] Evidence relating occupational exposure of frequent or sustained shoulder elevation to shoulder musculoskeletal symptoms is strongest for combined exposure to multiple physical factors, such as holding a tool while working overhead.[9]

Multiple theories exist as to the primary etiology of shoulder impingement, including anatomic abnormalities of the coracoacromial arch or humeral head[10,11]; "tension overload," ischemia, or degeneration of the rotator cuff tendons[12–14]; and shoulder kinematic abnormalities.[15,16] Regardless of the initial etiology, inflammation in the suprahumeral space, inhibition of the rotator cuff muscles, damage to the rotator cuff tendons, and altered kinematics are believed to exacerbate the condition.[1,17] Impingement is thought to be due to inadequate space for clearance of the rotator cuff tendons as the arm is elevated.[1,10,15] Therefore, factors that further minimize this space are believed to be detrimental to the condition.

Kinematic changes have been thought to be present in people with symptoms of impingement and to result in further decreases in the available supraspinatus muscle

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This study was approved by The University of Iowa Human Subjects Institutional Review Board.

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outlet or suprahumeral space.[15,17–19] Motions that bring the greater tuberosity in closer contact with the coracoacromial arch[20] are particularly problematic. These motions include excessive superior or anterior translations of the humeral head on the glenoid fossa, inadequate lateral (external) rotation of the humerus, and decreases in the normal scapular upward rotation and posterior tipping on the thorax, all occurring during humeral elevation. These kinematic changes have all been purported to occur in patients with symptoms of impingement.[15,17–20] Additionally, the hypothesized kinematic alterations in scapular motion have been linked to decreases in serratus anterior muscle activity, increases in upper trapezius muscle activity, or an imbalance of forces between the upper and lower parts of the trapezius muscle.[17,19,21]

Evidence to support the existence of abnormal electromyographic (EMG) or kinematic patterns in people with shoulder pain is limited. Investigations of altered scapulothoracic EMG patterns in patient populations have been nonspecific regarding subject diagnoses or restricted to testing of athletic activities.[22–24] Use of 2-dimensional (2-D) radiographic and fluoroscopic techniques has shown abnormal shoulder kinematics in some subjects with impingement during humeral elevation.[25,26] The results of these analyses are difficult to interpret, however, because a variety of diagnoses exist in these patients. More recently, Lukasiewicz et al[27] quantified 3-dimensional (3-D) scapular orientation at static positions of arm elevation in the scapular plane by comparing subjects with and without impingement syndrome. Subjects with impingement syndrome demonstrated less (approximately 8°–9°) posterior (backward) tipping of the scapula at 90 degrees and at maximal elevation as compared with subjects without impingement. Additionally, scapulothoracic asymmetry or "abnormal moiré patterns" during eccentric shoulder flexion with a 4.5-kg load in each hand were reported in a small sample of subjects with impingement syndrome.[28]

Conservative treatment of patients with impingement symptoms commonly includes exercise programs intended to restore "normal" kinematics or muscle activity patterns.[16,17,19,29–31] In particular, the muscular control of the scapula has become a recent focus of therapeutic intervention.[17,19] Due to limited scientific data from which to design exercise programs, these programs often vary widely.[16,17,19,30,31] Although previous investigations have provided important contributions, they are often constrained by static analysis,[25,27] 2-D analysis,[25,26] varied patient diagnoses,[24,25] a lack of control for exposure to overhead activity between subjects with and without symptoms of impingement,[24–28] small sample sizes,[22,25,26,28] or other methodologic limitations.[22–24,28]

The purpose of our study was to provide a 3-D analysis of both glenohumeral and scapulothoracic kinematics and associated scapulothoracic muscle activity in subjects with symptoms of shoulder impingement relative to subjects without shoulder impairment who were matched for occupational exposure to overhead work. In our study, we assessed both kinematic and EMG factors believed to be related to impingement. Our first hypothesis was that subjects with symptoms of shoulder impingement would have decreased scapular upward rotation, scapular posterior tipping, and humeral lateral rotation, as well as increased scapular medial (internal) rotation during humeral elevation. Our second hypothesis was that subjects with symptoms of shoulder impingement would have increased upper trapezius muscle EMG activity and decreased lower trapezius and serratus anterior muscle EMG activity during humeral elevation. Our third hypothesis was these differences would be consistent across all phases of the painful arc of humeral elevation in the scapular plane (60°–120°) (there would be no interaction of group and phase effects). In addition, occupational exposure to holding a tool while working overhead has been more strongly related to shoulder musculoskeletal symptoms than exposure to overhead work alone.[9] The effects of hand-held loads (additional weight held in the hand while elevating the arm) were also examined. Our fourth hypothesis was that kinematic differences among subjects would be greater under higher load conditions (there would be an interaction of group and load conditions).

Method

Subjects

The population of interest in this study was people whose occupation involved routine exposure to work tasks requiring their upper arms to be at or above shoulder level. Volunteers were recruited through mailings to workers and announcements at union meetings from a population of construction workers in the sheet metal and carpentry trades. This population was of particular interest because of their increased risk for developing shoulder problems.[3,8,9] In addition, we believe that people who do not engage in overhead activities, even though they might not have symptoms of shoulder impingement, may demonstrate abnormal kinematic patterns that could contribute to the development of shoulder impingement if they routinely used their arms in elevated positions. We believed that equal occupational exposure between the 2 groups would improve the potential to detect kinematic or muscle activity differences.

The experimental group was limited to people who had (1) a history of shoulder pain of greater than 1 week in

Table 1.
Subject Demographics

Variable	Subjects Without Shoulder Impairment (n=26)			Subjects With Shoulder Impingement (n=26)		
	$\bar{X}$	SD	Range	$\bar{X}$	SD	Range
Age (y)	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 (y)[a]	18.1	13.5	2.0–43.5	16.7	12.5	3–42
Average weeks worked per year[a]	48.0	6.5	26–52	47.0	7.6	20–52
Average hours worked per week[a]	42.2	6.6	35–65	41.9	4.7	40–60
Time working overhead (%)[a]	37.2	20.6	7.5–80	37.8	20.4	5–75
SPADI[b] pain scores				27.8	16.2	3.2–68.8
SPADI disability scores				19.5	16.8	0.9–65.1
SPADI total scores				23.6	15.4	6.3–67

[a] Subject self-reports.
[b] Shoulder Pain and Disability Index.

duration, localized to the proximal anterolateral shoulder region, (2) a positive impingement sign,[2,32] a painful arc of movement (60°–120°),[33] 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 degrees relative to the trunk. Subjects were excluded from the experimental group if any of the following were found during an examination: (1) reproduction of symptoms during a cervical screening examination (active and resisted range of motion [ROM], overpressure, quadrant test),[34] (2) abnormal results on thoracic outlet tests (Allen, Adson, Halstead),[35] (3) numbness or tingling in the upper extremity, or (4) a history of onset of symptoms due to traumatic injury, glenohumeral or acromioclavicular (AC) joint dislocation, or surgery on the shoulder. There is a lack of reliability data regarding cervical and thoracic outlet tests. Exclusion criteria for the comparison group included: (1) employment in an occupation involving overhead work for less than 1 year (possible inadequate exposure), (2) less than 150 degrees of glenohumeral flexion or abduction ROM at the shoulder, or visual observation of medial/lateral rotation ROM of less than normal limits, or (3) a history of pain, trauma, or dislocation of the glenohumeral or AC joints. The first author (PML) performed all assessments for inclusion and exclusion criteria.

Prior to initiating the study, a sample size of 25 subjects per group was calculated to provide 80% power to detect differences of 5 degrees or 10% of maximal voluntary contraction (MVC) between the 2 groups of interest.[36] Calculations were based on our judgment of what are clinically meaningful differences and variability estimates from previous studies on subjects without shoulder impairment.[25,37,38] Fifty-two construction worker volunteers—31 sheet metal workers and 21 carpenters (26 subjects per group)—met the inclusion and exclusion criteria of the investigation. Subjects with symptoms of shoulder impingement completed the Shoulder Pain and Disability Index (SPADI).[39] This shoulder questionnaire consists of 2 subscales: a pain subscale and a disability subscale. Scores on the SPADI can range from 0 to 100, with higher scores indicating worse function. The SPADI scores and demographic characteristics of the subjects are presented in Table 1. There were no differences between the groups for any of the demographic or work exposure variables (2-sample *t* tests). All subjects were male. The subjects with shoulder impingement reported the initial onset of symptoms as having been an average of 5.5 years (SD=3.2, range=0.6–10) previous to this investigation. Three of the subjects reported continual symptoms since onset, with the remainder reporting symptoms to be episodic. All subjects continued to work with pain. All subjects read and signed university-approved informed consent documents for human subjects prior to participation.

Instrumentation

Electromyographic data were collected with differential preamplified silver-silver chloride surface electrode assemblies.* These assemblies provide an interelectrode distance of 20 mm with 8-mm-diameter active electrodes and an on-site gain of 35. Signals were further amplified with GCS 67 amplifier* with a high input impedance (greater than 15 Ω at 100 Hz), a common mode rejection ratio of 87 dB at 60 Hz, and a bandwidth (−3 dB) of 40 to 4,000 Hz. Root mean square (RMS)-processed (25-millisecond time constant) signals were collected online with a microcomputer at a sampling rate of 300

* Therapeutics Unlimited, 2835 Friendship St, Iowa City, IA 52245.

Hz using a 12-bit A/D board (Dash 16F[†]). Raw signals were also monitored on an oscilloscope (Hitachi V-1100A[‡]) throughout data collection in order to verify signal quality.

The 3-D position and orientation of each subject's thorax, scapula, and humerus were tracked (40-Hz sampling rate) using the Polhemus FASTRAK electromagnetic motion capture system.[§40,41] The sensors were small and lightweight (2.3 × 2.8 × 1.5 cm, 17-g mass), and an additional sensor attached to a stylus was used to manually digitize palpated anatomical coordinates. Within a 76-cm source-to-sensor separation, the RMS system accuracy is 0.15 degree for orientation and 0.3 to 0.8 mm for position.[41–44] This system has been used frequently in shoulder biomechanics research.[37,45–49] Pilot testing with the FASTRAK system on and off was done with 5 subjects to determine the separation between the FASTRAK transmitter and EMG surface electrodes necessary to prevent electromagnetic artifact in the EMG signal. For all subjects, who maintained a 20.3-cm (8-in) minimum separation during testing, no electromagnetic artifact was detectable in the RMS magnitude or spectral analysis of the EMG signals.

Experimental Procedure

Surface electrodes were placed over the upper trapezius muscle (two thirds of the distance from the spinous process of the seventh cervical vertebra to the acromial process),[50] the lower trapezius muscle (one fourth of the distance from the thoracic spine to the inferior angle of the scapula when the arm was fully flexed in the sagittal plane),[51] and the lower serratus anterior muscle (over the muscle fibers anterior to the latissimus dorsi muscle when the arm was flexed 90° in the sagittal plane)[52] (Fig. 1A). A reference electrode was placed on the distal ulna of the left wrist.

Verification of signal quality was completed for each muscle by having the subject perform a resisted contraction in manual muscle test positions specific to each muscle of interest.[53] As a normalization reference, EMG data were collected during MVCs for each of these muscles with the arm in 75 degrees of humeral elevation relative to the trunk. This humeral position was the midpoint of the ROM analyzed (30°–120°). Data were sampled for two 3-second trials during manually resisted maximal contractions for each muscle. The highest value (averaged over 500 milliseconds) was used as the normalization reference. For the upper trapezius muscle contractions, the subject was seated and resistance was applied to abduction of the arm in the scapular plane.[54] Schuldt and Harms-Ringdahl[54] found this position to be superior to shoulder elevation in activating the upper fibers of the trapezius muscle. Serratus anterior and lower trapezius muscle contractions were performed in manual muscle test positions as described by Kendall and Kendall,[53] with the modification of the 75-degree humeral elevation position noted earlier. For the serratus anterior muscle, the subject was seated and resistance was applied to a forward thrust of the arm and protraction of the scapula.[53] For the lower trapezius muscle, the subject was prone and resistance was applied to the forearm downward toward the table.[53]

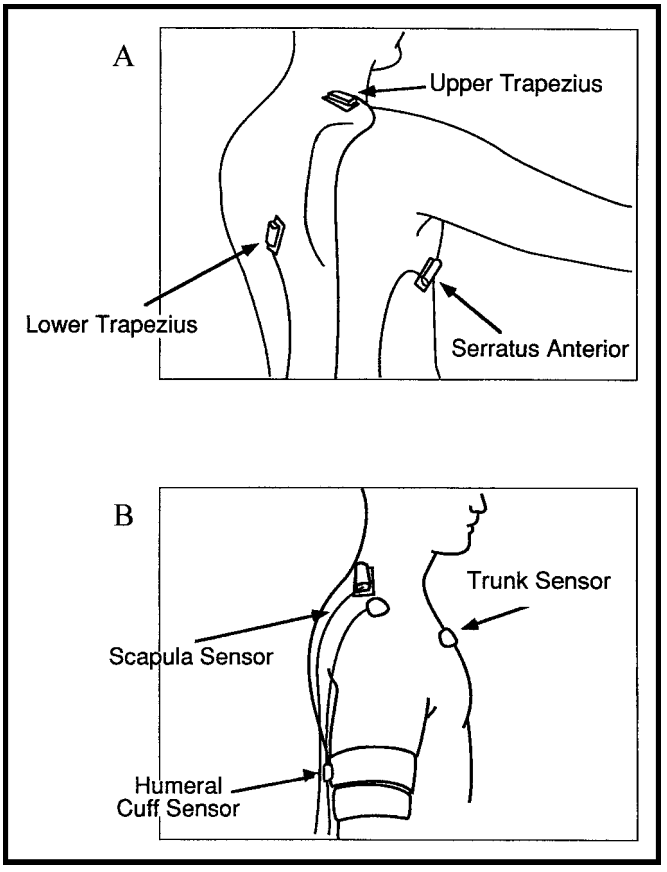

Figure 1.
(A) Surface electromyographic electrode placements, (B) electromagnetic sensor placements.

The FASTRAK sensors were attached with adhesive tape to the sternum and to the skin overlying the flat superior bony surface of the scapular acromial process. A third sensor was attached to a thermoplastic cuff secured to the distal humerus with Velcro straps[‖] (Fig. 1B). These surface sensor placements have been used previously and validated for measurement of scapular upward rotation to 2-D radiographic measurement of in vivo glenohumeral elevation (r^2=.94).[37] Further testing has compared similar surface sensor measurement of scapu-

[†] Keithly MetraByte, 28775 Aurora Rd, Cleveland, OH 44139.
[‡] Hitachi Denshi America Ltd, 150 Crossways Park Dr, Woodbury, NY 11797.
[§] Polhemus Inc, 1 Hercules Dr, PO Box 560, Colchester, VT 05446.
[‖] Velcro USA Inc, 406 Brown Ave, Manchester, NH 03108.

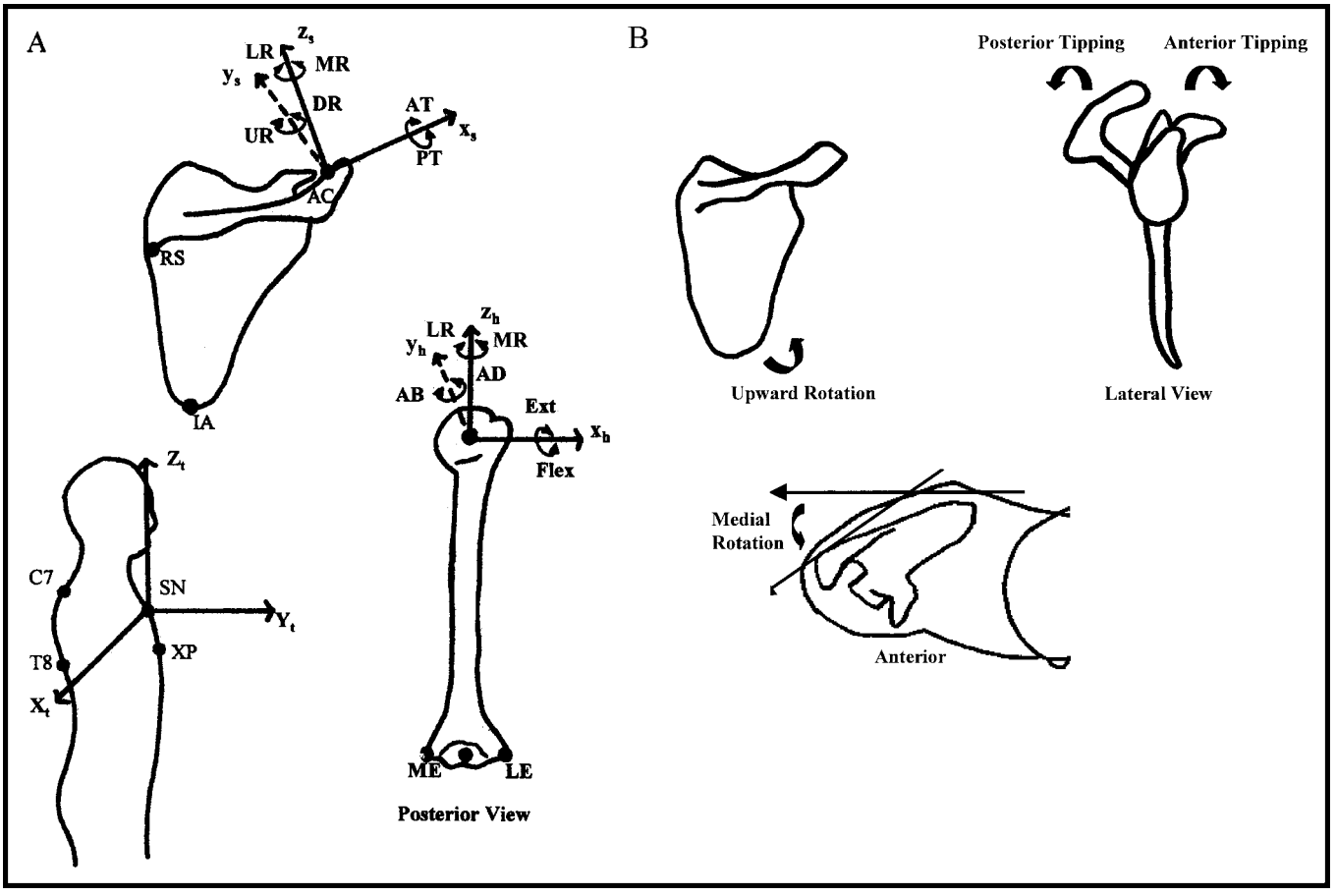

Figure 2.
(A) Local coordinate systems for the thorax, scapula, and humerus. C7=spinous process of the 7th cervical vertebra, T8=spinous process of the 8th thoracic vertebra, XP=xiphoid process, SN=suprasternal notch, RS=root of the spine of the scapula, IA=inferior angle of the scapula, AC=acromioclavicular joint, MR/LR=medial rotation/lateral rotation, DR/UR=downward rotation/upward rotation, PT/AT=posterior tipping/anterior tipping, ME=medial epicondyle, LE=lateral epicondyle, AD/AB=adduction/abduction, Flex/Ext=flexion/extension. Trunk axes are aligned with the cardinal planes. X_t is directed laterally, Y_t is directed anteriorly, and Z_t is directed superiorly. X_s is directed laterally from RS to AC, Y_s is directed anteriorly perpendicular to the plane of the scapula, Z_s is directed superiorly perpendicular to X_s and Y_s, Z_h is directed superiorly parallel to the long axis of the humerus, Y_h is directed anteriorly perpendicular to the plane formed by Z_h and a line from ME to LE, and X_h is directed laterally perpendicular to Z_h and Y_h. (B) Scapular motions.

lar motion during arm elevation to sensors fixed to pins embedded in the underlying bones (AR Karduna and colleagues, unpublished research, 1999). In a sample of 8 subjects, average surface measurements of posterior tipping (backward rotation about a medial to lateral scapular axis) at 60, 90, and 120 degrees of scapular-plane elevation were within 2 degrees of average measurements from bone-fixed sensors. Additionally, tracking of humeral movement by the humeral cuff sensor was validated on a subject with an external humeral fixator. The surface-mounted sensor closely represented the underlying angular movements of the bone (3° RMS error).[55]

While subjects stood with their arms relaxed at their sides, bony landmarks on the thorax, scapula, and humerus were palpated and digitized to allow transformation of the sensor data to local anatomically based coordinate systems (Fig. 2A). Kinematic and EMG data were then collected for 5 seconds in this resting standing posture. Humeral elevation in the scapular plane was matched to a metronome at one complete cycle every 4 seconds and guided to remain in this plane by a flat surface oriented 40 degrees anterior to the coronal plane.[38,56] Once the subjects were able to control the speed of motion in the appropriate plane, synchronized kinematic and EMG data from 5 repetitions of scapular-plane humeral elevation were collected under conditions of no external handheld load and with handheld loads of 2.3 and 4.6 kg (5 and 10 lb). The order of loading conditions was randomized between subjects. These load values were selected to represent a range of handheld loads that might reasonably be imposed on a construction worker from power tools or objects to be lifted overhead. Subjects were given approximately 2 to 3 minutes of rest between practice and test conditions. All

Table 2.
Within-Day Trial-to-Trial Reliability: Intraclass Correlation Coefficients (Type 2,1)[61] for Load and Phase Conditions

	Load Condition								
	No Load			2.3 kg			4.6 kg		
	31°–60°	61°–90°	91°–120°	31°–60°	61°–90°	91°–120°	31°–60°	61°–90°	91°–120°
Scapular upward rotation	.93	.93	.97	.94	.94	.98	.95	.96	.97
Scapular tipping	.98	.98	.97	.97	.97	.97	.96	.97	.97
Scapular medial rotation	.96	.97	.98	.97	.96	.98	.96	.97	.98
Humeral lateral rotation	.97	.97	.98	.97	.97	.97	.97	.98	.98
Upper trapezius muscle EMG[a]	.81	.85	.85	.78	.79	.81	.88	.84	.78
Lower trapezius muscle EMG	.84	.82	.90	.83	.82	.88	.83	.86	.82
Serratus anterior muscle EMG	.73	.73	.83	.84	.89	.83	.81	.83	.86

[a] EMG=electromyographic activity.

subjects were queried regarding the need for additional rest to prevent fatigue; however, no subjects required additional time. The dominant shoulder was tested for all subjects. Sensors were not removed and replaced between trials. Five subjects returned the day after their initial testing for repeat testing using the same protocol.

Data Reduction

Raw kinematic data were low-pass filtered (fourth-order zero-phase shift) at a 4.7-Hz cutoff frequency.[57] Absolute sensor orientation data were transformed to describe relative positions of the local coordinate systems for each segment. These local coordinate systems are defined in the Appendix and depicted in Figure 2A.[58] These coordinate systems allowed the sensors to be placed in locations where skin motion artifact was minimized. Sensor orientation was then mathematically rotated to be aligned with anatomically based and clinically meaningful axis systems. Generally, 2 of the anatomical landmarks defined the first anatomical axis, the combined 3 or 4 points from a segment defined a plane perpendicular to which a second axis was aligned, and the third axis was aligned perpendicular to the first 2 axes. A series of matrix transformations[59] produced a set of 4×4 matrices describing the position and orientation of the scapula and humerus.

Scapular orientation relative to the trunk was subsequently described as rotation about Z_s (medial/lateral rotation), rotation about Y'_s (downward /upward rotation), and rotation about X''_s (posterior/anterior tipping) (z, y′, x″ Cardan angles, Fig. 2). Humeral orientation relative to the thorax was described as rotation about z_h (plane of elevation), rotation about y'_h (elevation angle), and rotation about z''_h (axial rotation) (z, y′, z″ Euler angles, Fig. 2). Humeral orientation relative to the scapula was described as rotation about y_h (adduction/abduction), rotation about x'_h (flexion/extension) and rotation about z''_h (medial/lateral rotation) (y, x′, z″ Cardan angles, Fig. 2).

For EMG data, minimum values (averaged over 500 milliseconds) were determined during the resting standing posture, and RMS averages were determined for each trial and phase of motion. After subtraction of the minimum rest values, average motion values were expressed as a percentage of the MVC value (motion values are divided by MVC values and multiplied by 100).[60] This process creates a percentage of MVC value for each phase of motion that represents the activity level beyond the resting standing posture. For all kinematic and EMG variables, data from the middle 3 of the 5 collected motion trials were used in subsequent analyses.

Data Analysis

Intraclass correlation coefficients (ICC [2,1])[61] were used to establish the trial-to-trial reliability of the kinematic and EMG measurements. Between-day repeatability analysis compared subjects' values for the same phase and load condition over the 2 days and determined the within-subjects standard error of the mean. The experimental study design used a 3-factor analysis of variance (ANOVA) model with factors of group (subjects with shoulder impingement or subjects without shoulder impingement), load (0-, 2.3-, or 4.6-kg handheld load), and phase of movement (31°–60°, 61°–90°, and 91°–120° of humeral elevation in the scapular plane). These phases were of interest as they comprise the arc of motion where impingement is believed to occur.[20] After reliability testing, the remaining analyses used the mean of the 3 trials for each subject and condition. The dependent variables included all 3 angular variables for

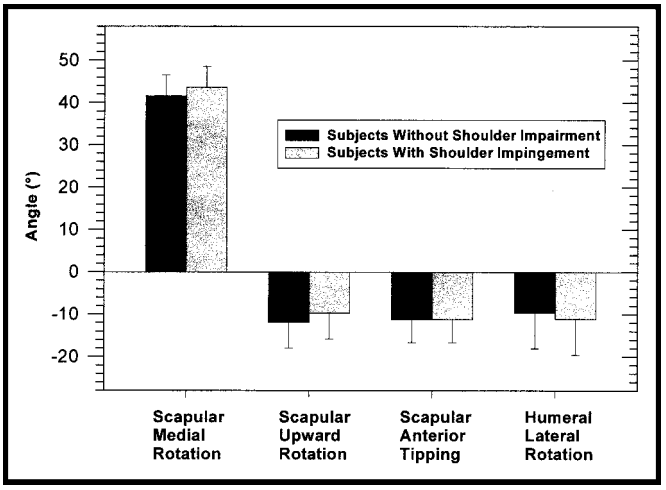

Figure 3.
Scapular position relative to the trunk and humeral position relative to the scapula (standing "rest" position). Positive values indicate medial rotation, downward rotation, and posterior tipping. Negative values indicate lateral rotation, upward rotation, and anterior tipping.

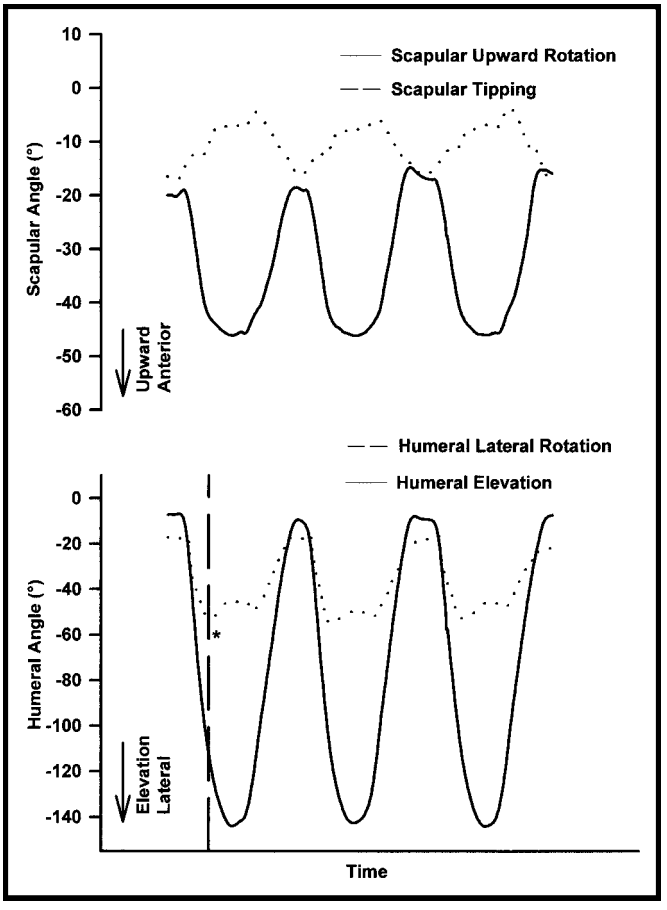

Figure 4.
Data for representative subject without shoulder impairment (one subject). Asterisk (*) indicates peak lateral rotation.

scapular orientation, as well as humeral lateral rotation relative to the scapula assessed as the position (last data point) at the completion of each phase and average normalized RMS amplitudes of each of the 3 selected scapular muscles throughout each phase. Several anthropometric, demographic, and exposure variables were considered as possible covariates using analysis of covariance, including age, number of years of exposure to the trade, percentage of time working overhead, and body weight. However, none of these covariates influenced the results of the analysis, and they were not retained in the final model. A significance level of .05 was used to test effects on each dependent variable. Tukey follow-up analyses were used to adjust for multiple pair-wise comparisons where appropriate. Interaction effects were tested first to determine any potential influence on group effects. For hypotheses 1 and 2, in the presence of an interaction, group differences were tested at each level of the interacting variable. In the absence of interactions, main effects of group (collapsed across load and phase) were of interest. For hypotheses 3 and 4, interaction effects of group and phase and of group and load, respectively, were of interest.

Results

Trial-to-trial ICC values for the dependent variables under each test condition are provided in Table 2. For the subset of 5 subjects, the standard error of the mean for between-day comparisons of all angular variables was 2.5 degrees or less for 70% of phase and load conditions and 3.3 degrees or less for all phase and load conditions. Data from the relaxed standing position for average scapular position relative to the trunk and the humeral position relative to the scapula (Fig. 3) did not differ between groups ($P>.10$, 2-sample t test). Scapular orientation angles represent the angles of the scapula relative to the cardinal planes of the trunk. For example, the scapular medial rotation angle is the angle of the scapular plane relative to the coronal or frontal plane.

Representative kinematic data from a subject in the comparison group during unloaded motion are presented in Figure 4. Although there was substantial variability among subjects, the general pattern in this group was for the scapula to upwardly rotate and move toward a less anteriorly tipped position as the arm was abducted in the scapular plane. Simultaneously, the humerus was laterally rotating relative to the scapula throughout most of the motion, with peak lateral rotation generally occurring between 90 and 120 degrees of humeral elevation. Based on visual inspection of the graphs, the subjects with symptoms of shoulder impingement also demonstrated scapular upward rotation throughout humeral elevation. However, the scapular tipping pattern in 31% of this group was toward a more anteriorly tipped position as the arm was abducted. In the comparison group, only 2 subjects (8%) displayed this pattern of increased anterior tipping throughout arm abduction.

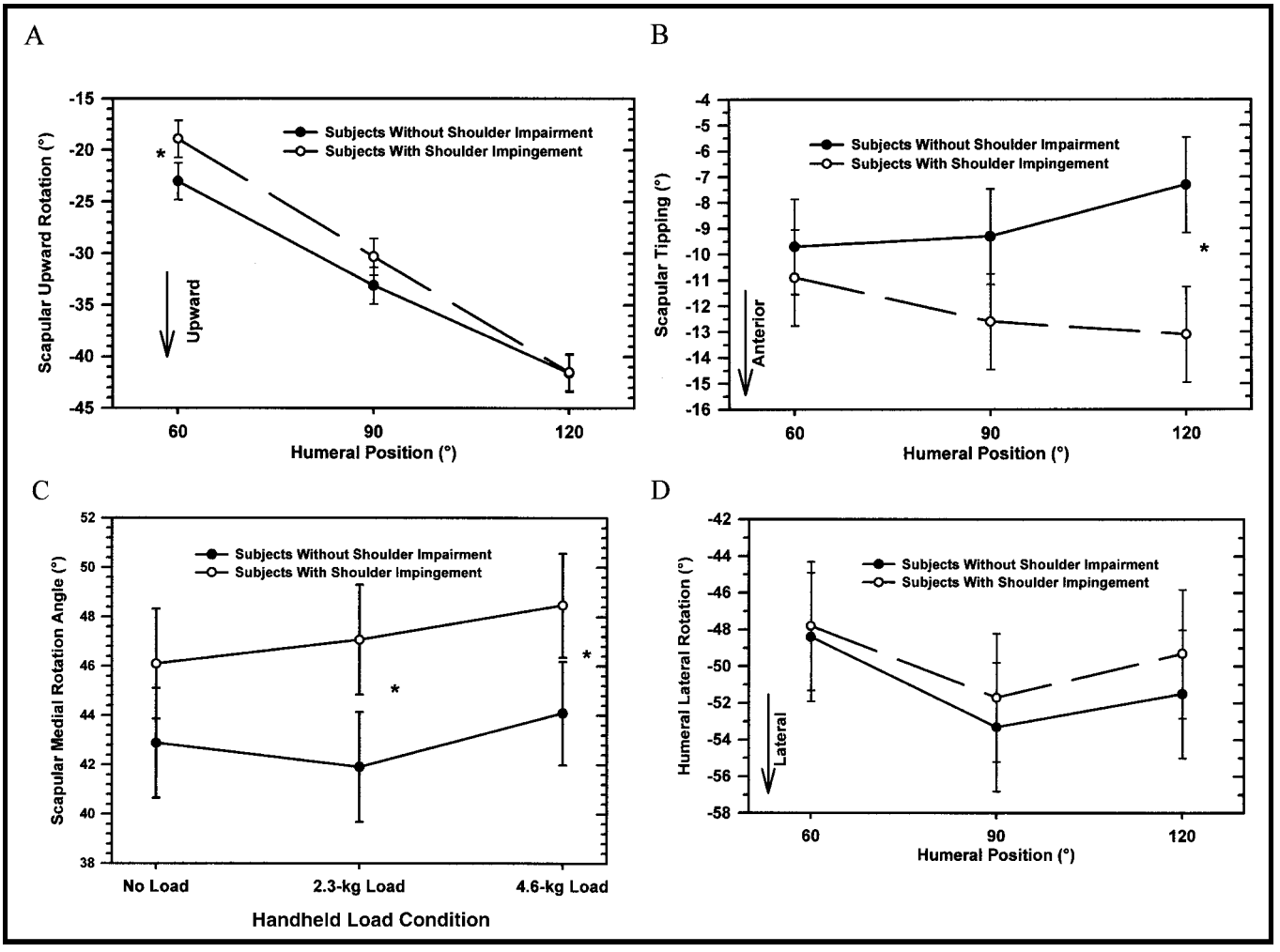

Figure 5.
Summary kinematic group data. (A) Scapular upward rotation (phase × group interaction). Asterisk (*) indicates groups significantly different at 60-degree humeral position (F statistic; *df*=1,50; *P*<.025; n=52). (B) Scapular tipping (phase × group interaction). Asterisk (*) indicates groups significantly different at 120-degree position (F statistic; *df*=1,50; n=52). (C) Scapular medial rotation (group × load interaction) (F statistic; *df*=1,50; n=52). Asterisk (*) indicates groups significantly different for 2.3- and 4.6-kg load conditions. (D) Humeral lateral rotation (group effects).

Results from the analyses of scapular and humeral rotations are presented in Figure 5. For upward rotation, the groups responded differently across the phases (group × phase interaction effect, $P<.005$, hypothesis 3). Subsequently, the effects of group were investigated for each phase (Fig. 5A). Averaged across all load conditions, upward rotation was decreased in the subjects with shoulder impingement (4.1°, $P<.025$) as compared with the comparison subjects at the 60-degree humeral position (hypothesis 1). At the 90-degree humeral position, the means were not different. At the 120-degree humeral position, the means were equivalent. There was no group × load interaction effect ($P>.50$) for upward rotation (hypothesis 4).

The analysis of scapular tipping also revealed a group × phase interaction effect (Fig. 5B, $P<.002$, hypothesis 3), and group differences were assessed for each phase. Averaged across load conditions, at the 60- and 90-degree humeral positions, group means were not different (1.2°, $P>.50$, and 3.3°, $P>.10$, respectively). At the 120-degree humeral position, the scapular position was 5.8 degrees more anteriorly tipped, on average, for the subjects with shoulder impingement than for the comparison subjects ($P<.003$, hypothesis 1). There was no group × load interaction for this analysis (hypothesis 4).

Group differences for scapular medial rotation did not depend on the phase of motion (no phase × group interaction effect, hypothesis 3), and subsequently results were averaged across phases. The groups responded differently across load conditions for this variable (group × load interaction effect, $P<.05$, hypothesis 4). Group differences, therefore, were assessed for each load condition (Fig. 5C). Under the 2.3- and 4.6-kg load conditions, the subjects with shoulder impingement demonstrated greater scapular medial rotation than the comparison subjects (5.2° and 4.4°,

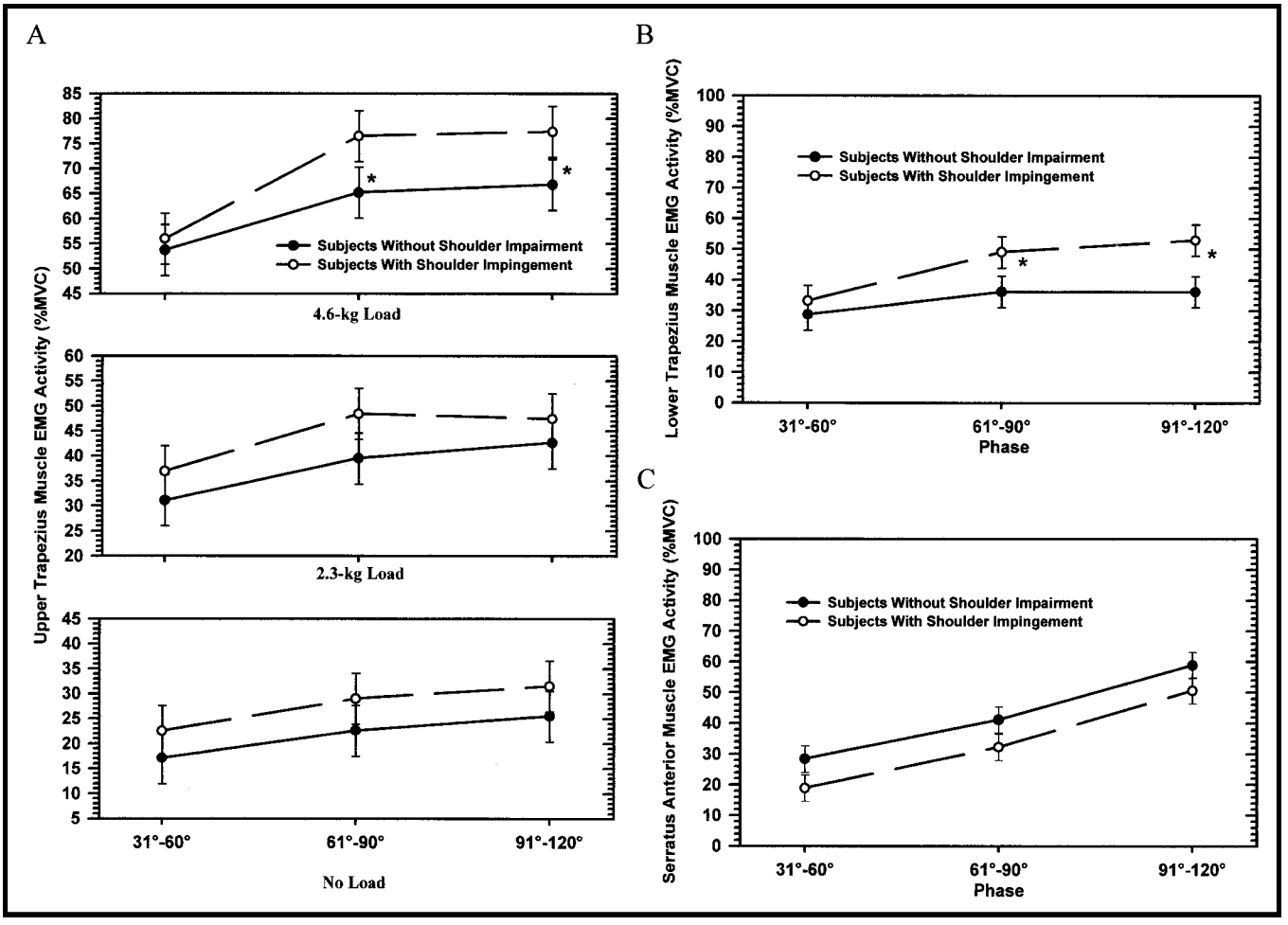

Figure 6.
Summary electromyographic (EMG) group data (expressed as percentage of maximal voluntary contraction [%MVC]). (A) Upper trapezius muscle (group effects for each load condition). Asterisk (*) indicates groups significantly different for 61- to 90-degree phase and 91- to 120-degree phase (F statistic; *df*=1,50; n=52). (B) Lower trapezius muscle (phase × group interaction). Asterisk (*) indicates groups significantly different for 61- to 90-degree phase and 91- to 120-degree phase (F statistic; *df*=1,50; n=52). (C) Serratus anterior muscle (group effects). Note changes in scale between graphs.

respectively), whereas group means were not different for the unloaded condition (hypothesis 1). Figure 5D presents the results of the analysis for humeral lateral rotation. There were no group main effects (hypothesis 1) or interaction effects (hypothesis 3 and 4).

Results from the analyses of the EMG variables are illustrated in Figure 6. Upper trapezius muscle group differences were influenced by both the phase and load conditions (3-way phase × load × group interaction effect, $P<.015$). Subsequently, the effects of group were analyzed at each phase and load combination (Fig. 6A). The subjects with shoulder impingement had more upper trapezius muscle activity for all phases and loads compared with the comparison subjects. Differences between the groups were noted for the 61- to 90-degree and 91- to 120-degree phases under the 4.6-kg load condition (11%, $P<.05$, hypothesis 2). For the lower trapezius muscle, there was again a group × phase interaction effect ($P<.003$, hypothesis 3). When analyzed for each phase, the subjects with shoulder impingement showed increased lower trapezius muscle activity for the 61- to 90-degree and 91- to 120-degree phases (13% and 17%, respectively; Fig. 6B; hypothesis 2). In the analysis of serratus anterior muscle EMG activity, data from 2 of the 52 subjects (1 subject in each group) were of inadequate quality and were not used in subsequent analysis. For the remaining subjects (n=50), there was a main effect for group ($P<.05$, hypothesis 2). Averaged across loads and phases, the subjects with shoulder impingement demonstrated a 9% reduction in serratus anterior muscle activity (Fig. 6C). There was no group × phase interaction for the serratus anterior muscle (hypothesis 3). For both the lower trapezius and serratus anterior muscles, there were no group × load effects, and results were collapsed across loads (hypothesis 4).

Discussion

In this study, we were primarily interested in comparing the 2 groups of subjects and determining whether any group differences were dependent on phase or load. With regard to scapular motion, inadequate upward rotation during the "painful arc of motion" is believed to be a potential contributor to the development or progression of impingement symptoms.[17,19] In our investigation, decreased upward rotation was noted at the completion of the first phase of interest (60° of humeral elevation) in the subjects with shoulder impingement. We believe that this less upwardly rotated scapular position early in the painful ROM may be detrimental and contribute to impingement. On average, however, the subjects with shoulder impingement appeared to be able to gradually compensate for this early decrease during the remainder of the ROM of interest.

As the predominant rotation of the scapula relative to the trunk, upward rotation of the scapula has been most commonly addressed in clinical treatment approaches and research studies.[17,25,26,62,63] Upward rotation elevates the lateral acromion and is necessary to prevent impingement under the lateral acromial edge. However, posterior tipping elevates the anterior acromion, which is the predominant site of impingement.[2,20] Although the range of tipping motion that occurs during elevation of the arm is substantially less than that of upward rotation, it may be more critical to obtaining adequate clearance of the rotator cuff tendons.

The tipping results for the 2 groups showed different patterns across the phases of interest. The subjects without shoulder impairment, on average, moved toward a less anteriorly tipped position as elevation progressed, whereas the mean of the subjects with shoulder impingement moved toward a more anteriorly tipped position. This pattern in the subjects with symptoms of shoulder impingement would place the anterior acromion in closer proximity to the rotator cuff tendons and increase the potential for impingement. These differences in tipping in the subjects with shoulder impingement are consistent with the findings of Lukasiewicz et al.[27] Support for the importance of posterior tipping to elevate the anterior acromion during humeral elevation is provided by previous investigations of simulated active scapular plane abduction[20] as well as passive positioning of the humerus relative to the scapula[64] in cadaver specimens. These authors reported the anterior acromion and coracoacromial ligament to be in close proximity to the supraspinatus tendon insertion in elevated positions. Flatow et al[20] stated that acromial contact with underlying soft tissues always remained on the anterior undersurface. The progression of surgical techniques for shoulder impingement is also consistent with the relative importance of a possible lack of elevation of the anterior acromion as compared with the lateral acromion in contributing to impingement. Acromioplasty has changed from early procedures involving removal of portions of the lateral acromion to present techniques involving removal of portions of the anterior acromion.[2,65]

Shoulder impingement has been attributed to inadequate lateral rotation of the humerus.[65,66] Decreased lateral rotation was believed to result in an inability of the greater tuberosity of the humerus to pass freely beneath the acromion during humeral elevation.[47,66] Our data did not support the hypothesis that there would be decreased lateral rotation in subjects with symptoms of shoulder impingement. The means for lateral rotation showed greater variability than any of the other kinematic measures. Despite the lack of group differences, it is possible that, in a subset of our subjects, a lack of lateral rotation was related to their impingement symptoms. We could find no data in the literature describing in vivo humeral medial/lateral rotation angles relative to the scapula during elevation of the arm.

We believe the clinical importance of the modest angular kinematic differences in the subjects with shoulder impingement (4°–6° of upward rotation scapular tipping and medial rotation) should be considered in light of the small size of the suprahumeral or subacromial space. Several researchers[20,67,68] have quantified the suprahumeral space using 2-D radiographs. With the arm adducted at the side, the acromiohumeral interval has been generally described as approximately 10 mm in subjects without shoulder impairment. The size of this space is believed to be further diminished with elevation of the arm.[20,69] The acromiohumeral interval was reported to gradually decrease with simulated active elevation of the arm using cadaver specimens, until reaching approximately 5 mm by 100 to 110 degrees of elevation in the scapular plane.[20] Prior to reaching 90 degrees of elevation relative to the scapula, the subacromial space must accommodate the articular cartilage, joint capsule and ligaments, rotator cuff tendons, and subacromial bursa. Using stereophotogrammetric 3-D mapping techniques, Flatow et al[20] reported the soft tissues to be in contact with the undersurface of the acromion during normal elevation of the humerus. We contend that even subtle decreases in the available suprahumeral space could contribute to the initiation or progression of shoulder impingement symptoms. This process could be further advanced by inflammation in the suprahumeral space, fibrosis or thickening of the tendons or bursa, or anatomic abnormalities. The magnitude of the angular differences in tipping and upward rotation observed in our investigation were equal to or greater than the 3- to 5-degree anatomical changes in

acromial slope that have previously been associated with rotator cuff tears and impingement syndrome.[10,11]

Abnormal scapulohumeral rhythm or decreases in upward rotation of the scapula during humeral elevation have been linked to "imbalances" in force production of the upper and lower portions of the trapezius muscle and the serratus anterior muscle.[17,19,21–23] In particular, based on clinical observation, we anticipated increased activation of the upper trapezius muscle in subjects with symptoms of shoulder impingement. The results of our investigation provided some support for this premise. There were increases in activation of the upper trapezius muscle in the subjects with shoulder impingement, but these increases did not reach statistical significance until the final 2 phases of interest for the 4.6-kg load condition. We also hypothesized that the lower trapezius muscle of subjects with symptoms of shoulder impingement would demonstrate decreased activation. Contrary to this expectation, the subjects with shoulder impingement demonstrated increased lower trapezius muscle activity for the 61- to 90-degree and 91- to 120-degree phases. Furthermore, this increase, on average, was greater than the increase seen in the upper trapezius muscle.

We found a decrease in activation of the lower serratus anterior muscle in the subjects with shoulder impingement, which averaged 9% across load and phase conditions. Decreased activation of this muscle has been suggested to potentially result in abnormal scapular motion and contribute to impingement symptoms.[22,23] During the 31- to 60-degree phase, the decreased serratus anterior muscle activity was consistent with decreased upward rotation in the subjects with shoulder impingement. However, after this phase, despite a continued lower level of activity in the serratus anterior muscle, the upward rotation values equalized between the 2 groups. At the same time, these final 2 phases were those in which increased activation of the upper and lower portions of the trapezius muscle became apparent in the subjects with shoulder impingement. This finding suggests to us that these trapezius muscle alterations were used to compensate for the decreased serratus anterior muscle activity with regard to the production of upward rotation of the scapula.

Changes in scapular tipping in the subjects with shoulder impingement, however, became greater as humeral elevation progressed across the phases of interest. The serratus anterior muscle is believed to provide the primary muscular force to produce posterior tipping of the scapula and stabilize the scapular inferior angle against the thorax during humeral elevation.[66,70,71] We find it more difficult to visualize the potential contributions of the upper and lower trapezius muscle to scapular tipping, but the lower trapezius muscle may be able to contribute to posterior tipping during portions of the range of humeral elevation.[72] The scapular tipping data from our investigation suggest the increases in trapezius muscle activation observed in the subjects with shoulder impingement were not able to adequately compensate for the decreased serratus anterior muscle activity relative to this kinematic variable, resulting in a lack of posterior tipping during the ROM of interest. Considering the hypothesized clinical importance of posterior tipping to elevate the anterior acromion, the decreased serratus anterior muscle activity in the subjects with shoulder impingement may be particularly relevant.

The results of our investigation, with regard to both kinematic and muscle activity data, suggest that increased attention to serratus anterior muscle function is warranted in rehabilitation programs for shoulder impingement. The inclusion of the scapulothoracic musculature in therapeutic exercise programs is a relatively recent addition.[17,19] Exercise programs vary widely, and general strengthening of all the scapulothoracic muscles is often advocated to "stabilize" the scapula. Other rehabilitation programs continue to emphasize only the rotator cuff musculature.

Electromyographic data do not provide a direct measure of muscle force production. Muscle length and the type and speed of contraction affect the EMG force relationship. The restriction of between-group comparisons to specific phases of motion and the control of the speed of motion between subjects were used to improve the interpretability of the EMG data. In addition, use of a normalization reference contraction is intended to allow comparisons across subjects, conditions, and muscles.[73] Consideration was given to a variety of reference contractions prior to choosing to normalize the data to MVCs. As relative contributions of the upper and lower portions of the trapezius muscle and serratus anterior muscle to humeral elevation in the scapular plane were of interest, normalization of all muscles to this dynamic motion was not a viable option. Controlled submaximal force levels are difficult to obtain for the muscles of interest (trapezius and serratus anterior). Subsequently, MVCs in the midrange of motion were used as the reference contraction.

The intent with this choice of normalization is to provide a quantification of the EMG signal relative to its maximum activity. Because pain might interfere with the ability to produce an MVC, all subjects were questioned regarding pain and discomfort with the normalization contractions. Only 5 of the 26 subjects with shoulder impingement reported pain or discomfort during any of the MVCs. Therefore, we did not believe that pain was a substantial confounding factor on the EMG results. If

the subjects with shoulder impingement experienced a systematic inability to maximally activate the muscles of interest, the true group differences in activation of the upper and lower portions of the trapezius muscle might be less than those reported. However, in such a scenario, true serratus anterior muscle group differences would be greater than those reported. We are unaware of any literature supporting a premise of inhibition to maximum contraction occurring selectively among specific scapulothoracic muscles in response to pain from subacromial impingement.

Other limitations common to the use of surface electrodes must also be noted. It is assumed that the signal is representative of the whole muscle or muscle group of interest. There are also potential alterations in the signal due to muscle movement below the electrode and cross talk from nearby muscles. The electrode placements were chosen to minimize cross talk from muscles such as the rhomboids and latissimus dorsi. Additionally, EMG analyses in this investigation were limited to 2 muscles (the serratus anterior muscle and upper and lower portions of the trapezius muscle). Although these muscle groups are believed to provide the primary muscular control of the scapula, no data are available from this study on any of the other scapulothoracic or glenohumeral muscles that may impart forces to the scapula.

In addition to direct between-group comparisons, the effects of handheld loads were of interest with regard to possible increases in group differences under loaded conditions (interactions of group and load). With the exception of the 3-way interaction of group, phase, and load for the upper trapezius muscle and the group × load interaction for scapular medial rotation, there were no interactions of group and load for any of the variables analyzed in this study. This finding may reflect the occupational exposures to routine lifting of tools and construction materials that subjects in both study groups experience on a daily basis. Previous investigations of the effects of loads on scapular kinematics have produced varying results.[37,62,63,74] Comparisons among studies are hampered by different methods of investigation, as well as differences in the handheld loads imposed and subject populations tested.

In interpreting our results, we believe that several factors regarding the subject sample should be considered. The population of interest was construction workers from trades with substantial exposure to overhead work. As these subjects continued to work despite intermittent periods of pain, they may have developed compensation strategies that may not be apparent in a population of subjects with more acute symptoms. Furthermore, SPADI scores for the subjects with shoulder impingement were relatively low. Subjects with greater impairment might be expected to show more substantial alterations in kinematics or muscle activity. The population from which our sample was obtained (workers in sheet metal and carpentry trades) is estimated to be 98% to 99% male.[7] Although there are no data identifying sex differences for the dependent variables of interest, the generalizability of the study results to women is uncertain. Additionally, mechanisms of shoulder impingement may differ in elderly individuals or people involved in athletic activities. Extrapolation of the results of this investigation to these populations is not recommended.

In addition to the acromion, several superior coracoacromial arch structures have been implicated as potential impingement sites, including the coracoacromial ligament, coracoid process, or undersurface of the AC joint.[2] Furthermore, although the supraspinatus tendon insertion into the humerus has been reported to be the most commonly affected, any or all of the tendons of the rotator cuff as well as the long head of the biceps muscle can be involved in impingement syndromes.[33] No attempt was made in this investigation to classify subjects as having various categories of impingement. Different impingement sites may relate to unique kinematic abnormalities, making it more difficult to ascertain overall group differences between subjects with shoulder impingement and subjects without shoulder impairment.

Currently, it is unknown whether kinematic and muscle activity alterations in subjects with symptoms of shoulder impingement are precursors to the development of impingement or a result of the condition. Longitudinal studies could allow a determination of whether any kinematic or muscle activity patterns, combined with exposure to frequent overhead activities, are predictive of the development of impingement symptoms. This information may eventually assist in the prevention of these and other shoulder disorders.

Clinical studies have begun to address the effectiveness of physical therapy for symptoms of shoulder impingement.[75] As therapeutic exercise programs evolve, comparative testing of different rehabilitation approaches is needed. To improve our understanding of the mechanisms by which shoulder function is enhanced through rehabilitation, outcome assessments should address kinematic and muscle activity alterations as well as symptoms and functional status.

Summary and Conclusions

The first hypothesis was supported by decreased scapular upward rotation in the first of the 3 phases of interest, increased anterior tipping in the third phase of interest, and increased scapular medial rotation under the load conditions for the subjects with shoulder impingement.

However, there were no detectable group differences in humeral lateral rotation. The second hypothesis was supported by increased upper trapezius muscle EMG activity in the final 2 phases under the 4.6-kg load condition and decreased serratus anterior muscle activity across all loads and phases for the subjects with shoulder impingement. However, the increased lower trapezius muscle activity in the subjects with shoulder impingement for the final 2 phases of motion was contrary to the hypothesized result. The third hypothesis was supported for scapular medial rotation, humeral lateral rotation, and serratus anterior muscle EMG activity; however, group differences for all other variables were phase dependent. The fourth hypothesis was supported by the results for scapular medial rotation and upper trapezius muscle EMG activity; however, no other group differences were magnified by the addition of external handheld loads.

The results of the scapular tipping analysis in our investigation concur with the findings of Lukasiewicz et al,[27] are consistent with cadaver investigations of acromial contact on underlying soft tissues, are supported by the progression of surgical techniques from lateral to anterior acromioplasty, and are functionally comparable to anatomical changes in acromial slope. Furthermore, the findings of decreased serratus anterior muscle function in the subjects with shoulder impingement are consistent with the decreased posterior tipping, given the unique role of the serratus anterior muscle in controlling the inferior angle of the scapula against the thorax. Additionally, the other kinematic alterations identified (decreased upward rotation and increased medial rotation) are consistent with decreased serratus anterior muscle activation. Subsequently, scapular tipping and associated serratus anterior muscle function are believed to merit increased attention in the rehabilitation of patients with symptoms of shoulder impingement related to occupational exposure to overhead work.

References

1 Matsen FA, Arntz CT. Subacromial impingement. In: Rockwood CA, Matsen FA, eds. *The Shoulder.* Philadelphia, Pa: WB Saunders Co; 1990:623–646.

2 Neer CS Jr. Impingement lesions. *Clin Orthop.* 1983;173:70–77.

3 Hagberg M, Wegman DH. Prevalence rates and odds ratios of shoulder-neck diseases in different occupational groups. *Br J Ind Med.* 1987;44:602–610.

4 Herberts P, Kadefors R, Andersson G, Petersen I. Shoulder pain in industry: an epidemiological study on welders. *Acta Orthop Scand.* 1981;52:299–306.

5 Herberts P, Kadefors R, Hogfors C, Sigholm G. Shoulder pain and heavy manual labor. *Clin Orthop.* 1984;191:166–178.

6 Rosecrance JC, Cook TM, Zimmermann CL. Active surveillance for the control of cumulative trauma disorders: a working model in the newspaper industry. *J Orthop Sports Phys Ther.* 1994;19:267–276.

7 Cook TM, Rosecrance JC, Zimmermann CL. *The University of Iowa Construction Survey.* Washington, DC: Center to Protect Worker's Rights; 1996. Publication No. 010-96.

8 Bjelle A, Hagberg M, Michaelson G. Occupational and individual factors in acute shoulder-neck disorders among industrial workers. *Br J Ind Med.* 1981;38:356–363.

9 Shoulder musculoskeletal disorders: evidence for work-relatedness. In: Bernard BP, ed. *Musculoskeletal Disorders and Workplace Factors: A Critical Review of Epidemiologic Evidence for Work-Related Musculoskeletal Disorders of the Neck, Upper Extremity, and Low Back.* 2nd ed. Cincinnati, Ohio: US Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health; 1997(3):1–72. Publication No. 97-141.

10 Zuckerman JD, Kummer FJ, Cuomo F, et al. The influence of coracoacromial arch anatomy on rotator cuff tears. *J Shoulder Elbow Surg.* 1992;1:4–14.

11 Aoki M, Ishii S, Usai M. Clinical application for measuring the slope of the acromion. In: Post M, Morrey B, Hawkins R, eds. *Surgery of the Shoulder.* St Louis, Mo: Mosby-Year Book; 1990:200–203.

12 Codman EA. *The Shoulder.* Boston, Mass: Thomas Todd; 1934.

13 Rathbun JB, Macnab I. The microvascular pattern of the rotator cuff. *J Bone Joint Surg Br.* 1970;52:540–553.

14 Nirschl RP. Rotator cuff tendinitis: basic concepts of pathoetiology. *Instr Course Lect.* 1989;38:439–445.

15 Fu FH, Harner CD, Klein AH. Shoulder impingement syndrome: a critical review. *Clin Orthop.* 1991;269:162–173.

16 Jobe FW, Bradley JP. The diagnosis and nonoperative treatment of shoulder injuries in athletes. *Clin Sports Med.* 1989;8:419–438.

17 Kamkar A, Irrgang JJ, Whitney SL. Nonoperative management of secondary shoulder impingement syndrome. *J Orthop Sports Phys Ther.* 1993;17:212–224.

18 Kibler WB. Role of the scapula in the overhead throwing motion. *Contemp Orthop.* 1991;22:525–532.

19 Paine RM, Voight M. The role of the scapula. *J Orthop Sports Phys Ther.* 1993;18:386–391.

20 Flatow EL, Soslowsky LJ, Ticker JB, et al. Excursion of the rotator cuff under the acromion: patterns of subacromial contact. *Am J Sports Med.* 1994;22:779–788.

21 Sahrman SA. Adult posturing. In: Kraus SL, ed. *TMJ Disorders Management of the Craniomandibular Complex.* New York, NY: Churchill Livingstone Inc; 1988:295–309.

22 Scovazzo ML, Browne A, Pink M, et al. The painful shoulder during freestyle swimming: an electromyographic cinematographic analysis of twelve muscles. *Am J Sports Med.* 1991;19:577–582.

23 Glousman R, Jobe F, Tibone J, et al. Dynamic electromyographic analysis of the throwing shoulder with glenohumeral instability. *J Bone Joint Surg Am.* 1988;70:220–226.

24 Peat M, Grahame RE. Electromyographic analysis of soft tissue lesions affecting shoulder function. *Am J Phys Med.* 1977;56:223–240.

25 Poppen NK, Walker PS. Normal and abnormal motion of the shoulder. *J Bone Joint Surg Am.* 1976;58:195–201.

26 Eto M. Analysis of the scapulo-humeral rhythm for periarthritis scapulohumeralis. *Nippon Seikeigeka Gakkai Zasshi.* 1991;65:693–707.

27 Lukasiewicz AC, McClure P, Michener L, et al. Comparison of 3-dimensional scapular position and orientation between subjects with and without shoulder impingement. *J Orthop Sports Phys Ther.* 1999;29:574–583.

28 Warner JJP, Micheli LJ, Arslanian LE, et al. Scapulothoracic motion in normal shoulders and shoulders with glenohumeral instability and impingement syndrome: a study using moiré topographic analysis. *Clin Orthop.* 1992;285:191–199.

29 Ellenbecker TS, Derscheid GL. Rehabilitation of overuse injuries of the shoulder. *Clin Sports Med.* 1989;8:583–604.

30 Wilk KE, Andrews JR. Rehabilitation following arthroscopic subacromial decompression. *Orthopedics.* 1993;16:349–358.

31 Pappas AM, Zawacki RM, McCarthy CF. Rehabilitation of the pitching shoulder. *Am J Sports Med.* 1985;13:223–235.

32 Hawkins RJ, Abrams JS. Impingement syndrome in the absence of rotator cuff tear (stages 1 and 2). *Orthop Clin North Am.* 1987;18:373–382.

33 Kessel L, Watson M. The painful arc syndrome: clinical classification as a guide to management. *J Bone Joint Surg Br.* 1977;59:166–172.

34 Kessler RM, Hertling D. *Management of Common Musculoskeletal Disorders: Physical Therapy Principles and Methods.* Philadelphia, Pa: Harper & Row; 1983:557.

35 Magee DJ. Cervical spine and shoulder. In: Magee DJ, ed. *Orthopedic Physical Assessment.* Philadelphia, Pa: WB Saunders Co; 1987:34–83.

36 Feldt LS. *Design and Analysis of Experiments in the Behavioral Sciences.* Iowa City, Iowa: Iowa Testing Programs, The University of Iowa; 1993.

37 McQuade KJ, Smidt GL. Dynamic scapulohumeral rhythm: the effects of external resistance during elevation of the arm in the scapular plane. *J Orthop Sports Phys Ther.* 1998;27:125–133.

38 Ludewig PM, Cook TM, Nawoczenski DA. Three-dimensional scapular orientation and muscle activity at selected positions of humeral elevation. *J Orthop Sports Phys Ther.* 1996;24:57–65.

39 Roach KE, Budiman-Mak E, Songsiridej N, Lertratanakul Y. Development of a Shoulder Pain and Disability Index. *Arthritis Care Res.* 1991;4:143–149.

40 An KN, Jacobsen MC, Berglund LJ, Chao EYS. Application of a magnetic tracking device to kinesiologic studies. *J Biomech.* 1988;21:613–620.

41 *3SPACE FASTRAK User's Manual, Revision F.* Colchester, Vt: Polhemus Inc; 1993.

42 Harryman DT Jr, Sidles JA, Harris SL, Matsen FA. Laxity of the normal glenohumeral joint: a quantitative in vivo assessment. *J Shoulder Elbow Surg.* 1992;1:66–76.

43 Pearcy MJ, Hindle RJ. New method for the non-invasive three-dimensional measurement of human back movement. *Clin Biomech.* 1989;4:73–79.

44 Sidles JA, Larson RV, Garbini JL, et al. Ligament length relationships in the moving knee. *J Orthop Res.* 1988;6:593–610.

45 Harryman DT Jr, Sidles JA, Clark JM, et al. Translation of the humeral head on the glenoid with passive glenohumeral motion. *J Bone Joint Surg Am.* 1990;72:1334–1343.

46 An KN, Browne AO, Korinek S, et al. Three-dimensional kinematics of glenohumeral elevation. *J Orthop Res.* 1991;9:143–149.

47 Browne AO, Hoffmeyer P, Tanaka S, et al. Glenohumeral elevation studied in three dimensions. *J Bone Joint Surg Br.* 1990;72:843–845.

48 Itoi E, Motzkin NE, Morrey BF, An KN. Contribution of axial arm rotation to humeral head translation. *Am J Sports Med.* 1994;22:499–503.

49 Johnson GR, Anderson JM. Measurement of three-dimensional shoulder movement by an electromagnetic sensor. *Clin Biomech.* 1990;5:131–136.

50 Jensen C, Vasseljen O, Westgaard RH. The influence of electrode position on bipolar surface electromyogram recordings of the upper trapezius muscle. *Eur J Appl Physiol.* 1993;67:266–273.

51 Nieminen H, Takala EP, Viikari-Juntura E. Normalization of electromyogram in the neck-shoulder region. *Eur J Appl Physiol.* 1993;67:199–207.

52 van der Helm FC. A finite element musculoskeletal model of the shoulder mechanism. *J Biomech.* 1994;27:551–569.

53 Kendall HO, Kendall FP. *Muscle Testing and Function.* Baltimore, Md: Williams & Wilkins; 1949.

54 Schuldt K, Harms-Ringdahl K. Activity levels during isometric test contractions of the neck and shoulder muscles. *Scand J Rehabil Med.* 1988;20:117–127.

55 Ludewig PM. *Alterations in Shoulder Kinematics and Associated Muscle Activity in Persons With Shoulder Impingement Syndrome* [dissertation]. Iowa City, Iowa: The University of Iowa; 1998:50–72.

56 Kondo M, Tazoe S, Yamada M. Changes of the tilting angle of the scapula following elevation of the arm. In: Bateman J, Welsh R, eds. *Surgery of the Shoulder.* Philadelphia, Pa: BC Decker Inc; 1984:12–16.

57 Yu B. *Determination of the Optimum Cutoff Frequency in the Digital Filter Data Smoothing Procedure* [master's thesis]. Manhattan, Kan: Kansas State University; 1988.

58 van der Helm FCT, Dapena J. Shoulder joints: definition of joint coordinate systems, joint motions and joint torques. Available at: http://www.mr.wbmt.tudelft.nl/schouder/dsg/standardization.html: ISB Subcommittee for Standardization and Terminology; 1996.

59 Craig JJ. *Introduction to Robotics: Mechanics and Control.* 2nd ed. New York, NY: Addison-Wesley Co; 1989.

60 Mirka GA. The quantification of EMG normalization error. *Ergonomics.* 1991;34:343–352.

61 Portney LG, Watkins MP. *Foundations of Clinical Research: Applications to Practice.* East Norwalk, Conn: Appleton & Lange; 1993.

62 Michaels I, Grievenstein J. Kinematics of shoulder abduction in the scapular plane. *Clin Biomech.* 1995;10:137–142.

63 Doody SG, Freedman L, Waterland JC. Shoulder movements during abduction in the scapular plane. *Arch Phys Med Rehabil.* 1970;51:595–604.

64 Brossmann J, Preidler KW, Pedowitz RA, et al. Shoulder impingement syndrome: influence of shoulder position on rotator cuff impingement—an anatomic study. *AJR Am J Roentgenol.* 1996;167:1511–1515.

65 Neer CS Jr. Anterior acromioplasty for the chronic impingement syndrome in the shoulder: a preliminary report. *J Bone Joint Surg Am.* 1972;54:41–50.

66 Soderberg GL. *Kinesiology: Application to Pathological Motion.* Baltimore, Md: Williams & Wilkins; 1986:109–129.

67 Weiner DS, Macnab I. Superior migration of the humeral head: a radiological aid in the diagnosis of tears of the rotator cuff. *J Bone Joint Surg Br.* 1970;52:524–527.

68 Petersson CJ, Redlund-Johnell I. The subacromial space in normal shoulder radiographs. *Acta Orthop Scand.* 1984;55:57–58.

69 Warner JJP, Kann S, Maddox LM. The "Arthroscopic Impingement Test." *Arthroscopy.* 1994;10:224–230.

70 Perry J. Normal upper extremity kinesiology. *Phys Ther.* 1978;58:265–278.

71 Kent BE. Functional anatomy of the shoulder complex: a review. *Phys Ther.* 1971;51:867–887.

72 van der Helm FC. Analysis of the kinematic and dynamic behavior of the shoulder mechanism. *J Biomech.* 1994;27:527–550.

73 LeVeau B, Andersson G. Output forms: data analysis and applications. In: Soderberg GL, ed. *Selected Topics in Surface Electromyography for Use in the Occupational Setting: Expert Perspectives.* Cincinnati, Ohio: US Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health; 1992:70–102. Publication No. 91-100.

74 van der Helm FCT, Pronk GM. Three-dimensional recording and description of motions of the shoulder mechanism. *J Biomech Eng.* 1995;117:27–40.

75 Ginn KA, Herbert RD, Khouw W, Lee R. A randomized, controlled clinical trial of a treatment for shoulder pain. *Phys Ther.* 1997;77:802–809.

Appendix.

Definitions for Local Coordinate Systems (LCS) for Each Segment

Thorax:

Z_t: The K_t unit vector corresponding to the positive Z_t coordinate direction of the thorax LCS and approximating the longitudinal axis of the thorax, defined by, $K_t=[(r_{SN/O}+r_{C7/O})/2-(r_{XP/O}+r_{T8/O})/2]/|(r_{SN/O}+r_{C7/O})/2-(r_{XP/O}+r_{T8/O})/2|$, where SN and XP are the suprasternal notch and the xiphoid process, and $r_{A/O}$ is a vector locating point A relative to point O. Point O is defined as the origin of the sternal sensor.

X_t: The I_t unit vector corresponding to the positive X_t coordinate direction of the thorax LCS and perpendicular to the plane defined by K_t and $r_{C7/SN}$ (formed from their cross product), $I_t=K_t\times(r_{C7/SN}/|r_{C7/SN}|)$.

Y_t: The J_t unit vector corresponding the positive Y_t coordinate direction and perpendicular to K_t and I_t, $J_t=(K_t\times I_y)$.

The origin of the thorax system is the point SN_t.

Scapula:

x_s: The i_s unit vector corresponding to the positive x_s coordinate direction defined by $i_s=(r_{AC/O}-r_{RS/O})/|(r_{AC/O}-r_{RS/O})|$, where AC and RS are the most dorsal palpable point of the AC joint and the root of the spine of the scapula, respectively, and point O is the origin of the scapula sensor.

y_s: The j_s unit vector corresponding to the positive y_s coordinate direction and perpendicular to the scapular plane, defined as $j_s=i_s\times[(r_{IA/O}-r_{AC/O})/|r_{IA/O}-r_{AC/O}|]$, where IA is the inferior angle of the scapula.

z_s: The k_s unit vector corresponding to the positive z_s coordinate direction and defined by $k_s=(i_s\times j_s)$.

The origin of the scapula system is the acromioclavicular joint.

Humerus:

z_h: The k_h unit vector corresponding to the positive z_h coordinate direction and approximating the longitudinal axis of the humerus is defined by $k_h=(r_{scuff/O}-r_{icuff/O})/|(r_{scuff/O}-r_{icuff/O})|$, where scuff and icuff are the superior and inferior points on the humeral cuff, and O is the origin of the humeral sensor.

y_h: The j_h unit vector corresponding to the positive y_h coordinate direction is defined by $j_h=k_h\times[(r_{LE/O}-r_{ME/O})/|r_{LE/O}-r_{ME/O}|]$, where LE is the lateral epicondyle and ME is the medial epicondyle.

x_h: The i_h unit vector corresponding to the positive x_h coordinate direction is defined by $i_h=(j_h\times k_h)$.