8-1-1996

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Three-Dimensional Scapular Orientation and Muscle Activity at Selected Positions of Humeral Elevation

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Elevation of the arm for overhead activities is accomplished by combined motion at multiple articulations of the shoulder, including the sternoclavicular, acromioclavicular, and glenohumeral joints (24,48). Some authors include the scapulothoracic articulation when describing shoulder anatomy and kinesiology (24,29). Due to the ligamentous and capsular attachments of the scapula to the clavicle and the clavicle to the sternum, scapulothoracic movement requires motion of the clavicle on the thorax at the sternoclavicular joint, motion of the scapula relative to the clavicle at the acromioclavicular joint, or some combination of both (24). Scapulothoracic motion, therefore, is a summation of sternoclavicular and acromioclavicular motion, and, subsequently, elevation of the arm is frequently described in terms of scapulothoracic and glenohumeral components.

Cathcart, while observing arm movements in living subjects, first suggested that glenohumeral and scapulothoracic motion occur synchronously when lifting the arm overhead (7). Codman later termed this synchronous motion, scapulohumeral rhythm (8). Since that time, a great deal of research in shoulder kinematics has been directed toward the study of scapulohumeral rhythm (2, 14,19,24,45,48). The majority of this previous research is limited to two-dimensional (2-D) studies of scapular upward rotation about an axis perpendicular to the plane of the scapula during humeral elevation.

Scapular motion is known to occur about other axes as well (13,34, 36,55). Poppen and Walker described a twisting movement of the scapula occurring in combination with upward rotation as the arm was elevated (45). A variety of terms has been used to define this motion. Scapular rotation around an axis roughly parallel to the scapular spine has been termed flexion/extension (13), anterior/posterior or forward/backward tilting (36,39), or anterior/posterior tipping (40). Around a vertical axis, scapular motion has been defined as anterior/posterior rotation (39), internal/external rotation (36), or winging (40). In this paper, rotation about an axis perpendicular to the plane of the scapula is defined as upward/downward rotation, rotation about an axis parallel to the scapular spine is described as anterior/poste-
Despite the knowledge of potential three-dimensional (3-D) scapular motion, inherent difficulties in scapular measurement associated with overlying skin movement have hindered 3-D kinematic analyses of the shoulder. Investigations of shoulder motion completed in 3-D frequently have been limited to humeral motions relative to the trunk (16,25) or they have been based on cadaver data (1). Other previous 3-D studies are often difficult to interpret clinically (23,26,31) because the chosen angular descriptions differ from common clinical understanding.

Descriptions of scapular rest position have been reported in 3-D (10, 34,36). However, the shoulder literature, providing clinically meaningful 3-D descriptions of scapular motion or orientation beyond rest positions, is sparse (34,36,55). Further, the majority of these previous 3-D studies have assessed scapular position during humeral elevation in the cardinal planes (26,34,55). Elevation of the arm for functional activities, however, rarely occurs in the cardinal planes, instead, occurring approximately midway between these planes in what has been described as the plane of the scapula (27,48). In addition, nearly all of these previous investigations (26,31,34,55) report only mean values for their particular sample, without providing an indication of the variability known to occur between subjects.

To produce the complex kinematics at the shoulder during humeral elevation, complementary action of scapulothoracic and glenohumeral muscles is required (24,49). Electromyographic (EMG) activity of the scapulothoracic muscles has been studied by numerous authors (3,4,6, 11,17,24,49,57). Although these studies verify the activity of all portions of the trapezius, the levator scapulae, rhomboids, and lower serratus anterior during arm elevation, disagreement exists as to their relative contributions to this activity. The use of differing electrodes (needle, fine wire, or surface), a lack of normalization procedures in most studies, a lack of standard electrode placements, and differences in instrumentation and methods all contribute to this variability between studies. Overall, the general understanding of muscle activity of the scapular rotators during arm elevation is predominately qualitative. Furthermore, associated discussions of muscle function are commonly related to only 2-D descriptions of scapular motion (2, 15,24).

Although there are minimal research data describing the contributions of accessory scapular motions of internal/external rotation and tipping to normal scapular kinematics, these accessory motions are frequently discussed and evaluated clinically (5,38,42). Abnormal scapular kinematics in one or all planes and associated abnormal muscle function are believed to contribute to shoulder pain and pathology (20,21,30). Culham and Peat (10) reported alterations in resting scapular orientation related to age and spinal posture in females. Significant changes in scapular internal rotation and increases in anterior tilt of the scapula occurred with increased age and increasing slope of the upper thoracic spine, while the scapular upward rotation angle was not affected by spinal posture or age (10). In addition, a study comparing scapular position (upward rotation and protraction) in relaxed standing between patients with shoulder overuse injuries and healthy subjects found no significant differences between groups for these scapular variables (22). The authors suggest that a lack of assessment of scapular tipping and internal rotation may have contributed to their nonsignificant findings (22). The results of previous investigations indicate that assessment of 3-D scapular orientation, including internal rotation and tipping, is warranted in future kinematic studies of patient populations.

A more complete understanding of scapular motion and muscle activity in functional planes of elevation in asymptomatic individuals is needed in order to provide a basis for further understanding of shoulder dysfunction in symptomatic individuals.

The purposes of this paper are: 1) to describe and compare 3-D scapular orientation at static humeral angles of elevation in the scapular plane and 2) to describe and compare muscle activity of the upper trapezius, lower trapezius, levator scapul-
Subjects

Twenty-five subjects (14 women and 11 men), without a history of shoulder pain, pathology, or range of motion restriction, voluntarily participated in this study. The eligible subject age range was limited to 18–40 years old. Demographic information for the subjects is presented in Table 1. All but two of the subjects (92%) were right-hand dominant. Each subject was given a verbal and written summary of information about the study and signed a consent form prior to participation.

Design

A one-way repeated measures design was used to determine the effect of humeral angle on scapular orientation and muscle activity. The independent variable humeral angle had three levels: 0, 90, and 140° of humeral elevation relative to the trunk. These angles were selected to provide data in the functional range of elevation. The dependent variable humeral angle had three levels: 0, 90, and 140° of humeral elevation relative to the trunk. Subsequent elevation of the humerus from this position resulted in a voltage output that was displayed on an analog meter placed in front of the subject (Figure 2). Voltage outputs consistent with the desired elevation angles were marked on the meter, thus allowing the subjects visual feedback to maintain positions within and between trials.

Instrumentation

A position control system was fabricated for this study to allow the subjects to consistently maintain the desired humeral angle within the scapular plane during the data collection process and replicate the positions for subsequent measurements. A gravity-referenced pendulum potentiometer was attached to a cuff on the humerus (Figure 2). A neutral arm position (anatomical position with the arm at the subject’s side) was obtained, and the measurement system was zeroed to this position. Subsequent elevation of the humerus from this position resulted in a voltage output that was displayed on an analog meter placed in front of the subject (Figure 2). Voltage outputs consistent with the desired elevation angles were marked on the meter, thus allowing the subjects visual feedback to maintain positions within and between trials.

Digitized 3-D coordinate locations were obtained via an electromagnetic linkage digitizer constructed for this project. Positioning of the pointer of the digitizer to a location within its working range resulted in voltage output from each of the precision rotary potentiometers. Custom data acquisition software and a 12 bit A/D board (Dash 16F, Metabyte Corporation, Stoughton, MA) were used for on-line data collection to a microcomputer. Calculations of x, y, z Cartesian coordinates from raw voltage values and linkage arm lengths were completed with custom software programs. Similar linkage digitizers have been used in previous shoulder kinematic research (37,47).

The digitizer and related software were calibrated for the measurement of 3-D linear distances over the working range. Resultant worst case linearity, hysteresis, repeatability, and accuracy were 1 mm, 2 mm, 2 mm, and 4 mm, respectively. Worst case angular errors were determined to be no greater than 2° (35).

Silver-silver chloride surface electrode assemblies with an interelectrode distance of 20 mm, 8-mm diameter active electrodes, and on-site preamplification (Therapeutics Unlimited, Iowa City, IA) were used to record EMG activity of the selected muscles. The signals were passed to a GCS 67 amplifier with adjustable gain settings, high input impedance (greater than 15 megohms at 100 Hz), a common mode rejection ratio of 87 dB at 60 Hz, and a bandwidth of 40–4000 Hz. The raw signals were root mean square processed with a time constant of 55 msec. All signals were collected on-line to a microcomputer simultaneously as voltages were collected from the digitizer. Electromyographic signals from each muscle were monitored on an oscilloscope (Tektronix 7313, Beaverton, OR) throughout data collection in order to verify signal quality.

Procedures

Electrode placement locations were chosen based on previous studies collecting surface EMG from the muscles of interest (33,50,53,58). All electrodes were aligned in the direction of the muscle fibers. The levator scapulae electrode was placed between the posterior margin of the sternocleidomastoid muscle and the anterior margin of the upper trapezius. In this region, the levator scapulae is superficially located (50,58). The upper trapezius electrode was placed one-third of the distance between C7 and the acromion process.
The lower trapezius electrode was placed one-half of the distance between the inferior angle of the scapula and the thoracic spine. The serratus anterior electrode was placed over the muscle fibers just lateral to the inferior angle of the scapula (12). A ground electrode was placed on the distal ulna of the left wrist. After electrode placement, verification of signal quality was completed for each muscle at each arm position.

Three maximum voluntary isometric contractions for each muscle were collected, sampling for 3 seconds after the first second of effort. Maximum contractions were collected for the lower trapezius and serratus anterior in traditional manual muscle test positions (28). The maximum contractions for the remaining muscles were collected with the subject seated. Upper trapezius voluntary isometric contractions were collected with maximum resistance to arm abduction at a position of 90° of humeral abduction in the scapular plane (51). Levator scapulae voluntary isometric contractions were collected with maximum resistance to right lateral flexion of the head, while the arm was actively held by the subject at 90° of abduction in the scapular plane (51).

Subjects were seated and stabilized to a lumbar support by a strap placed around their waist. Their trunk was aligned vertically to the trunk reference frame on the chair. Limitation of trunk movement from this position was controlled by placement of stabilizing bars, anteriorly contacting the sternum and posteriorly contacting the upper thoracic spine. This stabilization did not restrict scapular motion or muscle activity (Figure 2). Shoulder elevation in the plane of the scapula was controlled by having the subject elevate the right arm along a flat planar surface angled 30° anterior to the coronal plane.

The subject actively obtained each humeral position in a preselected random order, and data were collected while subjects maintained each position. Three trials were completed in each position. During each trial, the medial inferior edge of the spine of the scapula, the posterolateral tip of the acromion, and the inferior angle of the scapula were palpated and digitized. The three points used to describe the arm and trunk orientations were digitized from the humeral cuff and trunk reference frame, respectively. The reference frame to which the trunk was aligned was digitized at the beginning of the data collection session. During digitizing, EMG signals were simultaneously collected from the muscles of interest. Data collection began with the examiner triggering a foot switch, and data were collected at 300 Hz for 0.5 seconds at each point. The subject was allowed 30 seconds of rest between each position.

Digitized angular values for humeral positions were displayed on the computer terminal immediately upon completing data collection at each position. If digitized values were outside a range of ±5° of the targeted position, then that position was repeated before collecting data in the next position.

Data Reduction and Analysis

A local reference frame was established for each body segment using the three noncollinear points collected for that segment (56). The axis orientations for the trunk and scapula are illustrated in Figure 1. The trunk reference frame was established coincident with the cardinal planes. The three-dimensional angular orientation of the scapula and humerus at each arm position was described relative to the trunk using a Z, Y, X ordered Cardan angle rotation sequence (9,56). Rotations about Z, defined scapular internal/external rotation relative to the coronal plane. This first rotation can be considered as defining the orientation of the scapular plane. Rotations about Y, defined upward/downward rotation of the scapula about an axis perpendicular to the plane of the scapula, and rotations about X, defined anterior/posterior tipping of the scapula about a mediolateral axis (Figure 1).

Root mean square EMG voltage values were averaged for each position and across the 3-second period for each maximum voluntary isometric contraction. Resting EMG voltage values were then subtracted from both the maximal contraction and arm position data. The highest average maximum contraction of the three trials for each muscle and position was used as the normalization reference. Average values for each arm position were normalized as a percentage of the respective maximum voluntary isometric contraction.

The degree of similarity among the three trials at each arm position was assessed using type 3, 1 intraclass correlation coefficients (ICCs) for each dependent variable (32,46). The standard error of measurement was also calculated for the kinematic data. The mean of the three trials at each arm position was used in all subsequent analysis. Statistical Analysis System software (SAS Institute, Cary, NC) was utilized to compute a one-way repeated measures analysis of variance (ANOVA) for each dependent variable of interest. A significance level of .05 was used to test for statistical differences in the overall model. When a significant main effect for humeral angle was found, Tukey follow-up tests were performed to adjust the significance level and control the experiment-wise error rate at a .05 level.

RESULTS

Intraclass correlation coefficients assess the degree of similarity among the three trials at each arm position for each subject. The values for each of the kinematic and EMG variables across all humeral angles are presented in Table 2. The ICCs ranged from .78 to .93 and are indicative of
good within-session reliability for all dependent variables of interest (46). Additionally, the standard error of measurement calculated for the scapular angle data estimates the average error of the measurement for any given trial. These calculations reflect the repeatability of the measurement method as a whole, including repeatability of the instrumentation, repeatability of palpation of bony landmarks, and the ability of the subjects to replicate the specific arm position. The standard error of measurement was consistently 2° for scapular tipping angle at all three arm positions. For upward rotation and internal rotation angles, the standard error of measurement ranged from 2 to 3° across arm positions.

Means and standard deviations across subjects for the three scapular angular orientation variables are presented graphically in Figure 3 and numerically in Table 3. The mean scapular upward rotation angle increased progressively as the humeral angle increased. Although differing in magnitude, 100% of the individual subjects followed this general pattern from anterior to posterior tipping with increased arm elevation. Results of the repeated measures ANOVA revealed a significant main effect of humeral angle (p < .001) for each of the three scapular orientation variables. Follow-up testing of means across humeral angles resulted in significant differences for all pair-wise comparisons.

Means and standard deviations across subjects for the muscle activity variables are presented graphically in Figure 4 and numerically in Table 4. The mean EMG activity increased progressively as humeral angle increased for all of the muscles studied. All subjects demonstrated increased activity for all muscles at a 90° humeral angle as compared with the 0° humeral angle, except for levator scapulae values from one subject which remained unchanged at 1%. At the 140° humeral angle, three patterns were possible. Subjects presented with either a further increase in activity as compared with the 90° angle, a maintenance of the 90° muscle activity level (defined as a value falling within the 95% confidence interval for that subject’s mean value), or a decrease in activity from the 90° level.

For the upper trapezius, 64% of the subjects followed the first pattern of progressively increased activity, 24% plateaued at the 90° activity level, and 12% demonstrated slightly decreased activity at 140°. For the lower trapezius, 48% followed a pattern of progressively increased activity, 20% plateaued in activity at the 90° level, and 32% demonstrated decreased activity at 140°. Serratus anterior activity was more consistent across subjects, with 92% following a pattern of progressively increased activity and 8% (two subjects) demonstrating a decrease in activity from 90–140°. For the levator scapulae,
72% of the subjects followed a pattern of increased activity across humeral elevation angles and 28% plateaued at the 90° activity level.

Results of the repeated measures ANOVA revealed a significant main effect of humeral angle (p < .001) for each of the four EMG variables. Follow-up testing of means across humeral angles resulted in significant differences for all pairwise comparisons except for the lower trapezius values. For this muscle, the mean at a 0° humeral angle was significantly different from the means at the 90° and 140° humeral angles, but the values at the 90° and 140° angles were not significantly different from one another.

**DISCUSSION**

The results of this study provide a clinically relevant description of 3-D scapular orientation and associated muscle activity with humeral elevation in the plane of the scapula. Perhaps equally important to the understanding of normative profiles is the variability that is evident between subjects for both kinematic and EMG measures. When attempting to compare abnormal kinematics or muscle activity in a patient population, the expected variability from the mean among asymptomatic subjects is important to consider. Additionally, particularly with EMG variables, all asymptomatic subjects may not follow the pattern represented by the mean of the group. Between-subject variability has been reported to be present but has not been quantified in previous shoulder EMG literature analyzing shoulder elevation (3,57).

The variability in patterns of EMG activity reported in this study may explain the apparent contradiction in reports of lower trapezius activity among preceding investigations. Previous authors report increasing activity of the lower trapezius at increased humeral elevation angles (3, 17), decreasing activity after 90° (49), or activity changes being dependent on the plane of elevation (24). In the present study, patterns of increasing and decreasing activity were nearly equally present in individuals (48% increased, 32% decreased), consequently resulting in no significant increase in the group mean value between 90° and 140°.

Between-subject variability in scapular upward rotation values has frequently been noted in the 2-D literature (14,19). The magnitude of variability in the present study, with standard deviations ranging from 4 to 6°, is quite consistent with the reported 2-D values. In the previous 3-D literature (26,31,34,55), between-subject variability in scapular angles at a given humeral angle is often not addressed. In the present study, the magnitude of between-subject variability at all humeral angles tested was greatest for the scapular internal rotation angle, with standard deviations ranging between 6° and 9°. This suggests that scapular plane orientation is quite variable between subjects, although at rest, it averages very close to the 30° position previously defined in the literature (27). It should be noted that despite between-subject differences in the magnitude of scapular orientation values, the patterns of orientation between arm positions were quite consistent among subjects, with 100% demonstrating progressive upward rotation and posterior tipping and 84% demonstrating progressive external rotation. A lack of progressive upward rotation or posterior tipping in an individual subject could thus be considered abnormal relative to this sample.

Despite differences in experimental design and selection of subject groups, the results of this study at a 0° humeral elevation angle can be compared with previous studies describing an average rest position of the scapula. These comparisons are presented in Table 5. Measurements of mean upward rotation and internal rotation angles from the present study are consistent with the results of these previous investigations. Further, all studies report the scapula to be in an anteriorly tipped position at rest. The magnitude of the mean tipping angle measured in the present study is consistent with the findings.
of Culham and Peat (10). Both Lau-
mann and McQuade define the tip-
ing angle relative to different planes
or axes than the present study, and, there-
fore, absolute comparisons of this angle
between these studies are not appropriate (34,36).

Comparisons of this study’s re-
results to previous studies of 3-D scapu-
lar orientation during humeral eleva-
tion are constrained by further
complicating factors. Differences in
instrumentation (31,34,36), planes of
analysis (26,31,34,55), loading condi-
tions (36), and definitions of axis
orientations and determination of
angular values prevent the direct
comparison of magnitudes of angular
orientations. Nonetheless, the gen-
eral patterns of scapular rotations as
the humerus is elevated can be com-
pared. All previous studies describe
progressive upward rotation and pos-
terior tipping with increasing hu-
meral elevation. The results of the
present study demonstrate that these
same patterns are present during hu-
meral elevation in the scapular plane.
The description of scapular rotations
in the plane of the scapula as re-
ported in the present study allows a
closer approximation to movements
present during unconstrained func-
tional elevation. Additionally, the
progressive external rotation of the
scapula observed in the present study
supports Van Der Helm and Pronk’s
contention that the scapular plane is
steadily moving throughout humeral
elevation (55). Kondo et al and
McQuade, however, describe a more
constant scapular plane orientation
during humeral elevation (31,36).

Altered patterns of upward rota-
tion of the scapula have been hypothe-
sized to contribute to shoulder
problems. Synchronous upward rota-
tion of the scapula as the arm is ele-
vated is believed necessary to main-
tain an appropriate length tension
relationship for the deltoid. Alter-
tations in this relationship may impact
power production and total range of
elevation in all planes (24). Addition-
ally, Poppen and Walker assessed
scapulohumeral ratios of both symp-
tomatic and asymptomatic subjects
during 2-D scapular plane abduction
(45). These authors concluded that
abnormal ratios were associated with
disease, but normal ratios did not
rule out disease (45). Decreases from
the normal upward rotation have also
been theorized to decrease the sub-
acromial space and contribute to im-
pingement (20,42).

In addition to changes in upward
rotation, abnormalities in scapular
tipping patterns warrant increased
attention in patients with impinge-
ment symptoms. Flatow et al, based
on simulated humeral elevation in
vidual to impingement or exacerbate
preexisting impingement symptoms.

Instability of the shoulder has
also been related to abnormal scapu-
lar kinematics of both upward rota-
tion and internal rotation angles.
Ozaki demonstrated a significant de-
crease in scapular upward rotation
values during humeral elevation in
patients with involuntary inferior and
multidirectional instability as com-
pared with asymptomatic volunteers
(41). In addition, Kibler hypothe-
sized that excess “antetilt” of the gle-
roid during a throwing motion may
increase stress on the anterior gleno-
humeral structures and predispose
the subject to glenoid labral tears
and subsequent anterior instability
(30). This excessive “antetilted” ori-
entation would be defined as exces-
sive internal rotation, using the ter-
mological of the present study.

If an abnormal scapular motion
pattern is considered contributory to
a clinical pathology, the rehabili-
tation approach should consider mus-
cle forces that may restrict or en-
hance the desired scapular kine-
matics. As the pectoralis minor in-
serts into the coracoid process, excess
active or passive tension in this mus-
cle may impede normal posterior tip-
ning. Likewise, normal upward rota-
tion may be restricted by excess
tension in the rhomboids or levator
scapulae.

Electromyographic descriptions
of trapezius and serratus anterior ac-
tivities during humeral elevation have
commonly been related to the 2-D
kinematic patterns of scapular up-
ward rotation (2,15,24,44). Little dis-
ussion has related muscle activity to
the patterns of tipping and external
rotation that are also occurring with
humeral elevation. Due to its inser-
tion into the medial border and infe-
rior angle of the scapula, the progres-
sive activity seen in the serratus
anterior with humeral elevation
should contribute to posterior tip-
ing and external rotation of the
scapula as well as upward rotation.
The role of the trapezius in contrib-

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The scapula demonstrated a
pattern of progressive
upward rotation, decreased internal
rotation, and movement from
an anteriorly
tipped position as
humeral elevation
angle increased.
uting to scapular tipping and internal/external rotation is more difficult to visualize. However, the downward and medially directed fibers of the lower trapezius may also assist in producing posterior tipping and external rotation moments as the humerus is elevated. Alterations in patterns of EMG activity from the scapular muscles, which have been found in some symptomatic subject groups (21,43, 52), may impact the normal rotations of the scapula about all three axes as the humerus is elevated. Consequently, rehabilitation approaches to scapular muscle strengthening should consider the effects on tipping and internal/external rotation motions as well as upward rotation.

Limitations should be noted when interpreting the surface EMG signal describing levator scapulae activity. The levator scapulae is superficially located at the level of the fifth cervical vertebrae between the posterior margin of the sternocleidomastoïd and the anterior margin of the upper trapezius. For subjects with small necks or poorly defined musculature, this area was somewhat difficult to locate. The levator scapulae EMG signal may have been influenced by cross talk from the upper trapezius in some subjects, although the overall low level of activity observed from the levator suggests no substantial impact of upper trapezius cross talk on the mean values. Although collected in a similar fashion in previous studies (3,43), the acquisition of serratus anterior EMG data with surface electrodes also has limitations. However, the normalization of the data minimizes the influence of electrode location and allows an adequate representation of this muscle's activity.

A complete description of muscle function of the scapular rotators is contingent upon a thorough understanding of 3-D scapular kinematics. Moments created by these muscles are dependent upon their line of action and the axis of rotation of the scapula, which has yet to be described using a 3-D model. In addition, the functional roles of these muscles will change substantially throughout the range of shoulder elevation due to constant changes in the axis of rotation and lines of action (54). Objective assessment of scapular upward rotation alone may not provide adequate information toward understanding pathologies of the shoulder that are believed related to mechanisms of abnormal kinematics and muscle activity. A comprehensive kinematic assessment of the shoulder should include scapular tipping and internal/external rotation measurements as well.

SUMMARY AND CONCLUSIONS

This study describes the 3-D orientation of the scapula and corresponding EMG activity of the scapular rotators during humeral elevation in the scapular plane. The scapula demonstrated a pattern of progressive upward rotation, decreased internal rotation, and movement from an anteriorly to a posteriorly tipped position as humeral elevation angle increased. Electromyographic activity of the levator scapulae, upper trapezius, lower trapezius, and serratus anterior also increased progressively with increased humeral elevation angle. The secondary rotations of the scapula (tipping and internal/external rotation) are believed to be clinically significant contributors to abnormal kinematics in shoulder dysfunction. Investigation of these accessory rotations in clinical populations is warranted. In addition, further 3-D kinematic analysis of the shoulder complex is needed in combination with EMG data to enhance our understanding of shoulder muscle function.

ACKNOWLEDGMENTS

The authors would like to thank Dr. Gary Smidt and Dr. Rich Shields for their input at various stages of this project.

REFERENCES

8. Codman EA: The Shoulder, Boston, MA: Thomas Todd, 1934
16. Engin AE, Chen SM: Statistical data...


32. Lahey MA, Downey RG, Saal FE: Intra-class correlations: There's more than meets the eye. Psychol Bull 93:586–595, 1983


