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ORIGINAL RESEARCH

Errors in Shoulder Joint Position Sense Mainly Come from the Glenohumeral Joint

Yin-Liang Lin[1,2] and Andrew Karduna[1]
[1]University of Oregon; [2]Lerner Research Institute, Cleveland Clinic

While synchronous movement of the glenohumeral and scapulothoracic joints has been emphasized in previous kinematics studies, most investigations of shoulder joint position sense have treated the shoulder complex as a single joint. The purposes of this study were to investigate the joint position sense errors of the humerothoracic, glenohumeral, and scapulothoracic joints at different elevation angles and to examine whether the errors of the glenohumeral and scapulothoracic joints contribute to the errors of the humerothoracic joint. Fifty-one subjects with healthy shoulders were recruited. Active joint position sense of the humerothoracic, glenohumeral, and scapulothoracic joints was measured at 50°, 70°, and 90° of humerothoracic elevation in the scapular plane. The results showed that while scapulothoracic joint position sense errors were not affected by target angles, there was an angle effect on humerothoracic and glenohumeral errors, with errors decreasing as the target angles approached 90° of elevation. The results of a multiple regression analysis revealed that glenohumeral errors explained most of the variance of the humerothoracic errors and that scapulothoracic errors had a weaker predictive relationship with humerothoracic errors. Therefore, it may be necessary to test scapular joint position sense separately in addition to the assessment of the overall shoulder joint position sense.

Keywords: coordination, proprioception, scapula

Coordination of movement between the scapula and humerus is important for providing smooth and efficient motion of the entire shoulder complex. Assessing the synchronous movement of the glenohumeral and scapulothoracic joints has been emphasized in both clinical practice[1] and research investigations.[2–5] Scapular position influences the articulation of the glenohumeral joint and the length of the muscles around the glenohumeral joint.[1,6] During arm elevation, the seminal work of Inman et al demonstrated that the scapulothoracic joint contributes approximately one-third of the range of motion of the humerothoracic joint.[5] Recent studies have found that the scapula rotates with three-dimensional motions, consisting of upward rotation, posterior tilt, and external/internal rotation.[7,8]

Precise movement patterns depend on appropriate sensory input.[9] Proprioception is a type of sensory input originating from Golgi tendon organs, muscle spindles, and the mechanoreceptors of the muscles, tendons, joint capsule, ligaments, and tissues around the joint.[10] There are 3 submodalities of proprioception: joint position sense (JPS), kinesthesia, and sensation of resistance.[10] Besides input from the visual and vestibular systems, the central nervous system relies on proprioception information to maintain functional joint stability.[9]

For the shoulder complex, JPS has been tested with several different models, in which an error between a presented target and repositioning position represents the accuracy of JPS. Paradigms that use passive positioning with either active or passive repositioning are commonly reported in the literature.[11,12] Other studies have used the paradigm of active joint position sense, in which the subject actively moves to the target position and then actively reproduces the target.[13–16] Motion in different planes has been used to test shoulder JPS, including internal and external rotation,[12,14,15] elevation in different planes,[13,16] and functional movements.[17,18] Since most functional activities involve muscle contraction, the active joint position sense may better represent the afferent input necessary for functional activities.[13] Elevation may be a more appropriate protocol for representing functional activities, as internal and external rotation mainly comes from the glenohumeral joint and is not as functional a movement for the general population.

Although many kinematic studies focus on the coordination patterns of the glenohumeral and scapulothoracic joint, most of the studies investigating shoulder JPS have treated the shoulder complex as a single joint and only measured the motion of the humerothoracic joint.[11–16] Only 4 studies were identified that have investigated JPS of the scapulothoracic joint. Tripp et al[18,19] conducted 2 studies testing the effect of fatigue and testing position on multijoint position reproduction acuity of throwing motion. They used three-dimensional variable errors scores, which combined the errors in different directions to represent the overall JPS of the scapulothoracic, glenohumeral, elbow, and wrist joints. Two other studies specifically measured the scapular JPS in scapular elevation/depression and protraction/retraction.[20,21] It is still unknown whether JPS errors of the glenohumeral and scapulothoracic joints contribute to JPS errors of the humerothoracic joint in function movements.

In healthy subjects, it has been shown that the JPS errors of the humerothoracic joint decrease as the target angles approached 90° of arm elevation.[13,22–24] JPS errors of the elbow have shown the same pattern.[25] Therefore, the purpose of this study is to investigate the JPS errors of the glenohumeral and scapulothoracic joints at

Lin and Karduna are with the Department of Human Physiology, University of Oregon, Eugene, Oregon, USA. Lin is also with the Department of Biomedical Engineering, Lerner Research Institute, Cleveland Clinic, Cleveland, Ohio, USA. Address author correspondence to Andrew Karduna at karduna@uoregon.edu.

different elevation angles and to examine whether both errors of the glenohumeral and scapulothoracic joints would contribute to the errors of the humerothoracic joint. We hypothesized that both errors of the glenohumeral and scapulothoracic joints would follow the same pattern as those of the humerothoracic joint, and errors of both the glenohumeral and scapulothoracic joints would be correlated with the errors of the humerothoracic joint.

Methods

Subjects

Fifty-one healthy subjects (21 males and 30 females; 7 left-handed and 44 right-handed) with an average age of 21.1 years (SD 3.5), average body mass of 66.6 kg (SD 14.1), and average body height of 168 cm (SD 9) were recruited for this study. Anyone with a history of shoulder or neck disorders in the past 3 years was excluded. The study was approved by the Office for Protection of Human Subjects at the University of Oregon and all subjects signed an informed consent form.

Instrumentation

Thoracic, scapular, and humeral kinematics were sampled at 120 Hz with a magnetic tracking device (Polhemus Liberty, Colchester, VT, USA), which included a transmitter, 3 sensors, and a digitizer. The accuracy of the tracking device is 0.15°, as reported by the manufacturer. The sensors were mounted on the manubrium of the sternum, the flat area of the acromion, as well as on the distal humerus via a custom-molded Orthoplast cuff and Velcro strap.[3,13] The transmitter was positioned posterior to the subject and at the height of the subject's shoulders. The subject sat on an ergonomically designed kneeling chair (Better Posture Kneeling Chairs, Jobri, Konawa, OK, USA) and fitted with a head-mounted display (Z800, eMagine, Bellevue, WA, USA). The display blocked visual feedback of upper extremity motion, and also displayed the target angle and real-time humerothoracic angle to the subject (Figure 1).

Figure 1 — Sensor placement and testing position.

Anatomic landmarks were palpated and digitized, using the standards recommended by the International Society of Biomechanics (ISB).[26] The thoracic anatomic coordinate system was derived from the T8, xiphoid process, C7, and jugular notch. The digitization points for the scapula were the root of the scapular spine, the inferior angle of the scapula, and the laterodorsal point of the acromion. The humeral coordinate system was defined with the second option of the ISB proposed standard, which includes the center of the humeral head, medial epicondyle, lateral epicondyle, ulnar styloid process, and medial styloid process.[26] The center of the humeral head was calculated using a least squares algorithm and was defined as the point that moved the least during several small arcs of motion.[27]

Protocol

JPS was tested with an active position reposition protocol and on the dominant shoulder. The protocol was modified from the work of King and Karduna.[28] There were 3 target positions of humerothoracic elevation in the scapular plane (50°, 70°, and 90°). Each target position was repeated 4 times, resulting in 12 trials. The order of the trials was randomized and there was a 5-second break between each trial. The subject was instructed to practice at least 3 sets of 3 successive arm elevations in the scapular plane to help with familiarization of the motion. Since JPS errors were not found to vary between planes of elevation[13] and shoulder movements occur more often and naturally in the scapular plane,[29] this plane was chosen for testing.

LabVIEW (Version 2012, National Instruments, Austin, TX, USA) was used to control visual and auditory guides during testing. At the beginning of the trial, a black screen was displayed and the subject was asked to relax with the arm at their side. Two white lines were shown on a black screen, indicating the boundary of the predetermined target position (positive and negative 1° from the target). For all target angles, the white lines were always set at the same position of the screen. The subject was instructed to elevate the arm with the elbow extended and thumb pointing up. A dynamic red line, representing real-time humerothoracic angles of the subject, appeared on the screen when the humerothoracic angle was within 10° of the target. In addition, when the subject deviated more than 5° from the scapular plane (35° anterior to the frontal plane), a vertical green line would appear on the side of the screen, which prompted the subject to move away from the line and back into the scapular plane (Figure 2).

The subject was instructed to elevate the arm until the red line was positioned between the white lines, with no green line displayed. After the subject had maintained the red line between the white lines for 1 second, the target disappeared and only a black screen was left. For the rest of the trial, the display remained black, thus removing all visual feedback. The subjects were instructed to hold their arm at the target position and memorize their arm position (3 s) until

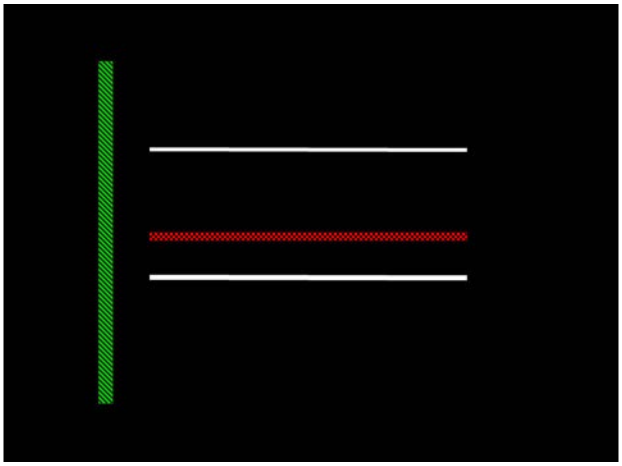

Figure 2 — The target shown in the head-mounted display. The white lines indicate the target. The red line (checkerboard pattern for print publication) represents the real-time humerothoracic elevation angle. If the testing arm is the right arm, as in this example, the appearance of the left green line (diagonal stripes for print publication) indicates the arm deviates from the scapular plane to the midline.

they heard verbal instructions from the computer, indicating that they should return the arm to the side. After holding the arm at the side for 2 seconds, another verbal cue from the computer prompted the subject to reposition their shoulder to the target position without any visual guide. When the subjects believed the target had been reached, they pushed a button on a wireless trigger with their contralateral hand. This triggered a verbal cue for the subject to relax their arm to the side, at which point the trial ended. Between trials, a blue screen was displayed with a countdown timer and instructions to keep the arm at the side. No feedback related to the accuracy of performance was provided to the subjects.

Data Reduction

Based on the ISB standard for the humerothoracic and glenohumeral motion, the following Euler sequence was used: plane of elevation, elevation, and axial rotation. Because the plane of elevation and axial rotation were controlled, only the errors in elevation were considered for the humerothoracic and glenohumeral joints. For the scapulothoracic joint, because the scapula was not constrained in 1 dimension, we chose to use the helical angle to represent the scapulothoracic motion. The helical angle is the rotation angle about the helical axis.[30] Although the helical axis is not aligned with the anatomic axes, the helical angle represents the scapulothoracic three-dimensional angular motion.

The humerothoracic and glenohumeral elevation angles of the subject at the presented target position during the holding time (3 s) were averaged (θ_p). The repositioned elevation angle was the angle at the moment that the subject pushed the trigger (θ_r). For the humerothoracic and glenohumeral elevation angles, the error (θ_e) was the difference between the angles at the repositioned position and present target position ($\theta_e = \theta_r - \theta_p$).

The rotation matrix of the scapulothoracic joint at the presented target position and at the midpoint of the holding time was recorded (R_p). The rotation matrix of the scapulothoracic joint was also recorded at the moment that the trigger was pushed (R_r). The error of the scapular helical angle (θ_e) was derived from the rotation matrix at the repositioned position with respect to that at presented target position ($R_{pr} = R_p^{-1} \cdot R_r$).

For the humerothoracic and glenohumeral joints, θ_e could be either positive or negative, representing that the repositioning position overshot or undershot the target position, while for the scapulothoracic joint, θ_e was always positive and it was hard to define the overshoot or undershoot according to the direction of the helical axis. Therefore, root-means-square (rms) errors were calculated for the humerothoracic, glenohumeral, and scapulothoracic joints to represent overall JPS errors, which combines accuracy and precision.[31] The equation below was used for this calculation (n is number of repetitions for each target angle, which was 4 in the current study).

$$\text{Root-mean-square error } = \sqrt{\left(\frac{1}{n}\right)\Sigma_{i=1}^{n}\left(\theta_e\right)^2}$$

Statistical Analysis

A one-way repeated-measure analysis of variance (ANOVA) was used to examine the difference of the errors between the target elevation angles for each joint. The dependent variables were rms errors of humerothoracic, glenohumeral, and scapulothoracic joints. The independent variable was elevation angle, which had 3 levels: 50°, 70°, and 90°. If there was an effect of angle, post hoc polynomial contrasts were conducted to test whether the trends were linear. The significance level was set at .05.

A Pearson correlation was used to examine the relationship of the errors between joints. Then a multiple regression model was run to investigate the contribution of the glenohumeral and scapulothoracic errors to the humerothoracic errors at each elevation angle. Unique variance (ΔR^2) was also calculated to show the variance of the humerothoracic errors that were explained by only either the glenohumeral errors or scapulothoracic errors.

Results

There was a significant effect of angle on the rms errors of the humerothoracic and glenohumeral joints ($P < .001$) (Figure 3A, 3B). The linear contrasts revealed significant linear decreases in the rms errors of the humerothoracic and glenohumeral joints ($P < .001$) as the target angle increased. However, the scapulothoracic rms errors were around 3° at each target angle and the effect of angle on the scapulothoracic errors was not significant ($P = .55$) (Figure 3C).

The results of the Pearson correlation show that the correlation between the humerothoracic and glenohumeral errors was stronger ($r = .76$–$.90$) than the correlation between the humerothoracic and scapulothoracic joints ($r = .13$–$.70$), especially at 70° and 90° (Table 1). Therefore, when the regression model was run, the glenohumeral errors were entered first (Table 2). At each angle, the model with the predictors of the glenohumeral and scapulothoracic errors was significant and explained more than 60% of variance in the errors of the humerothoracic joint. Of the 2 predictors, the glenohumeral joint had a stronger predictive relationship with the humerothoracic joint than the scapulothoracic joint, based on the standardized regression coefficient (β) and ΔR^2. At the target position of 70°, the scapulothoracic error was not a significant predictor of the humerothoracic joint. For all target angles, for each 1° increase in the glenohumeral error, there was an increase in the humerothoracic error, which ranged from 0.87° to 1.08°. Each 1° increase in the scapulothoracic error resulted in an increase (0.18° to 0.91°) in the humerothoracic error.

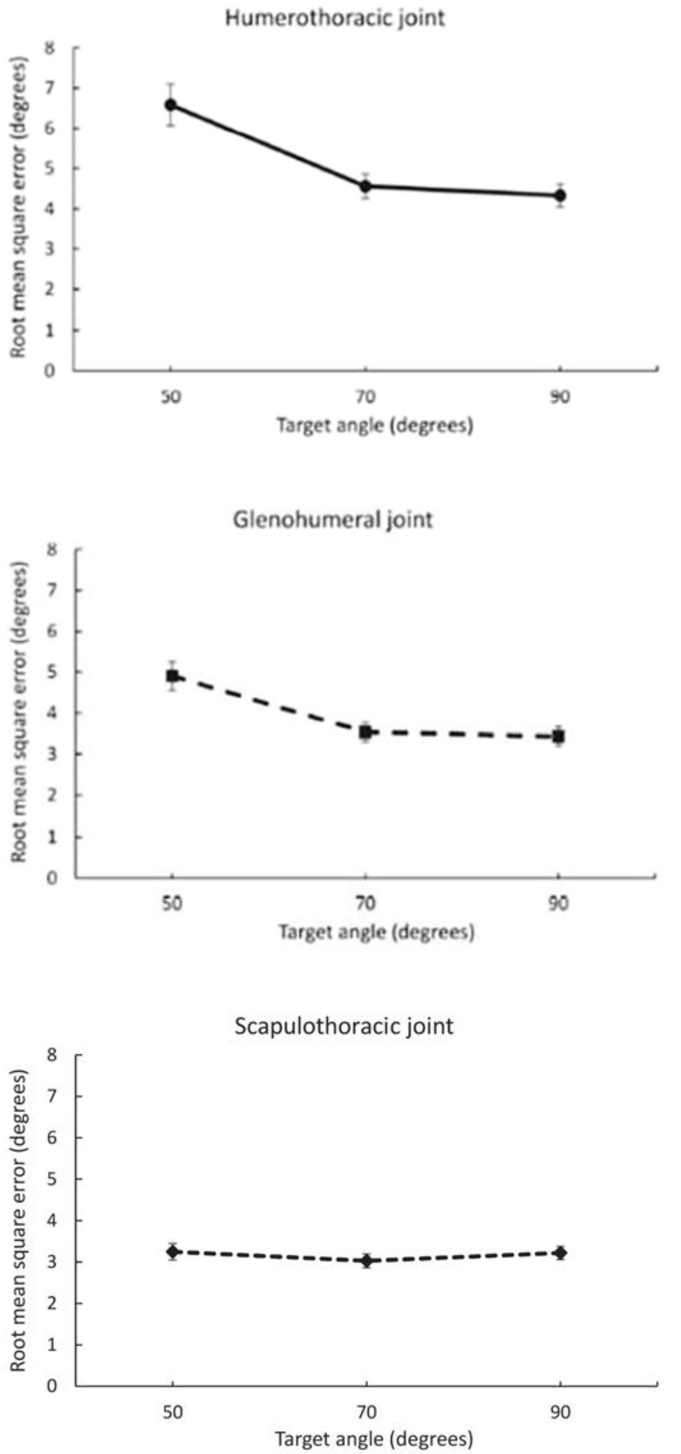

Figure 3 — Root-mean-square errors of (A) humerothoracic joint, (b) glenohumeral joint, and (c) scapulothoracic joint at 50°, 70°, and 90° of the humerothoracic elevation in the scapular plane.

Discussion

We investigated JPS of the humerothoracic, glenohumeral, and scapulothoracic joints at different target angles during elevation in the scapular plane and examined the contribution of glenohumeral and scapulothoracic errors to humerothoracic errors. We hypothesized that the rms errors of the glenohumeral and scapulothoracic joints would decrease as target angles approach 90° of arm elevation and the errors of both glenohumeral and scapulothoracic joints would predict humerothoracic joint errors. The results partially supported our hypotheses. The rms errors of the glenohumeral joint were reduced from 4.9° to 3.4° as the targets increased from 50° to 90° of arm elevation, which followed the pattern of the humerothoracic joint (6.6° to 4.3°). However, the rms errors of the scapulothoracic joint remained constant at around 3° at all elevation angles. For the regression models, although the humerothoracic error was significantly predicted by the glenohumeral and scapulothoracic errors at each angle, the glenohumeral errors explained most of the variation of the humerothoracic errors.

When the shoulder complex is treated as one joint (humerothoracic joint) and shoulder JPS is examined at different elevation angles, JPS errors are lower at 90° of arm elevation when compared with lower elevation angles.[13,22–24] The decrease of the JPS errors with arm elevation target angles follows a linear relationship.[13] In the current study, the results of the humerothoracic joint confirmed the findings of the previous studies. The glenohumeral joint also showed the same pattern, and the errors of the glenohumeral joint significantly predicted those of the humerothoracic joint and explained most of the variance of the humerothoracic errors. Therefore, the observed pattern of the humerothoracic joint can be mainly attributed to the glenohumeral joint. The mechanism of this pattern is still not clear, but it may be due to the increase of the muscle activation level around the glenohumeral joint during arm elevation. Muscle spindles are the main contributing resource for JPS[32] and the sensitivity of the muscle spindles is associated with the level of the muscle contraction.[33] It also has been found that external load improves JPS.[34] Therefore, the decrease of errors may be due to the increase of muscle activation as the arm is elevated. However, Chapman et al tested this hypothesis by tilting subjects backward when testing shoulder JPS. They found the effect of the arm orientation with respect to the trunk on the JPS errors is more dominant than the effect of the gravity.[35] Therefore, in addition to muscle activation levels, another possible mechanism is that our nervous system can sense our joint position more precisely around 90° of arm elevation. It may be that the central nervous system tends to return the arm to the position where it is most likely to be positioned.[28] It has been found that nonhuman primates perform tasks close to the chest and mouth for 50% of the time.[36] Therefore, the arm would overshoot toward the head at the targets of lower angles but the accuracy is better at the target of 90°, which is around the level of the mouth. According to a recent study conducted in our laboratory with a similar protocol, patients with impingement syndrome do not demonstrate this pattern, although on average the magnitude of their errors are similar.[37] More work needs to be done to better understand the mechanism of our results.

The errors of the scapulothoracic joint did not decrease with increases in elevation angle, which did not support our hypothesis. This may be due to structural differences between the glenohumeral and scapulothoracic joints. Unlike the glenohumeral joint, the scapulothoracic joint is a so-called pseudo-joint without a real joint structure. The muscles of the glenohumeral joint generate torque against the gravity to move the humerus,[38] but the muscles wrapping around the scapula coordinate to move and rotate the scapula along the thoracic cage.[39] The upper trapezius elevates and retracts the scapula, the lower trapezius stabilizes the scapular rotation axis and upward rotates the scapula, and the serratus anterior substantially contributes to scapular upward rotation and posterior tilt.[39,40] Therefore, although in general the activation of the scapular muscles increases with arm elevation, the timing and activation

Table 1 Results of Pearson correlation between humerothoracic (HT), glenohumeral (GH), and scapulothoracic (ST) joints at each target angle

	HT Error at 50°	GH Error at 50°	HT Error at 70°	GH Error at 70°	HT Error at 90°	GH Error at 90°
GH error at 50°	0.90*					
ST error at 50°	0.70*	0.47*				
GH error at 70°			0.77*			
ST error at 70°			0.13	0.05		
GH error at 90°					0.76*	
ST error at 90°					0.38*	0.24

* $p < .05$.

Table 2 Results of multiple regression at each target angle

	b	β	*p*	ΔR²
HT error at 50° ($R^2 = .91$, $p < .001$)				
GH error at 50°	1.08	0.74	< .001	.42
ST error at 50°	0.91	0.35	< .001	.10
HT error at 70° ($R^2 = .60$, $P < .001$)				
GH error at 70°	0.95	0.76	< .001	.58
ST error at 70°	0.18	0.10	.290	.01
Errors of HT at 90° ($R^2 = .63$, $P < .001$)				
Error of GH at 90°	0.87	0.71	< .001	.48
Error of ST at 90°	0.39	0.21	.022	.04

Note. HT = humerothoracic joint; GH = glenohumeral joint; ST = scapulothoracic joint.

level is different in each muscle and there is no clear peak of overall muscle activation at 90° of elevation.[41,42] Consequently, the effect of muscle contraction on the accuracy of scapular JPS may not be as strong as that of the glenohumeral joint.

When JPS of multiple joints was compared between different angles, there was no angle effect on the proximal joints. In a previous study in our laboratory, JPS was assessed with the targets that involved both elbow and shoulder flexion.[28] End point acuity was found to be best at the targets where the hand was closer to the head. Although targets were presented according to the angles of the shoulder and elbow, which is different from the current study, they found that JPS errors of the shoulder (the proximal joint) did not depend on the angles, but there was angle effect on the elbow (the distal joint). These results are similar to the finding of the current study, in which there is no angle effect on the scapulothoracic joint (the proximal joint) but the JPS errors of the glenohumeral joint (the distal joint) depended on the target angle. The mechanism of this phenomenon still needs more investigation with JPS testing protocols involving multiple joints.

The multiple regression models demonstrated a similar relationship between the humerothoracic, glenohumeral, and scapulothoracic errors across elevation angles. The model with the predictors of the glenohumeral and scapulothoracic errors was significant at each target angle, but the predictive relationship between the scapulothoracic and humerothoracic joints is weak, according to standardized regression coefficient (β) and ΔR^2. Although it has been well established that scapular movement contributes to overall shoulder movement,[4,5,7] there is a dissociation between JPS errors of the humerothoracic and scapulothoracic joints, given the results of the weak relationship between the scapulothoracic and humerothoracic errors as well as the fact that there is no angle effect on the scapulothoracic errors in the current study.

At each target angle, for each 1° increase in the glenohumeral error, there was an increase in the rms error of the humerothoracic joint, which ranged from 0.87° to 1.1°. Because the variance of humerothoracic errors was primarily explained by glenohumeral errors, when JPS of the humerothoracic joint is examined, the results mainly represent the glenohumeral errors. Since proprioception deficits have been demonstrated in patients with chronic rotator cuff pathology,[43] anterior glenohumeral dislocations,[44] and shoulder instability,[45] future studies may need to investigate the proprioception of the scapula in patients with shoulder injuries. In the clinical setting, it may be hard to test the scapular JPS during elevation. Scapular JPS could be tested separately with isolated scapular elevation/depression and protraction/retraction motions.[20]

Tripp et al[19] also investigated JPS of multiple joints of the upper extremity. They studied end point acuity and JPS of individual joints of the upper extremity at the positions of arm-cock and ball-release in overhead-throwing athletes. They found no clear pattern of principle component analysis showing that the errors of the individual joints contribute to the end point acuity. They found when all the variance was pooled, the proximal joints (scapulothoracic and glenohumeral joints) accounted for more variance than the distal joints (elbow and wrist joints). The difference between the study of Tripp et al and the current study may be due to different statistical models and different movements used for the test. In the current study, we restricted elevation to the scapular plane with thumb pointing upward while Tripp et al used the movements of arm-cock and ball-release, which involve more joints and degrees of freedom.[19]

There are some limitations in the current study. First, we chose to use the helical angle to represent three-dimensional scapular movement. Although it reduces the number of the variables for the scapular movement, the helical angle does not represent the scapular movements observed in the clinic, such as upward/downward rotation, protraction/retraction, or tipping. Therefore, scapular JPS errors in the current study do not represent errors in any specific plane. In addition, the subjects in the current study were young and healthy. The results may not be generalized to the population that is older or with shoulder injuries.

The results of the current study show that the humerothoracic errors decreased as the target elevation angle increases. While the glenohumeral joint demonstrated the same pattern, the scapulothoracic errors did not depend on the target angle. At each target angle, the glenohumeral errors accounted for most of the variance of the humerothoracic errors. Therefore, the humerothoracic errors are chiefly dependent on the glenohumeral joint. Since the assessment of scapular kinematics is important in the evaluation of patients with shoulder injuries, it may be necessary to test the JPS of the scapula separately in addition to the assessment of overall shoulder JPS.

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Erratum: Lin and Karduna (2017)

In the original publication of this article, Figure 3c was a duplicate of Figure 3b and was therefore incorrect. The correct image for Figure 3c has been added and this online version is corrected. We apologize for this error.