Original

**Determination of In-vivo Glenohumeral Translation during Loaded and Unloaded Arm Elevation**

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**Abstract**: An understanding of normal joint kinematics is essential to develop treatments that restore normal joint mechanics; however, reports of kinematics during dynamic motion are rare. This study thus investigated glenohumeral (GH) translation in vivo during loaded and unloaded shoulder abduction. Nine healthy shoulders were studied from our patient cohort (average age, 31 years). We created 3D models of the scapula and humerus using computed tomography (CT) images and recorded fluoroscopic images during active abduction in neutral rotation in the plane of the scapula using a hand-held 3kg weight or no additional load. 3D motions were determined using model-based 3D-to-2D registration. Glenohumeral translation was determined by finding the location on the humeral head with the smallest separation from the plane of the glenoid. The humerus moved an average of 2 mm during arm abduction, from inferior to the center of the glenoid. There were no statistically significant differences between the unloaded and loaded conditions. Variability in humeral translation decreased with abduction using both 3-kg and 0-kg conditions, with significantly lower variability showing above a 70° GH abduction. We showed that humeral translation to the center of the glenoid maximizes joint congruency for optimal shoulder function and joint longevity. This data should lead to better strategies for shoulder injury prevention, enhanced rehabilitation, and improved surgical treatments.

**Key words**: shoulder kinematics, fluoroscopy, model-image registration

**Introduction**

Various factors including the rotator cuff are important for stabilizing the glenohumeral joint over a wide range of motions and dynamic conditions. Indeed, inadequate control of glenohumeral translation during dynamic activities is implicated in subacromial impingement syndrome, degenerative arthritis of the shoulder, and many other joint-damage mechanisms.

Single-plane fluoroscopic imaging has been used for the past 15 years to record and quantify the motions of knee replacements during dynamic activities. This technique was recently used

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to assess the shoulder joint with and without implanted devices\textsuperscript{1-3} ; however, it remains difficult to measure dynamic glenohumeral translation and reports are scarce of quantitative 3D measurement of shoulder motion during clinically relevant motions. This study was thus motivated by the assumption that treatment and rehabilitation of shoulder injuries could be improved with better knowledge of glenohumeral mechanics during dynamic activities in healthy and damaged joints.

This study investigated glenohumeral translation \textit{in vivo} during loaded and unloaded shoulder abduction in the scapular plane. With the arm at the side and muscles relaxed, we assumed the humeral head would move with gravity to a relatively inferior position on the glenoid. With abduction against gravity, the rotator cuff, deltoid muscle, and other tissues will stabilize the glenohumeral joint and draw the humeral head to the center of the glenoid concavity. Thus, we hypothesized that the humeral head would be relatively inferior with respect to the glenoid with the arm at the side, moving to the center of the glenoid with arm elevation in a healthy shoulder. We also hypothesized that there would be no difference in glenohumeral translation for loaded and unloaded conditions in healthy shoulders. Because the joint is actively stabilized with increasing abduction, we also hypothesized that kinematic variability would decrease with arm abduction.

\textbf{Materials and methods}

Nine healthy shoulders in nine volunteer subjects (8 males, 1 female; average 31.1 years, 27 to 38 years old) were studied. All shoulders were asymptomatic, had no history of injury, and lacked any clinical or radiographic signs of pathology. All subjects provided informed consent to participate in this study. CT scans of each shoulder were acquired at 0.5-mm intervals and 3D models of the scapula and proximal humerus were created in two stages. First, computed tomography (CT) images of the exterior cortical bone edges were segmented using commercial software (SliceOmatic, Tomovision, Montreal, CA, USA), and then these point clouds were converted into polygonal surface models (Geomagic Studio, Raindrop Geomagic, Research Triangle Park, NC, USA).

The subject was positioned in front of a fluoroscope and motions were recorded during active abduction in neutral rotation from arm at side to full abduction in the plane of the scapula. The subjects performed two trials: one trial holding a 3 kg weight and one unloaded trial.

3D motions of the scapula and humerus were determined using model-based 3D-to-2D registration (Fig. 1). A custom shape-matching program was used to obtain six-degrees-of-freedom shoulder kinematics. Estimated measurement errors for this process were 0.5 mm for scapular plane translations, and 0.5 degrees for shoulder abduction\textsuperscript{4, 5}.

The glenoid plane was defined as the line parallel from the superior bony edge to the inferior glenoid edge and included the line defining the perpendicular short axis of the glenoid (Fig. 2). The glenoid center was defined as the midpoint of the long axis. Humeral translation was referenced to the glenoid center in the superior/inferior direction. Glenohumeral translation was determined in each data frame by finding the location on the humeral head with least separa-
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Fig. 1. 3D-to-2D model-to-image registration was used to determine 3D motion of the scapula and humerus during dynamic arm elevation with and without handheld weights.

Fig. 2. The Glenoid plane was defined as parallel to a line from the superior bony edge to the inferior glenoid edge and including the line defining the short axis (a perpendicular line intersecting the midpoint of the long axis) of the glenoid.

Fig. 3. (a.) The glenoid center was defined as the midpoint of the long axis. (b.) Humeral translation was referenced to the glenoid center in the superior/inferior direction. Glenohumeral translation was determined in each data frame by finding the location on the humeral head with the smallest separation from the plane of the glenoid.

Motion data were grouped into 10° intervals of glenohumeral (GH) abduction for loaded and unloaded conditions, and compared from 30° to 90° using t-tests with a Bonferroni correction with significance at $P < 0.05$. The F-test was used to compare kinematic variability between the initial position and each position of incremental abduction.
Results

The humerus moved an average of 2 mm, from inferior to central on the glenoid, during arm abduction under both the unloaded and 3-kg loaded conditions (Fig. 4). The humeral head was centered within 1 mm from the glenoid center above 70° GH abduction. There were no statistically significant differences in translations between unloaded and 3-kg loaded conditions. All shoulders exhibited the same pattern of motion and the main source of variability seemed to reflect the definition of the glenoid center, resulting in an offset of each shoulder’s data from a consistent point on the glenoid. The standard deviation decreased gradually over the motions for both conditions, with significantly lower variability in glenohumeral translation above 70° GH abduction.

Discussion

Glenohumeral joint pathology results from a variety of mechanical and non-mechanical causes, and a better understanding of normal joint kinematics is essential for treatments to restore normal joint dynamics. Some authors suggest geometric mismatch between the humeral head and glenoid as one cause of pathology in high stress areas. Thus, the objective of this study was to analyze the superior-inferior translations of the humeral head relative to the glenoid in vivo during 3-kg loaded and unloaded arm abduction. Limitations of our study include the need to use ionizing radiation to observe motion, the low number of participating subjects, and reduced measurement accuracy of single-plane fluoroscopy compared to biplane fluoroscopic or radiographic techniques.

A variety of methods have been used to describe humeral head translation and the importance of passive stabilizers; however, these studies have provided few consistent findings. Poppen and Walker observed on radiographs that the humeral head moved upward relative to the glenoid during unloaded abduction between 0° and 30°, with little additional translation thereafter for unloaded conditions. In contrast, Deutsch et al described a more centered position of the humeral head in healthy volunteers holding a weight equal to 2.5% of their body weight, and no significant change in position during abduction.

Other studies using x-ray imaging have also suggested that the glenohumeral joint behaves as

![Fig. 4. The humerus translated from inferior to central locations on the glenoid during active arm abduction. The standard deviation (STDV) decreased gradually during the motion, with significantly lower variability at above 70° and at the end of GH motion compared to the initial position with unloaded and 3-kg-loaded conditions. Glenohumeral translations were not different for unloaded and loaded conditions.]
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a perfectly congruent ball and socket joint. Conversely, some cadaver studies showed glenohumeral translation during abduction. Nobuhara et al. evaluated movement of glenohumeral contact and suggested an inherent articular mismatch between the humeral head and glenoid. In addition to, Warner et al. measured contact area and pressure on the glenoid over the range of abduction and concluded that the glenohumeral joint was relatively incongruent (small contact area and high peak pressures) for low arm angles and increasingly congruent (high contact areas and low peak pressures) for the arm abducted above 30°. These authors also suggested articular mismatch as the factor permitting humeral head translation at lower degrees of abduction, but subsequent measurements of glenoid contact area with 222N and 444N joint compressive loads revealed no significant differences in the contact patterns. Similarly, Greis et al. also evaluated glenoid contact areas with the same loads and found no significant differences. Notably, these in vitro studies require assumptions about muscle forces, joint loads and coordination of motion, all of which are difficult to quantify in vivo, and such uncertainties make it more difficult to interpret and directly apply in vitro study findings to clinical treatment and interpretation.

Open magnetic resonance (MR) imaging recently showed three-dimensional glenohumeral motion in vivo with varied results. Graichen et al. studied glenohumeral translations using MR with supine subjects holding a series of five static positions. They described inferior translation of the humerus from 30° to 150°, and found a more central humeral position when the arms were supporting a steady 1 kg load. Both of these findings are quite different from our fluoroscopic data on upright subjects, suggesting that subject posture and/or dynamic motion may be important variables determining glenohumeral translation. Supporting this hypothesis, Beaulieu et al. studied upright subjects in an open MR system and reported that the humeral head remained more-or-less centered on the glenoid over a full range of motion, deviating from the glenoid center by less than 3 mm.

Boyer et al. used both biplane fluoroscopic imaging and MR-derived bone models to determine glenohumeral kinematics during unloaded dynamic abduction in five subjects. They found the average humeral contact position was located approximately 5 mm from the glenoid center in the posterior-superior quadrant for abduction from 0° to 90°, and significant variability among the five shoulders tested. In a separate study, Matsuki et al. expressed translations based upon the relative positions of local bone coordinate system origins and the calculated glenohumeral center of rotation, which differed from our evaluation using contact points with the smallest distance between the two bones. Thus, in the supero-inferior direction, translations calculated with the three different methods were roughly parallel showing statistically significant differences.

The glenohumeral kinematic data support the hypotheses that the humerus will move superior with abduction, from inferior to a location near the glenoid center, and that healthy shoulders will show no differences in glenohumeral translation for loaded and unloaded conditions. We also used scapulohumeral rhythm (SHR) to provide insight into neuromuscular control and fundamental biomechanics of the shoulder using the same healthy subjects and technique. SHR decreased (more scapular motion) with increasing abduction, in that scapulothoracic motion was significantly reduced through the range of 35 degrees to 45 degrees of glenohumeral motion.
with a 3-kg load, whereas glenohumeral translation showed no differences for 0-kg and 3-kg conditions. These results indicated that muscular stabilization of the scapula with external loading increased in the healthy shoulders to provide a critical platform for upper extremity activity. Numerous other studies have also shown the humeral head moving to the glenoid center during elevation in healthy shoulders \(^7\, 9\, 13\, 14\, 18\)–\(^21\), in contrast, injured shoulders with diagnoses of cuff deficiency, instability, and trauma exhibit humeral translation away from the glenoid center \(^7\, 9\, 18\)–\(^22\). Therefore, we assume that humeral translation to the center of the glenoid provides maximum joint congruency for optimal shoulder function and joint longevity.

Our data also support the prediction of decreased inter-subject variability in glenohumeral translation with increasing abduction. Greater centering and joint contact forces are developed with increased abduction, thus a stable joint provides efficient linkage for the rotator cuff with the deltoid muscle and scapular function in elevated postures. Active translation of the humeral head away from the glenoid center could therefore indicate insufficient passive and/or active stabilization and is likely causative of gradual joint degeneration due to local articular cartilage and labrum overload \(^20\, 22\)–\(^27\). Further studies are clearly required to fully understand the mechanisms providing glenohumeral stability during dynamic motion, and we believe 3D fluoroscopic analysis of shoulder kinematics can and will provide such information about shoulder function. This enhanced understanding will facilitate better strategy development to prevent shoulder injuries, enhance rehabilitation, and improve surgical treatments.

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Conflict of interest statement disclosure

We have no financial affiliation or involvement with any commercial organization that has a direct financial interest in any matter included in this manuscript, except as disclosed in an attachment and cited in the manuscript. Any other conflict of interest is also disclosed in an attachment.

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