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Comparison of scapular local coordinate systems

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ABSTRACT

Background: Our purposes were to compare between the original and current recommended standard methods of three-dimensional scapular rotation descriptions and to examine the prevalence of gimbal-lock for scapular motion during scapular plane abduction. Additionally we compared these standards to an alternative method and a glenoid based description.

Methods: Eleven asymptomatic subjects were studied using electromagnetic sensors secured to bone-fixed pins in the scapula and humerus during two repetitions of scapular plane abduction. Anatomical landmarks defined scapular axes. Scapular angular data were analyzed at humerothoracic elevation angles from initial to maximum elevation. Repeated measures ANOVAs were performed for each variable with a significance level of $P < 0.05$. An anatomical model was used to compare the standards to the alternative and glenoid methods.

Findings: For scapular upward rotation and tilting, larger differences occurred between standards at higher angles of elevation. The current standard measured 12.4° less upward rotation and 6.1° greater posterior tilting at maximum elevation as compared to the original. The current standard measured 11.6° less scapular internal rotation across all elevation angles. Using the original landmarks, six subjects attained a mean end-range humerothoracic elevation of 147.4° (SD 12.1°), with a mean end-range scapular upward rotation of 54.4°. The alternative method was more closely aligned to the glenoid method than the current standard.

Interpretation: Significant differences were found between the two standards. The current standard interprets the same scapular motion with less internal rotation and upward rotation, and more posterior tilting than the original. No subjects reached upward rotation positions nearing gimbal-lock. Axis orientations also affect clinical interpretation. The alternative method appears worthy of further consideration as shoulder kinematic measurement further evolves.

1. Introduction

Grood and Suntay proposed in 1983 a joint coordinate system for standardizing description of three-dimensional (3D) biomechanical human movement in a clinically meaningful and consistent manner (Grood and Suntay, 1983). A decade later, van der Helm (1997) described a standardized system to define shoulder positions. Subsequently, the Standardization and Technology Committee of the International Society of Biomechanics (ISB) developed joint coordinate system standards for human joints (Wu et al., 2005). Initially, the three proposed anatomical landmarks for the scapular local coordinate system were the root of the scapular spine (trigonum spinae), the posterior acromioclavicular (AC) joint, and the inferior angle of the scapula (angulus inferior) (van der Helm, 1997; Fig. 1). Many investigations of 3D shoulder kinematics quantify normal and abnormal scapular kinematics using these original scapular landmarks (Ebaugh et al., 2005; Karduna et al., 2001; Lin et al., 2005; Ludewig and Cook, 2000; Ludewig et al., 2009; McClure et al., 2001; Tsai et al., 2003; van der Helm and Pronk, 1995).

More recently, a modification of the original landmarks was proposed and incorporated into the current published and recommended standard (de Groot, 1997; Meskers et al., 1998; Wu et al., 2005). In this new system, the AC joint landmark was replaced in favor of the posterolateral acromion (angulus acromialis – AA) realigning the scapular axes such that the potential for singular positions (gimbal-lock) involving scapular upward rotation (2nd rotation of the scapula about the anteriorly directed *x*-axis approaching 90°) was reduced during shoulder motion measurement (Fig. 1). Singular positions need to be avoided during joint motion measurement because these orientations render Euler sequences unsolvable (van der Helm, 1997; Zatsiorsky, 1998). Fur-

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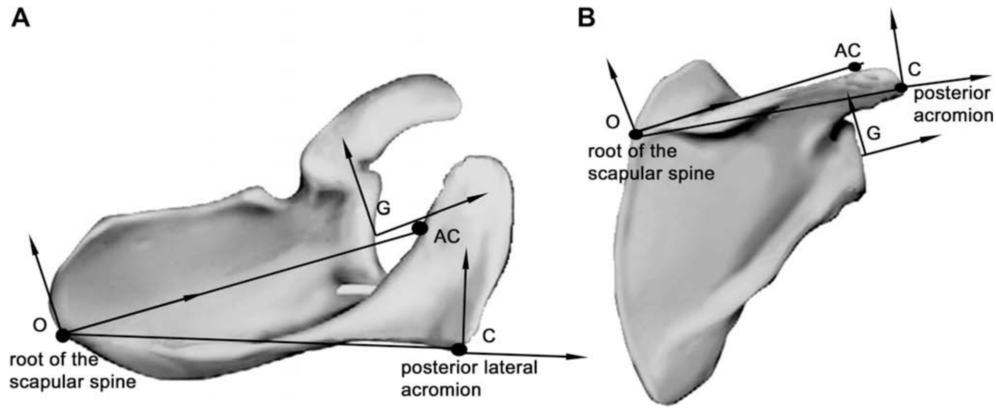

Fig. 1. Superior (A) and posterior (B) views of anatomical estimations of *x* (anterior) and *z* (lateral) axes derived from the root of the scapular spine, comparing the original (O) acromioclavicular (AC) landmark, and the current (C) landmark of the posterolateral acromion, as well as a glenoid (G) based coordinate system. Based on the axis alignment, the current system will result in a more internally rotated and less upwardly rotated scapular position description as compared to the original recommended standard.

thermore, positions nearing singular positions (within 20°) become sensitive to error which can cause large standard deviations in the interpreted kinematic values both within and between subjects (van der Helm, 1997; Zatsiorsky, 1998). The current standard *z*-axis is directed with less superior inclination by about 10° (Fig. 1), thus lowering the reported angular values for upward rotation, and reducing the potential to reach 70° of scapular upward rotation (de Groot, 1997).

Since the *z*-axis realignment was proposed, a body of literature also exists which incorporates this new posterolateral acromion landmark (de Groot, 1997; Meskers et al., 1998; Myers et al., 2005; Wu et al., 2005), however, the old landmark also continues to be used. Data from these two different sets of anatomical landmarks are often loosely compared without knowing the exact influence of differing axis alignments on the same shoulder motion. Although some comparisons between the two coordinate systems with regard to variability were made by de Groot (1997), no quantitative analysis has been presented in the literature examining the magnitude of measurement differences between these methods of scapular motion description. In addition to reducing upward rotation values (de Groot, 1997), the axis realignment should also reduce the scapular internal rotation angle (Fig. 1A) and subsequently alter the posterior tilting angular values.

An additional consideration regarding axis alignments is clinical interpretation. Anatomically, the original standard's AC joint landmark and resultant *z*-axis lies in a position that is closer to the plane of the scapula than the posterior lateral acromion (Wu et al., 2005; Fig. 1). Clinically, scapular upward rotation is understood to occur about an axis perpendicular to the plane of the scapula. This means that scapular rotations using the original standard are more consistent with common clinical interpretation. The current proposed standard creates an offset in axis alignments from the scapular plane (Fig. 1) that may confound clinical interpretation.

An alternative method, as described by Pearl et al. (1992) utilizes the midpoint of the posterolateral acromion and the tip of the coracoid process (Fig. 2). This method may also merit further discussion because it would seem to follow the plane of the scapula similarly to the AC landmark, yet lower the orientation of the axis such that it would reduce the magnitude of upward rotation values (Fig. 2). Such an alignment might also be closer to a glenoid centered axis system often used in imaging studies (Graichen et al., 2005; Poppen and Walker, 1976).

The purpose of this study was to compare 3D scapular kinematic values obtained from the original and current ISB recommended shoulder standards during humeral elevation in the scapular plane. We also sought to examine scapular upward rotation values at maximum humeral elevation to determine how the two ISB standards related to potential singular positions. Scapular kinematic data were bone-fixed measurements. We hypothesized that in comparison to the original ISB standard, the current standard would describe scapular position values with decreased scapular internal rotation and upward rotation and increased posterior tilting for the same scapular orientation. Additionally, using an anatomical model, we compared both original and current ISB scapular standards to a system based on the AA/coracoid midpoint (Pearl et al. method), and to a glenoid based axis system.

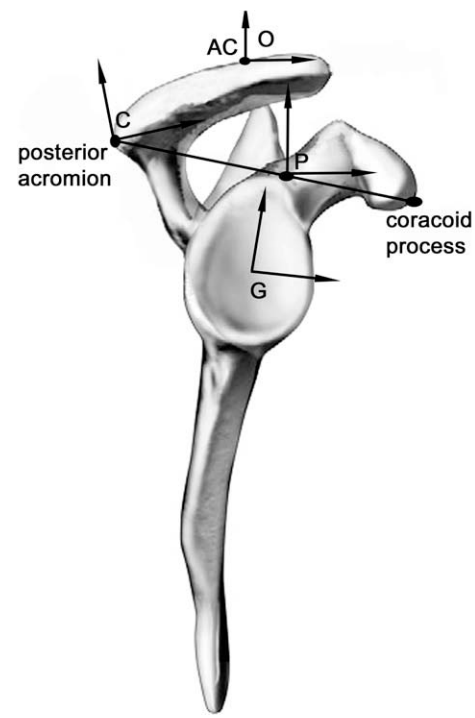

Fig. 2. Lateral view of the original (O) acromioclavicular (AC) and posterolateral acromion landmarks. Also shown is a reference point (P) proposed by Pearl et al. (1992) in which the second scapular landmark is calculated as the midpoint between the posterolateral acromion and the coracoid process. Associated *x* (anterior) and *y* (superior) axes demonstrate the current standard (C) to be most posteriorly tilted, and the glenoid system (G) to be most anteriorly tilted.

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2. Methods

Eleven healthy asymptomatic subjects (six male, five female; mean age: 29.6 years, mean height: 1.74 m, mean weight: 77.3 kg) participated in this study. They were all prescreened by a licensed physical therapist and free of symptomatic shoulder pathology. The volunteer subjects represented a convenience sample. To enroll in the study, the asymptomatic volunteers needed to be within the ages of 18–45 years, and they were excluded if observed to demonstrate visible scapular dyskinesia during weighted or non-weighted humeral elevation (Kibler, 1991; Kibler and McMullen, 2003). At the initial visit, the study procedures were explained to each subject and consent was obtained, following University Institutional Review Board approved informed consent process and procedures. The non-dominant shoulder complex was tested for nine subjects. A total of eight left and three right shoulders were examined.

2.1. Instrumentation

Motion was captured with a Flock of Birds 3D mini-bird electromagnetic tracking system (Ascension Technology Corporation, Burlington, VT). Static accuracy for this device for a sensor within a 1.2 meter range from the transmitter has been reported under laboratory conditions to be 1.8 mm and 0.5° (Ascension Technology Corporation, 2003). Kinematic data were received and processed using Motion Monitor software (Innovative Sports Training, Chicago, IL).

2.2. Procedures

This investigation was a subpart of a larger study of shoulder complex motion (Ludewig et al., 2009). In summary, under sterile conditions, 2.5 mm diameter distally threaded pins were inserted by an orthopaedic surgeon until they engaged the far cortex. Prior to pin placement, the skin and subcutaneous tissues were anesthetized down to the periosteum with local anesthetic injections. The skin was incised around each pin insertion site. The first pin was placed into the scapular spine at the acromial base. The second pin was placed in the distal aspect of the clavicle, with the third pin placed in the humerus just distal to the deltoid insertion. Data from two of these pins (scapula and humerus) were used for the analysis in this dataset. Fluoroscopy was used to verify pin placement. Pin housings holding electromagnetic sensors were secured to the pins (Fig. 3) and all pins and housings were manually checked for secure placement and a lack of rotation or toggle. A surface motion sensor was attached to the anterior trunk just below the sternal notch using adhesive tape.

Fig. 3. Subject setup with electromagnetic sensors fixed to bone-pins and surface sensor on the thorax.

The global coordinate system was the Flock of Birds transmitter mounted on a solid, rigid plastic base aligned with the horizontal. Local coordinate systems were established through the digitizing of anatomical landmarks for each segment following both the original and current shoulder protocols (van der Helm, 1997; Wu et al., 2005). Landmarks were palpated by a physical therapist and digitized using a blunt-tip stylus with known tip offsets that was connected to the Flock of Birds system. Kinematic testing was completed with subjects in standing within the accuracy range or the transmitter. Each subject completed two repetitions of scapular plane abduction. Subjects were given instruction to maintain light finger tip contact during the motion with a flat planar surface angled 40° anterior to the subject's frontal plane using approximately 3 s to raise the arm and 3 s to lower the arm. Prior to elevation, a separate file was recorded with the subjects in standing with the arms relaxed at the side to define the initial position. Subjects were asked to rate their pain from pin insertion sites during the active movement on a 0–10 point ascending numerical rating scale. Upon completion of motion testing, the bone-pins were removed and the incision sites were closed with stitches or adhesive bandages as appropriate. Each subject also had a follow-up re-evaluation at 7–10 days post testing to remove sutures and ensure proper healing had occurred.

2.3. Data reduction and analysis

The dependent variables were the 3D scapular kinematic values (internal rotation, upward rotation, and tilting) which were analyzed with reference to the trunk using the Y, X', Z'' (internal rotation, upward rotation, tilting) sequence as defined by both Karduna et al. (2001) and Wu et al. (2005). Kinematic motion analysis involved selecting scapular data at humerothoracic elevation angles of initial, 30°, 60°, 90°, 120°, and maximum elevation relative to the trunk using a Y, X',Y'' (plane of elevation, elevation angle, axial rotation) sequence to define humeral position (Wu et al., 2005). All dependent variables were checked for normality and found to meet criteria for parametric statistics (Feldt, 1993). After Inter-Class Coefficients (ICCs, Type 3,1) and the standard error of measurement (SEM) (Fleiss, 1986) were calculated at each humeral angle to establish trial-to-trial reliability of the kinematic data, the two repetitions of scapular plane abduction were averaged.

For each dependent variable, a two-way repeated measures ANOVA was performed comparing between conditions (original and current ISB protocols) and selected angles (initial, 30°, 60°, 90°,120° and maximum humeral elevation) with an alpha level set at 0.05. In the presence of significant interactions of condition and angle, Tukey post hoc testing was conducted comparing between conditions at each specified humeral elevation angle

2.4. Anatomical model calculations

Based on available Computerized tomography (CT) scan imaging (1 mm helical scans) of one subject, the scapula was reconstructed to a 3D model using Mimics software (Materialise, Ann Arbor, MI). Anatomical landmarks for both original and current ISB standards were identified, as well as the coracoid landmark as described by Pearl et al. (1992). In addition a glenoid plane was defined based on superior, inferior, anterior and posterior landmarks on the glenoid rim. Using Matlab software, reference frames from the anatomical model were reconstructed for the original and current standard, the Pearl method, and a glenoid based system. The Pearl et al. method replaced the midpoint of the AA and coracoid process in the generation of the z-axis and the scapular plane, but otherwise followed the ISB standard. The glenoid based system had the *z*-axis perpendicular to the glenoid plane, the *y*-axis directed superiorly toward the superior glenoid tubercle, and the *x*-axis directed anteriorly perpendicular to the other two axes. Matrix transformations were used to describe each of the original and current axes systems relative to the Pearl et al. method and the glenoid based system. Further, the effects of error in identifying the inferior angle landmark (angulus inferior) were also assessed by offsetting this landmark location 1 cm in each direction (superior/inferior, medial/lateral, and anterior/posterior) relative to the plane of the scapula and reporting the corresponding influence on the three scapular rotations. The location of the inferior angle landmark (angulus inferior) contributes to the definition of the scapular plane.

3. Results

Reported average pain ratings for scapular plane abduction were 1.9/10 on a 0–10 ascending pain scale. Trial to trial ICCs ranged from 0.84 to 0.99 across the dependent variables**.** Standard Errors of Measurement (SEMs) ranged from 0.85° to 3.35° for the same variables**.**

For scapular internal rotation, there was no significant interaction between ISB standard and angles of humerothoracic elevation. However, across all angles measured, the current ISB standard consistently measured decreased scapular internal rotation values compared to the initial ISB standard ($P < 0.001$, df = 1.10, $F = 61.95$) The average differences between standards was 11.6° (Fig. 4A).

An interaction effect was present for scapular upward rotation between ISB standard and angles of humerothoracic elevation ($P < 0.001$, df = 5.50, $F = 91.56$). In other words, the effect of the standard was dependent on the angle of elevation considered. As humerothoracic elevation increased, the measurement gap between the two standards increased, with the current standard measuring decreased upward rotation as compared to the original standard ($P < 0.001$, df = 1.10, $F = 156.09$). With the arms relaxed at the side, the current standard measured 8.1° less upward rotation than the original standard in that initial position. At maximum scapular plane abduction, this difference grew linearly to 12.4° (Fig. 4B). The overall mean upward rotation difference across all angles was 10.2°. All follow-up comparisons between standards were statistically significant at all humerothoracic angles.

An interaction effect was present for scapular tilting between ISB standard and angles of humerothoracic elevation ($P < 0.001$, $df = 5.50$, $F = 10.87$) (Fig. 4C). Beyond the initial position with the arms relaxed at the side, the current ISB standard consistently measured increased posterior tilting as compared to the original standard ($P < 0.001$, $df = 1.10$, $F = 36.50$) with a mean difference across all angles considered of 3.8°. As noted with scapular upward rotation, as scapular plane abduction increased, the difference between the two standards increased linearly. With the arms relaxed at the subject's side there was no tilting difference, however at maximum scapular plane abduction the discrepancy between standards was 6.1° of scapular tilting. With the exception of the initial relaxed position, all follow-up comparisons between standards were statistically different.

Six of the eleven subjects attained unrestricted end-range scapular plane abduction. In the other cases, the angle of insertion of the clavicular pin and housing impeded extreme end-range scapular plane abduction. In those cases, during humeral elevation, the deltoid came in contact with the clavicular housing, thereby preventing full scapular plane abduction. The subjects that achieved unrestricted and full range of humerothoracic elevation had a mean of 147.4° (SD 12.1°) of humeral elevation relative to the trunk and a mean maximum scapular upward rotation of 54.4° (Table 1) using the original standard. The maximum scapular upward rotation measured in any subject using the original standard was 63.8°. No subject achieved scapular upward rotation values that approached a singular position.

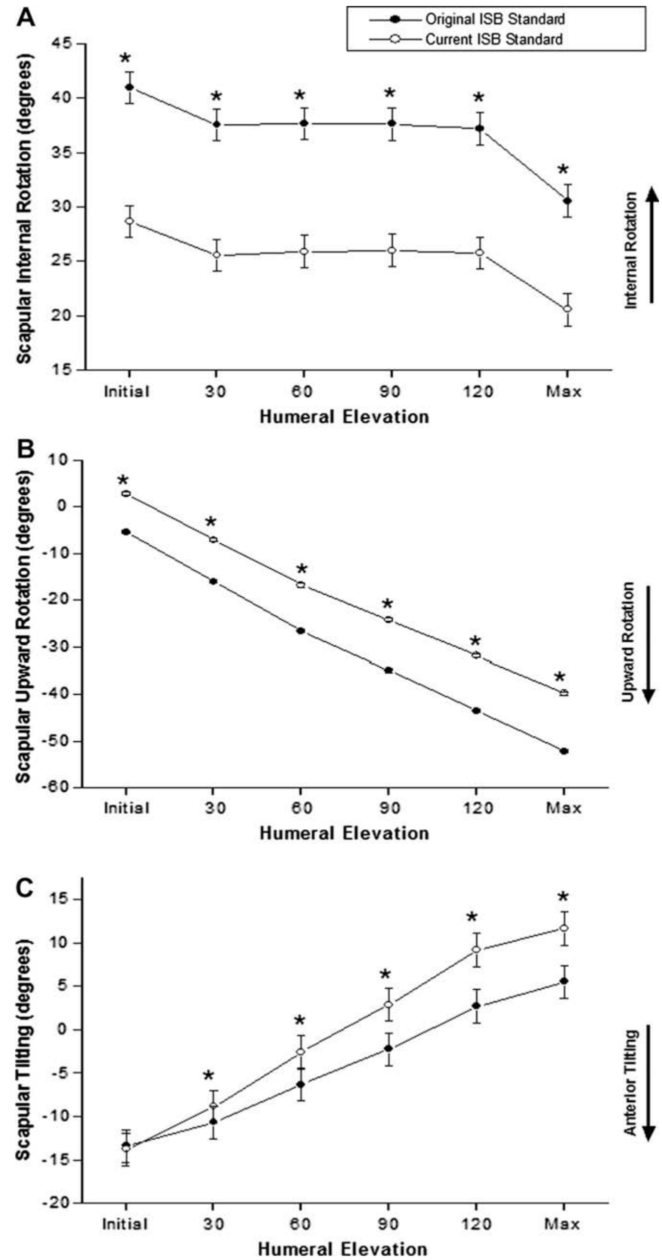

Fig. 4. Mean and standard error values for scapular internal rotation (A), upward rotation (B) and tilting (C) (in degrees) across humerothoracic elevation angles (in degrees) for original and current International Society of Biomechanics (ISB) standards. Asterisk (*) indicates conditions significantly different between standards.

Comparisons between the ISB standards and the Pearl et al. and glenoid based systems are provided in Table 2. The Pearl et al. approach reduced scapular upward rotation similarly to the current ISB standard, but resulted in an increased internal rotation angle relative to the original standard. The Pearl et al. approach was also more closely aligned to the glenoid based system than the current standard (Table 2).

Offsetting the inferior angle landmark was demonstrated to affect only the tilt angle because the *z*-axis alignment was unchanged. When the landmark was offset in a superior/inferior

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Table 1
Scapular upward rotation (UR) values at maximum scapular plane abduction (SAB) across International Society of Biomechanics (ISB) standards for subjects achieving unrestricted humeral elevation relative to the trunk.

Subject	1	2	3	4	5	6	Mean	SD
Maximum SAB	137.2	136.1	148.0	165.9	140.0	157.3	147.4	12.1
Maximum scapular UR original ISB standard	62.3	46.1	45.4	54.9	53.9	63.8	54.4	7.8
Maximum scapular UR current ISB standard	45.5	37.1	31.5	45.9	45.3	53.1	43.1	7.6

Table 2
Comparison of anatomically modeled coordinate systems for 3D scapulothoracic angular rotations (degrees).

Coordinate system comparison	Scapular internal rotation	Scapular upward rotation	Scapular tilting
Pearl relative to original	10.0° more	9.0° less	0.5° anterior
Pearl relative to current	17.3° more	2.9° more	4.7° anterior
Pearl relative to glenoid	6.5° more	0.1° more	12.8° posterior
Original relative to glenoid	3.6° less	7.5° more	14.3° posterior
Current relative to glenoid	11.1° less	4.8° less	17.1° posterior

direction or medial/lateral direction, the tilt angle was altered 2.4° or less. When the landmark was offset in an anterior/posterior direction the tilt angle was altered 2.8°.

4. Discussion

Our results indicate use of the current ISB reporting standard results in scapular values with significantly less internal rotation, significantly less upward rotation, and significantly more posterior tilting as compared to the original ISB standard. Our results also demonstrate that these differences vary depending on the magnitude of humerothoracic elevation in the scapular plane. These differences have implications for both technical and clinical interpretation. Our review of the literature found no previous studies objectively comparing or describing measurement differences between the original and current ISB standards. Our study provides comparative data using a precise bone-fixed tracking method.

Although the specific magnitude differences between standards were not directly known a priori, the general pattern of results was geometrically predictable. In order to shift the *z*-axis downward and backward, the associated coordinate system would need to rotate about the *x*- and *y*-axes, resulting in decreased upward rotation and increased internal rotation, respectively (Fig. 1). The internal rotation difference is a fixed offset, as this is the first rotation, while the upward rotation and tilting differences increase across the range of motion as these rotations occur secondarily about previously rotated axes. The Pearl et al. method reduces upward rotation because of the lower midpoint landmark, but increases internal rotation because the landmark is forward relative to the posterior AC joint landmark (Fig. 2). Offsetting the inferior angle landmark only offsets tilting as the *z*-axis is unchanged and changes in the landmark result in a rotation about the *z*-axis (tilt). The errors for this landmark can be reasonably large (1 cm) with minimal affect on the angular offset (2–3°) because of the relatively large distance between landmarks.

The majority of 3D scapular kinematic studies are non-invasive and incorporate either the use of an electromagnetic or optical motion tracking system using surface skin sensors, or a palpation method to track the underlying scapula during humeral elevation (Ebaugh et al., 2005; Hébert et al., 2002; Lin et al., 2005; Ludewig et al., 1996; Ludewig and Cook, 2000; Meskers et al., 1998, 2007; Tsai et al., 2003; van der Helm and Pronk, 1995). Prior research has identified that surface sensor tracking of the scapula above 120° humeral elevation is substantially affected by skin motion artifact (Karduna et al., 2001). As a result of using the bone-fixed method of data collection, we were able to precisely track scapular motion above 120° of humeral elevation without skin artifact error. A non-constant discrepancy between elevation angles was observed between scapular position described by the original and current standards during humeral elevation. Differences were greatest at increasing degrees of humeral elevation. This indicates in interpreting shoulder kinematic literature, one must take into consideration which standard was used (initial versus current), as well as the range of motion being described.

As our results indicate that the scapular landmarks chosen impact the reported 3D kinematic values, it is essential that authors clearly describe which landmarks were used in reporting their data. Moreover, comparisons between 3D scapular kinematic studies need to relate the method of data description and the resulting influences when comparing the results. Kinematic studies that use the current ISB standard will not result in the same kinematic values as data collected using the original standard, even if the underlying motion and position were identical.

The primary rationale for a change from the AC landmark in the current ISB standard was the potential for singularity pertaining to scapular upward rotation approaching 90° during end-range humeral elevation (de Groot, 1997). Although our "*n*-value" was relatively small, the current investigation brings into question the prevalence of the singularity phenomenon occurring with scapular upward rotation described using the original standard. None of the subjects that we analyzed at end-range scapular plane abduction reached scapular upward rotation values that neared a singular position, even including subjects nearing 170° humerothoracic elevation (Table 1). This means in our sample population, even subjects that achieved end-range elevations did not encounter confounding scapular upward rotation positions in which internal rotation and tilt positional orientations become unsolvable (Zatsiorsky, 1998). It is possible that subjects with a larger range of motion could reach a near singular position, but range of motion above 120° may not be routinely accurately measurable with non-invasive methods.

Using a palpation method, de Groot (1997) presented data demonstrating increased standard deviations for scapular internal rotation and tilt, and high scapular upward rotation values at or near end-range humerothoracic arm abduction in a sample of five healthy male subjects. However, these data are based on a scapula to global reference frame description, which increased the upward rotation values as compared to the standard scapulothoracic description. Further, all of the potential concerns with scapular positions identified were above 135° of humerothoracic elevation. Most functional motion of the humerus occurs below 120° of humerothoracic elevation (Pearl et al., 1992). There is also no evidence of valid surface sensor or palpation based data above 120° of humerothoracic elevation (de Groot, 1997; Karduna et al., 2001). Although palpation methods are reliable, they have not been validated to bone-fixed measures in actively elevated positions. The vast majority of scapular kinematic studies utilize surface sensors over the scapula or the palpation method. Since validity of measures at higher angles is unknown, higher ranges of motion are not often a component of functional motion (Pearl et al., 1992), and our bone-fixed scapular measurements did not approach gimbal-lock for any subjects, even at end-range elevation, the concerns regarding use of the AC joint landmark may be overstated. Because of the clinical interpretation of upward rotation as occurring about an axis perpendicular to the scapular plane, if researchers are most interested in accurately representing this plane and not measuring end-range motions, it may be justifiable to use the original standard.

As shoulder kinematics research evolves, investigators will continue their analyses of not only shoulder function and dysfunction, but also the methods and protocols for how data are measured and reported. When the ISB first introduced recommended standards, their stated goals included encouraging their use, providing first hand feedback, and facilitating revisions. Various methods have been proposed to quantify scapular position, two of which have been recommended as standards at one time or another. Neither standard is typically used in imaging studies, where the reference frame is commonly based off of the glenoid. The Pearl et al. method is more closely aligned with the glenoid based coordinate system than the current standard. This approach also lowers the scapular upward rotation value similarly to the current standard, thus reducing any risk of singularity in measurement of end-range of elevation motions. This approach merits further consideration in shoulder biomechanics research as the coracoid is also a consistently palpable landmark.

The limitations of this study include a relatively small sample size of 11 asymptomatic subjects, and invasive testing methods of shoulder motion. Despite the sample size, our study was adequately powered to find statistical and clinically meaningful differences, because the standards were compared within subjects for the same motion. For the comparisons made to the anatomical model, between subject variation is not represented. However, for the original and current standard comparisons, the anatomical model was representative of the in vivo results with model rotations within 2° of the average in vivo values.

Subject pain ratings were monitored throughout motion testing with a relatively low average pain rating of under 2/10 and thus pain was not believed to interfere with measurement of normal shoulder motion. Moreover, for purposes of this analysis, the only shoulder motion analyzed was that of humerothoracic elevation in the scapular plane. Discrepancies between the standards may be greater in other planes of motion. Also the humeral motion was forced to an average scapular plane of 40° anterior to the coronal plane. For individual subjects, their true scapular plane may be greater or less than this average plane. The initial position with the arms relaxed at the side represents the smallest possible differences between the standards.

Because of the discrepancy that we found between the two accepted standards, and the standards and alternative approaches, we advocate clear description in published articles and presentations which standard is used and careful comparison of data between studies, accounting for the offsets in values. We also advocate further consideration of the use of the Pearl et al. method. The choice of axis system will also influence values determined in calculations of scapulohumeral rhythm.

5. Conclusions

The current ISB standard reported scapular orientations with decreased internal rotation, decreased upward rotation and increased posterior tilt when compared to the original ISB standard. Non-constant discrepancies were found such that greater discrepancies occurred at higher angles of humerothoracic elevation for both scapular upward rotation and tilting. Our study of asymptomatic shoulders detected no incidence of gimbal-lock with either standard, even at end-range humerothoracic elevation. The alternative proposed method was more closely aligned to the glenoid based coordinate system than the current standard. This alternative method appears worthy of further consideration as shoulder kinematic measurement further evolves. However, the alternative method over represents the anatomical scapular plane and the current standard under represents it. If the plane of the scapula is deemed the most critical in a particular measurement application, the original standard may be appropriate.

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