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Comparing in vivo three-dimensional shoulder elevation kinematics between standing and supine postures

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Background: It is often assumed that body posture, standing vs. supine, changes shoulder muscle activation and range of motion, but these altered shoulder mechanics have not been objectively assessed. We expected the supine posture might facilitate scapular rotation and change subacromial pressure. The purpose of this study is to evaluate the influence of body posture on shoulder kinematics during arm elevation.

Methods: Ten males and eight females with a mean age of 33 years participated in this study. Shoulder kinematics were assessed during scapular plane elevation in the standing and supine postures by using single-plane fluoroscopic images. Kinematics were measured using 3-dimensional to 2-dimensional model-image registration techniques: matching the 3-dimensional bone model derived from computed tomography onto each fluoroscopic image. Glenohumeral superior/inferior translation, acromiohumeral distance, and scapular rotations were compared between the postures. The effect of sex also was evaluated.

Results: With the arm at the side position, the humeral head in the supine posture was located 0.5 mm superior compared to the standing posture ($P < .001$). During humeral elevation, the humeral head significantly shifted more inferiorly in the supine posture than in standing; the biggest mean difference was 0.6 mm, $P = .003$. But acromiohumeral distance during elevation was not significantly affected by the body posture ($P = .05$). Scapular upward rotation and posterior tilt were significantly different between the postures ($P < .001$). Sex had statistically significant, but quantitatively small, effects on shoulder kinematics.

Conclusions: Body postures affect shoulder kinematics during humeral elevation. This knowledge will be useful to optimize rehabilitation exercises and for diagnostic insight.

Physiotherapy plays an important role in conservative treatment as well as in postoperative rehabilitation for various shoulder disorders, such as rotator cuff tendinopathy,[28] glenohumeral arthritis,[23] or pseudoparalysis.[20] Functional shoulder motions are mostly done in the standing or sitting posture for activities of daily living, but shoulder exercises are often performed in the supine posture.[31,39] We expect that supine exercise would work for scapulothoracic muscle fatigue syndrome, such as scapular dyskinesis, to reduce required muscle force, to assist in scapular rotation, and to correct thoracic alignment. Although humeral and scapular kinematics can differ between body postures, little is known about the differences in shoulder kinematics between the standing and supine postures during humeral elevation. The comparison

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between postures might illuminate the facilitating effect of scapular rotation and the risk of subacromial pain and be useful as an adjunct to the diagnosis and treatment of shoulder disorders.

Previous studies have demonstrated that changes of body posture can cause different shoulder kinetics. Electromyographic examination has demonstrated differentiated recruitment of five deltoid muscle regions for activity in different body postures.[29] Similarly, a supine posture induced shoulder repositioning error at 90° and 110° and decreased the percentage of maximum voluntary contraction for the anterior deltoid.[38] The active abduction range of shoulder motion in an erect posture averaged 23.6° more than that in a slouched posture.[14] Evaluations of acromiohumeral distance (AHD) demonstrated greater space in healthy volunteers than in thoracic hyperkyphotic cases in the standing posture.[5] However, continuously measured values for humeral position and scapular rotation in different postures have not yet been reported. Furthermore, several studies have demonstrated sex differences in scapular kinematics.[35,36] Rotator cuff thickness,[13] muscle strength,[37] humeral bone length,[1] and acromiohumeral structure[10] are different between sexes, thus sex may also affect the amount of kinematic and AHD change between the postures.

To elucidate three-dimensional (3D) motion of the shoulder, various techniques have been used in recent studies such as radiostereometric analysis,[7] electromagnetic tracking devices,[22] magnetic resonance imaging,[33] or computerized tomography (CT).[27] Three-dimensional to two-dimensional (2D) image registration techniques are also commonly used for in vivo dynamic analysis and can provide suitable accuracy for various natural joints as well as prosthetic joints.[8,34,44] This method avoids the use of skin-attached markers, which are difficult to use in the supine posture and do not rigidly track the motion of the underlying bones. The method only requires CT and single-plane fluoroscopy capabilities, which are widely available.

The primary purpose of this study was to evaluate the influence of body posture, standing or supine, on shoulder kinematics during arm elevation in the scapular plane using 3D to 2D image registration techniques. We hypothesized that the humeral head would be positioned more superiorly in the supine posture than in the standing posture during elevation, due to the effect of gravity, and that would result in smaller AHD and shifted scapular kinematics across the arc of motion. This study also aimed to assess sex differences in shoulder kinematics as a secondary outcome.

Materials and methods

Participant information and consent

The study protocols for image acquisition and data analysis were approved by the Research Ethics Committee at both Sapporo Medical University and Hokkaido Esashi Hospital. Eighteen healthy volunteers who had no complaint around the shoulder girdle were prospectively recruited for this study. All participants were examined for the absence of past history, contracture, rotator cuff impairment, and any shoulder joint deformity by a single surgeon (A.S.). Both upper extremities were included except for one male right shoulder with a history of throwing pain and an apparent deficit of internal rotation. Thus, the remaining 35 shoulders were included in this study. They consisted of 10 males and 8 females with a mean age of 33 years (range, 19-47 years). All subjects received approved explanation for this study including the risk of radiation exposure, and they provided informed consent. There was particular concern for truly informed consent in the female volunteers; thus, we recruited female subjects among medical workers who were familiar with the risk of radiation.

Image acquisition and 3D modeling

A single-plane flat-panel pulsed fluoroscopy system (Sonialvision G4; Shimadzu, Kyoto, Japan) was used to record scapular plane elevation (field of view, 375 × 375 mm or 421 × 421 mm; pixel spacing, 0.28 × 0.28 mm), and the recording frequency was set at 6 Hz to diminish radiation exposure.[42] First, the participants stood without any constraints with their back at approximately 30° to the x-ray beam so that the scapular body was parallel to the image intensifier. Then, they were asked to elevate the arm in the scapular plane from the arm at the side with neutral forearm rotation to maximum active elevation (average apparent angle, 177°) with external forearm rotation so that the thumb pointed backward at end range of motion. The motion was performed at a comfortable pace, at approximately 3 seconds per activity. Before recording fluoroscopic images, the volunteers practiced the motion several times until feeling comfortable, and three trials of the activity were recorded for each shoulder. To minimize the influence of muscle fatigue, there was a pause for few seconds between trials. For examination in the supine posture, the participants lay down with their back against a padded examination table. The activity and recording procedures were the same as for examination in the standing posture.

CT scans (Revolution GSI; GE Healthcare, Milwaukee, WI, USA) of the shoulder were acquired with a 0.625-mm slice pitch (image matrix, 512 × 512; pixel spacing, 0.59 × 0.59 mm). From these images 3D models of the humerus and scapula were created using a segmentation software program (ITK-SNAP; Penn Image Computing and Science Laboratory, Philadelphia, PA, USA). Anatomical coordinate systems were set in each 3D bone model using a 3D modeling software program (Geomagic Studio; 3D Systems, Rock Hill, SC, USA). Similar to previous studies,[16,25] the origin of the humerus was set at the centroid of the best-fit sphere of the humeral head. The y-axis was defined as a line parallel to the humeral shaft (Fig. 1, *A*). The neck plane was determined by selecting three points on the anatomical neck, and the z-axis was set so that it was parallel to the line formed by the neck plane and the plane perpendicular to the y-axis.[25] The x-axis was perpendicular to both the y- and z-axis. The scapular coordinate system was set according to previously reported methods (Fig. 1, *A*).[25]

Model image registration and data processing

Using a validated open-source software program (JointTrack; www.sourceforge.net/projects/jointtrack),[18,25] bone models were projected onto the fluoroscopic images, and 3D positions and orientations were determined by repeated adjustment to match the silhouettes of the bone models with the silhouettes on the fluoroscopic images. The root-mean-square errors of this matching method with single-plane fluoroscopic images were in-plane translation, 0.47 mm; out-of-plane translation, 1.53 mm; in-plane rotation, 0.76°; out-of-plane rotation, 3.72°.[25] A single surgeon (A.S.) performed the measurement procedure for all shoulders with fluoroscopic images from one trial that had the best image quality.

Humeral and scapular rotations relative to the coordinate system of the fluoroscopic images and the glenohumeral joint kinematics were computed using Cardan angles (z-x-y order).[16,25] Humeral elevation was defined as the absolute angle between the humeral y-axis and the vertical axis of the image (Fig. 1, *B*). The position of the humeral origin relative to the scapular origin along the scapular y-axis was defined as glenohumeral superior/inferior position. Scapular rotations around the image x-axis and the

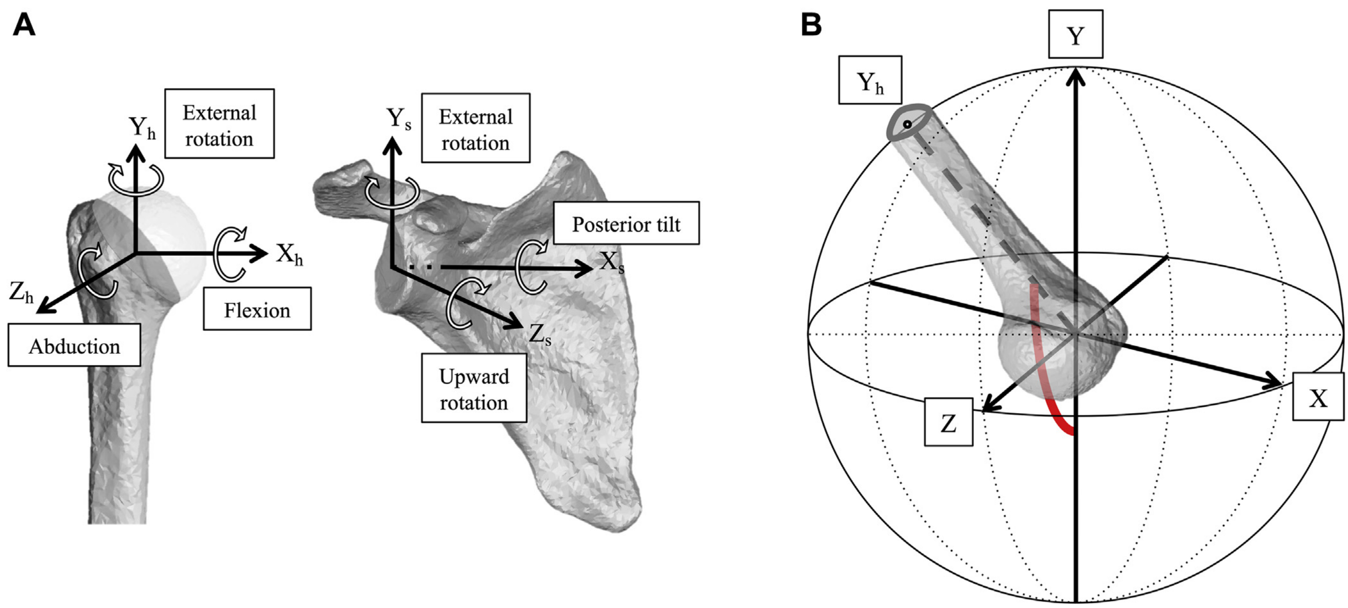

Figure 1 (**A**) The anatomic coordinate system of humerus and scapula on the *right* side. *Left* shoulders had similar coordinate systems, but positive rotations according to anatomic directions. (**B**) Y-axis, the vertical axis in the room; Z-axis, the axis perpendicular to the image detector; black dotted line, the humeral longitudinal axis (Y_h-axis); red curved line, the absolute angle defined as "humeral elevation."

z-axis were represented as the anterior/posterior tilt and the upward/downward rotation, respectively (Fig. 1, *A*). Moreover, AHD was computed using a custom program (MATLAB; The MathWorks Inc., Natick, MA, USA) as the closest distance between the inferior surface of the acromion and the proximal humerus including the greater tuberosity and humeral head. For evaluating intraobserver reproducibility, each measurement was retried three months after the first examination. The intraclass correlation coefficients were 0.87 in the glenohumeral superior/inferior position, 0.95 in AHD, and 0.99 in scapular upward rotation and posterior tilt.

To account for differences in subject size, displacements (eg, superior/inferior position) and distances (eg, AHD) were normalized with the humeral head diameter of each shoulder, which was represented by the diameter of the best-fit sphere of the humeral head. The corrected measurement value in each case was calculated by using the following formula: (individual value/individual humeral head diameter) × (mean humeral head diameter of all subjects), a method previously used for size normalization of contact kinematics in total knee arthroplasty.[8,40] The kinematic data were plotted as a function of the humeral elevation angle and interpolated by a spline curve. The data were calculated based on the spline curve at each 10° increment of humeral elevation from the starting position to maximum elevation.

Statistical analysis

Statistical analyses were performed using the SPSS statistics software (version 24.0; IBM, Armonk, NY, USA). The Student's t-test was used for comparison of humeral head diameter between men and women. Two-way repeated-measures analysis of variance was used to analyze kinematic data between two body postures and between sexes in each body posture. The post-hoc paired t-test or Student's t-test was performed to compare values at each increment of humeral elevation between the postures or sexes, respectively. A *P* value <.05 was considered to be statistically significant in all analyses. In the post-hoc power analysis using this sample size for primary outcome, the power was 0.82 in the setting for two-tailed comparison, effect size = 0.5 and α error = 0.05.

Table I
Measurements of humeral head diameter.

	Total	Male	Female
Number of shoulders	35	19	16
Diameter, mm*	44.8 (3.8)	47.5 (2.4)	41.5 (2.1)
95% CI	43.5-46.0	46.4-48.6	40.5-42.5

95% CI, 95% confidence interval.
Values are given as mean (standard deviation).
*$P < .001$.

Results

Glenohumeral superior/inferior translation and AHD

The results of humeral head diameter measurements are summarized in Table I. The humeral head of males was significantly larger than that of females. All distance and displacement measures were normalized to the mean humeral head diameter for all subjects.

Humeral position relative to the glenoid was significantly affected by the different postures ($P < .001$; Fig. 2, *A*). At the initial arm position, the humeral position in the supine posture was significantly superior compared to the standing posture, averaging −0.4 ± 0.8 mm and −0.9 ± 0.8 mm, respectively ($P < .001$). As the humerus was elevated, the head in the standing posture shifted more superiorly than that in the supine posture. The biggest difference in the mean humeral position between postures was 0.6 mm at 120° humeral elevation ($P = .003$). A significant sex difference in the humeral position was seen in the standing posture ($P = .01$); the biggest mean difference was 0.6 mm at 70° humeral elevation ($P = .04$). On the other hand, there were no differences between sexes in humeral translation in the supine posture ($P = .98$, Fig. 2, *B*).

AHD depicted a monomodal change that was not significantly affected by posture ($P = .05$; Fig. 3, *A*). The smallest mean AHD in the supine and standing postures was 2.9 ± 1.5 mm at 80° and 90° humeral elevation, respectively. In comparing sexes, a significant difference was detected only in the standing posture ($P < .001$; Fig. 3, *B*),

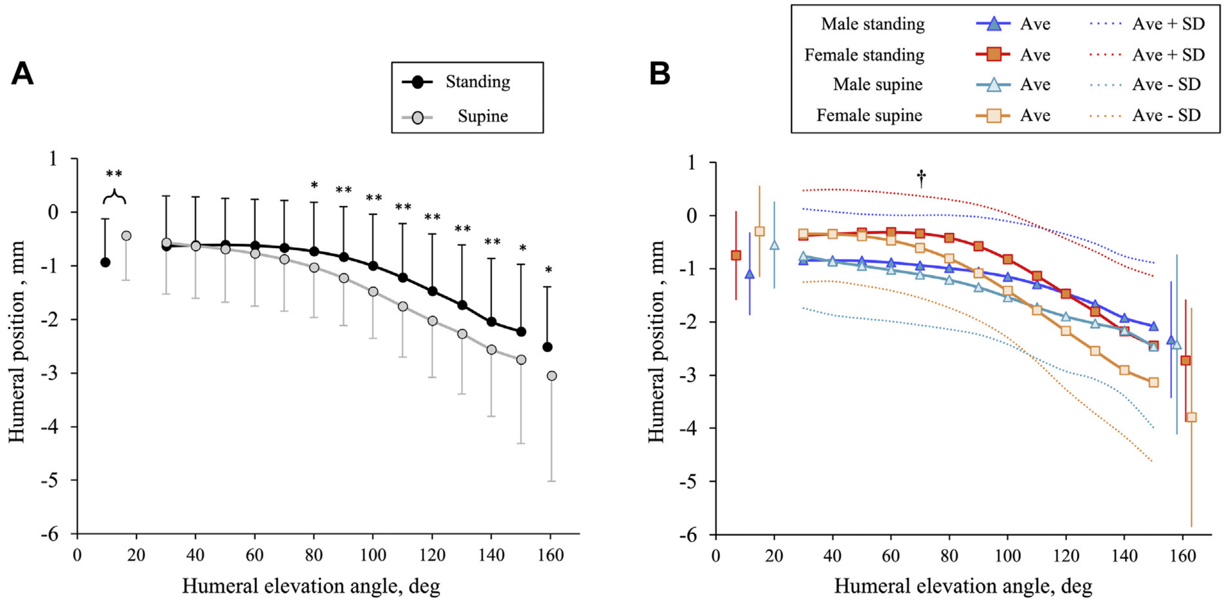

Figure 2 (**A**) Superior/inferior humeral head translation relative to humeral elevation for standing and supine postures. There was a significant difference between the postures ($P < .001$ in ANOVA). (**B**) The normalized translation measurements by gender and body posture indicated a significant difference in the standing posture ($P < .01$ in ANOVA) but not in the supine ($P = .98$ in ANOVA). *$P < .05$ and **$P < .01$ in paired t-test between the postures. †$P < .05$ in unpaired t-test between sexes in the standing posture.

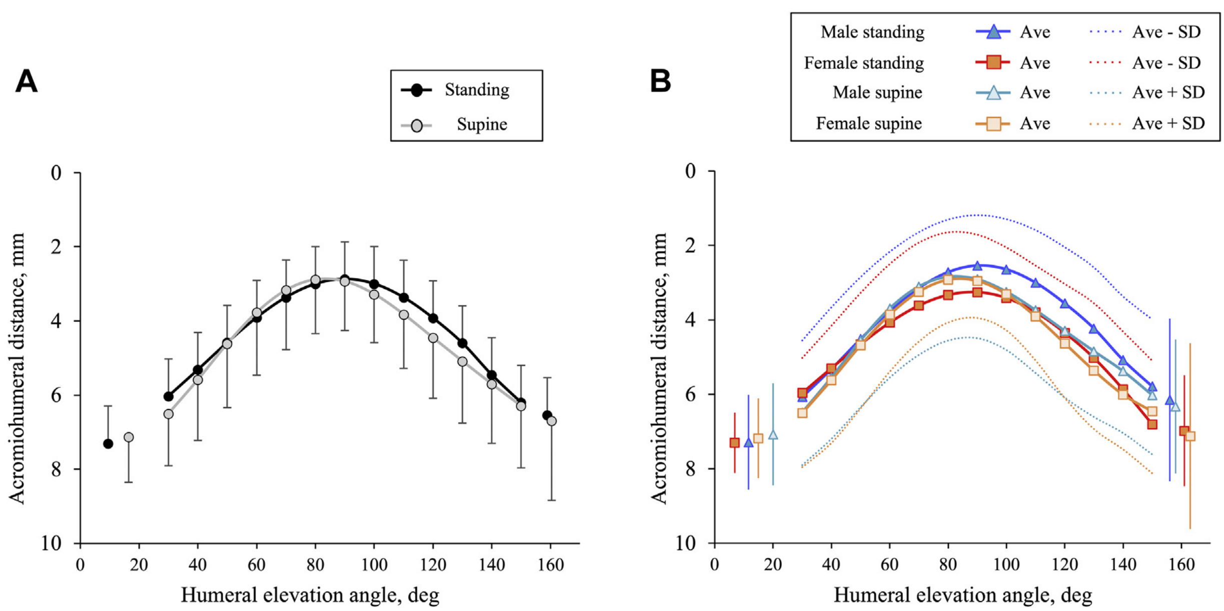

Figure 3 (**A**) Acromiohumeral distance relative to humeral elevation for standing and supine postures. There was no significant difference between the postures ($P = .05$ in ANOVA). (**B**) Normalized acromiohumeral measurements by gender and body posture indicated a significant difference between sexes in the standing posture ($P < .001$ in ANOVA) but not in the supine ($P = .08$ in ANOVA). Post-hoc tests in the standing posture did not indicate significant pair-wise differences.

but there were no significant pair-wise differences at specific elevation angles with post-hoc tests. The supine posture had no significant differences between sexes ($P = .08$).

Scapular rotations: upward rotation and posterior tilt

The scapular upward rotation angles were significantly different between postures ($P < .001$; Fig. 4, *A*). At the initial arm position, the mean upward rotations for the supine and standing postures were $27.0° \pm 6.5°$ and $5.3° \pm 6.8°$, respectively ($P < .001$). As the humerus was elevated, the difference between the postures diminished, and no pair-wise differences were detected at 100° or more of humeral elevation. In comparing sexes, there was a significant difference only in the standing posture ($P < .001$; Fig. 4, *B*). The biggest difference between sexes in the standing posture was 5.3° at 50° humeral elevation ($P = .03$).

Scapular posterior tilt was significantly greater in the supine posture ($P < .001$; Fig. 5, *A*), and pair-wise post-hoc tests revealed significant differences at all humeral elevation angles. The scapula tilted posteriorly with increasing humeral elevation, and the difference in tilt between postures also increased. There were significant differences between sexes only in the supine posture ($P < .001$; Fig. 5, *B*), and a pair-wise difference was detected only at the maximum humeral elevation ($P = .02$).

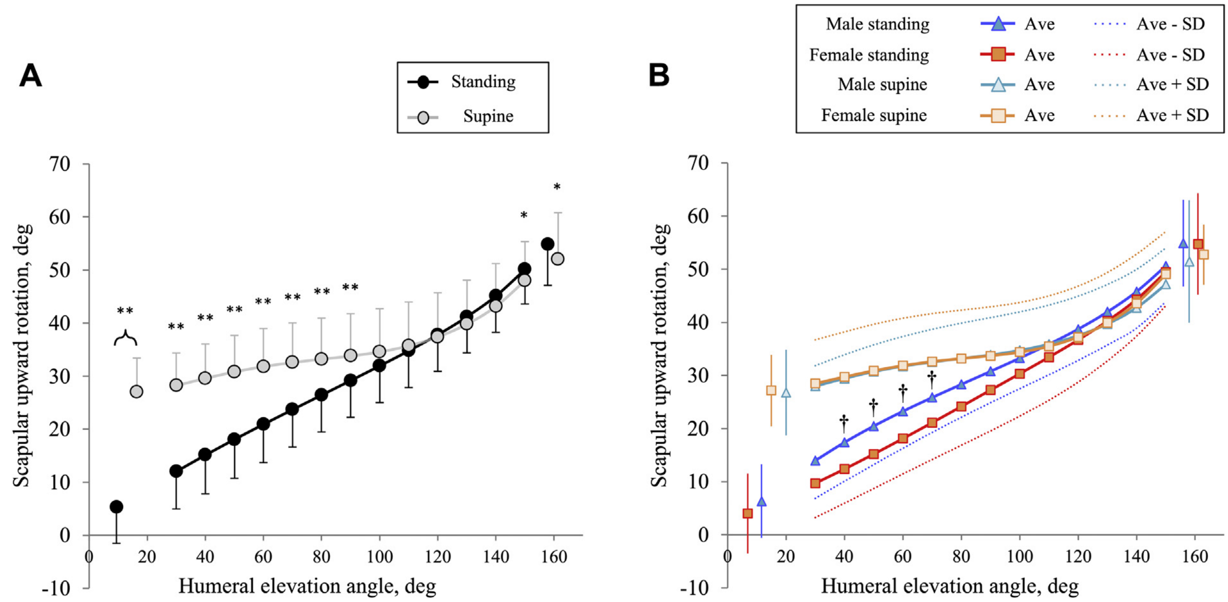

Figure 4 (**A**) Scapular upward rotation relative to humeral elevation for standing and supine postures. There was a significant difference between the postures ($P < .001$ in ANOVA). (**B**) The scapular upward rotation by gender and body posture. There was a significant difference between sexes in the standing posture ($P < .001$ in ANOVA), but not supine ($P = .65$ in ANOVA). *$P < .05$ and **$P < .01$ in paired t-test between the postures. †$P < .05$ in unpaired t-test between sexes in the standing posture.

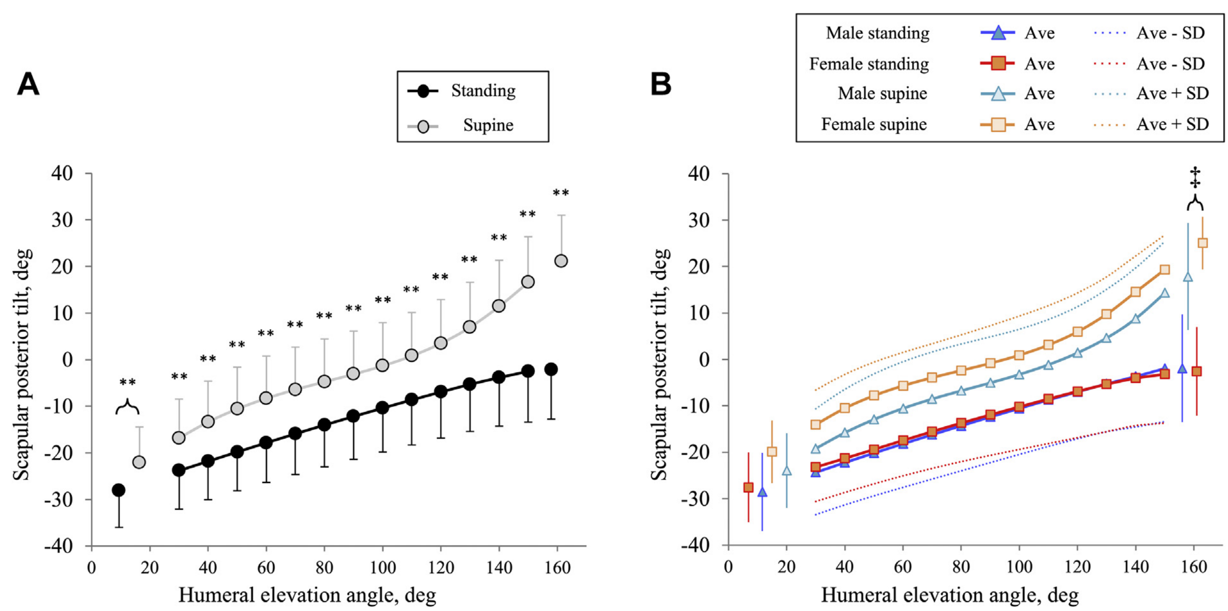

Figure 5 (**A**) Scapular posterior tilt relative to humeral elevation for standing and supine postures. There was a significant difference between the postures ($P < .001$ in ANOVA). (**B**) The tilt by gender and body posture. There was significant difference between sexes in the supine posture ($P < .001$ in ANOVA), but not in standing ($P = .72$ in ANOVA). **$P < .01$ in paired t-test between the postures. ‡$P < .05$ in unpaired t-test between sexes in the supine posture.

Discussion

This study assessed differences in shoulder kinematics during scapular plane elevation between standing and supine postures using 3D/2D image registration techniques. Humeral head position relative to the glenoid was significantly affected by body posture and sex. However, AHD showed no significant differences between postures or sexes. Scapular rotations demonstrated different kinematic patterns between postures.

Our results show that the humeral head in the supine posture was located more superiorly on the glenoid than that in the standing posture with the arm at the side; however, the humeral head in the standing posture was positioned significantly more superiorly than that in supine posture after 80° of humeral elevation. This pattern of motion is likely influenced by gravity and muscular activity. In the standing posture, the arm and humeral head may be pulled inferiorly by gravity at the resting position. And then, rotator cuff and deltoid muscle activity increase during humeral elevation against gravity. Michiels and Bodem[29] compared muscle activity between postures and reported significant reduction of the deltoid activity in the supine posture. These varying muscle activation patterns likely explain the differences in humeral translations between postures. Posture-associated humeral translation differences in healthy shoulders were statistically significant but quite small. It will be interesting in future studies to determine if these translation differences increase in unstable or pathologic shoulders.

Previous studies have reported that AHD had changed in a monomodal or parabolic pattern during arm elevation,[3,17] similar to what we observed. Our results show AHD was smaller between 60° and 120° of humeral elevation, corresponding to the painful arc,[15] with the smallest distance of approximately 3 mm regardless of the posture. We hypothesized that AHD in the supine posture would be smaller than that in the standing posture, but no significant difference was observed. This implies healthy shoulder girdle muscles and structures work to maintain AHD regardless of body posture. One cadaveric study has reported that upward rotation of the scapula decreased AHD.[12] Another study has indicated that decreased posterior tilt of the scapula was associated with smaller AHD.[5] Thus, a combination of joint forces and relative bone positions may change the area of the acromiohumeral closest point. Patients with dysfunction in scapulothoracic or rotator cuff muscles, or the glenohumeral joint capsule, may reveal differences in AHD or in closest point locations with different postures.

Confirming our hypothesis, scapular upward rotation and posterior tilt were greater in the supine posture than those in the standing posture. Upward rotation in the standing posture showed a linear pattern, which was consistent with previous reports.[2,6,9,30] On the other hand, the supine upward rotation trend changed slope at around 120° of humeral elevation. A radiographic study has also reported that scapular upward rotation in the supine posture was smaller than that in the standing posture.[19] There may be several factors associated with the differences in the scapular orientations. One factor might be the compression force to the inferior angle and the medial border of the scapula from the fluoroscopy system examination table in the supine posture.[46] The change of spinal alignment might also be associated with the differences.[11,41] In the supine posture, kyphosis of the thoracic spine decreases, and the scapulae are retracted.[4,14,21] Another factor might be gravity. In the standing posture, the weight of the arm can rotate the scapula downward. The key observation is that the supine posture places the scapula in an ideal position for arm elevation, with consistent retraction, and this posture may be useful to assist scapular motion in shoulders with dysfunction.

We normalized humeral translations according to humeral head diameter because we assumed that kinematic differences between sexes would be due to the difference in body size, specifically bone geometry.[13,26] For example, AHD in females would be narrower than that in males, but it does not translate to women have a higher risk of subacromial impingement. To our knowledge, this method for normalizing distances and displacements in the shoulder has not been previously reported, but similar schemes are used to size-normalize displacements in other joint studies.[8,40] After normalization, the differences between sexes tended to be small and may be clinically irrelevant. Scapular rotations also showed quite a similar kinematic tendency between sexes. Muscle strength would also influence their kinematics to some extent,[36] but this study suggested that kinematic differences between sexes may be quantitatively small in unloaded scapular plane elevation.

This study has several limitations. First, the 3D to 2D image registration techniques using single-plane fluoroscopy have poorer accuracy in out-of-plane evaluation.[25] We chose the single-plane analysis because of the lower radiation exposure and broader field of view than bi-plane analysis. Second, this study included bilateral shoulders. Previous studies have indicated kinematic differences between dominant and nondominant shoulders.[36,45] The influence of hand dominance should be small because the primary purpose of this study was to compare kinematics between the postures. Finally, the definitions of coordinate system and joint motion in this study were not provided according to the recommendation of International Society of Biomechanics, which are intended primarily for use with skin-affixed markers and motion capture.[43] We followed previous studies that used similar techniques, so the results can be compared directly.[16,24,26,32] Despite these limitations, this study reports significant differences in shoulder kinematics between body postures and provides a new normative basis for healthy shoulder kinematics. Comparing shoulder mechanics in multiple postures may be useful to reveal subtle muscular weakness or stiffness around the shoulder girdle or other shoulder dysfunction. We believe this new knowledge will contribute to future investigations of pathological shoulders.

Conclusion

We analyzed dynamic shoulder kinematics during scapular plane elevation between standing and supine postures using 3D to 2D image registration techniques in healthy shoulders. The body posture affected the humeral head translation relative to the glenoid, but there were no differences in AHD. Scapular kinematics, especially upward rotation and posterior tilt, were significantly different between the postures. Understanding the differences in shoulder kinematics between the postures will be helpful to develop physiotherapy maneuvers and to provide diagnostic insight for shoulder dysfunction in practice.

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