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Short communication

Measuring dynamic in-vivo glenohumeral joint kinematics: Technique and preliminary results

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Abstract

Rotator cuff tears are a common injury that affect a significant percentage of the population over age 60. Although it is widely believed that the rotator cuff's primary function is to stabilize the humerus against the glenoid during shoulder motion, accurately measuring the three-dimensional (3D) motion of the shoulder's glenohumeral joint under in-vivo conditions has been a challenging endeavor. In particular, conventional motion measurement techniques have frequently been limited to static or two-dimensional (2D) analyses, and have suffered from limited or unknown in-vivo accuracy. We have recently developed and validated a new model-based tracking technique that is capable of accurately measuring the 3D position and orientation of the scapula and humerus from biplane X-ray images. Herein we demonstrate the in-vivo application of this technique for accurately measuring glenohumeral joint translations during shoulder motion in the repaired and contralateral shoulders of patients following rotator cuff repair. Five male subjects were tested at 3–4 months following arthroscopic rotator cuff repair. Superior–inferior humeral translation was measured during elevation, and anterior–posterior humeral translation was measured during external rotation in both the repaired and contralateral shoulders. The data failed to detect statistically significant differences between the repaired and contralateral shoulders in superior–inferior translation ($p = 0.74$) or anterior–posterior translation ($p = 0.77$). The measurement technique overcomes the limitations of conventional motion measurement techniques by providing accurate, 3D, in-vivo measures of glenohumeral joint motion during dynamic activities. On-going research is using this technique to assess the effects of conservative and surgical treatment of rotator cuff tears.

Keywords: Shoulder; Kinematics; Rotator cuff; In vivo

1. Introduction

Rotator cuff injuries affect 30–40% of the population over age 60 (Milgrom et al., 1995) and have a major impact on medical care costs. Shoulder function following rotator cuff surgery is unpredictable, with a significant percentage of patients experiencing long-term shoulder disability. The rotator cuff is believed to provide dynamic stability by centering the humerus against the glenoid during shoulder motion. Thus, to understand why shoulder function is often compromised following rotator cuff surgery, it is necessary to measure translation of the humerus relative to the glenoid. Without these data it is impossible to objectively assess the functional results of rotator cuff tear treatment.

Accurately measuring in-vivo glenohumeral joint motion remains a challenging endeavor. In an effort to overcome limitations associated with conventional motion measurement techniques, we have developed a technique for tracking the position of the humerus and scapula from biplane X-ray images based on their three-dimensional (3D) shape and texture. The accuracy of this technique has been assessed in cadavers (Bey et al., 2006), but application of the technique for measuring in-vivo joint kinematics has not been described. To demonstrate the in-vivo application of this technique, we measured 3D glenohumeral joint kinematics in the repaired and contralateral shoulders of patients who had undergone rotator cuff repair. We hypothesized that glenohumeral joint translations would be greater in the repaired shoulder than in the contralateral shoulder.

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2. Methods

Following IRB approval, five male subjects (age: 65.4 ± 8.6) enrolled in the study. Each subject had surgical repair of a supraspinatus tendon tear 3–4 months prior to enrolling in the study. All tears were arthroscopically repaired to bone by the same surgeon using a double-row technique (Lo and Burkhart, 2003). Each subject's contralateral shoulder was asymptomatic, with no history of injury or surgery.

Subjects were positioned with their shoulder centered within a biplane X-ray system (Tashman and Anderst, 2003). X-ray images were acquired at 60 Hz while subjects performed two tasks: coronal-plane elevation from a resting position (arm at the subject's side) to approximately 120° of humerothoracic elevation, and external rotation with the arm adducted from a resting position of full internal rotation to maximal external rotation. Each task was performed with the subject holding a 3-pound hand weight. Subjects performed each motion at a frequency of 0.25 Hz, so that each motion (from resting to ending position) took 2 s. Subjects performed three trials of each motion, and both shoulders were tested. Following testing, bilateral CT scans of the entire humerus and scapula were acquired. Using custom software, the humerus and scapula were segmented, interpolated, and scaled to have cubic voxels with dimensions similar to the X-ray image pixel size.

The 3D position and orientation of the humerus and scapula were determined from the biplane X-ray images using a model-based tracking technique with a dynamic accuracy of ± 0.4 mm and $\pm 0.5°$ (Bey et al., 2006). This technique determines the position and orientation of a bone by optimizing the correlation between two digitally reconstructed radiographs (produced from the CT-based bone model) and the two biplane X-ray images. Transformations between each bone's 3D position and anatomical axes were determined from the CT-based bone models using custom software developed to locate anatomical landmarks and construct standardized anatomical coordinate systems (Fig. 1) (Wu et al., 2005). To minimize side-to-side variability in kinematics due solely to anatomical axes, the same anatomical landmarks identified on the repaired shoulder were used for the contralateral shoulder. This was accomplished by mirror-imaging the contralateral shoulder CT-based bone models, manually co-registering these bone models with the repaired shoulder's bone models, and then transferring the anatomical landmark locations to the contralateral shoulder's bone models. To characterize joint motion, all six kinematic parameters (three rotations, three translations) were calculated to describe the motion of the humerus relative to the scapula. Humeral rotations were calculated with an Euler angle sequence where the three rotations defined the plane of elevation, amount of elevation, and amount of internal/external rotation (Karduna et al., 2001). Humeral translations (anterior–posterior, medial–lateral, superior–inferior) were normalized relative to the resting position of each activity. Thus, the reported translations represent the change in position relative to the resting position of the humerus. For the elevation motion, superior–inferior translations were measured in 5° increments from 10° to 70° of glenohumeral elevation. For the external rotation motion, anterior–posterior translations were measured in 5° increments from 50° of internal rotation to 15° of glenohumeral external rotation. Range of motion varied between subjects, so these rotation limits represent the rotation angles that were common to all subjects. The plane of elevation is not reported since it was prescribed as part of the experimental protocol, and medial–lateral translations were not reported since motion in this direction is not commonly associated with any pathologic condition and is of little clinical significance.

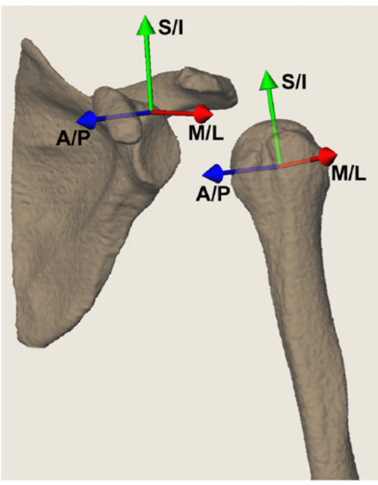

Fig. 1. The humerus and scapula coordinate systems were constructed from the CT-models according to the convention recommended by the International Society of Biomechanics (Wu et al., 2005). Translations and rotations of the humerus were expressed relative to the scapula coordinate system. A/P = anterior–posterior axis, M/L = medial–lateral axis, S/I = superior–inferior axis.

For the elevation motion, the effects of shoulder condition (repaired vs. contralateral) and elevation angle on superior–inferior translation were assessed with repeated-measures two-way ANOVA. For the external rotation motion, the effects of shoulder condition (repaired vs. contralateral) and rotation angle on anterior–posterior translation were also assessed with repeated-measures two-way ANOVA. Significance was set at $p < 0.05$.

3. Results

During the elevation motion, the elevation angle had a significant effect on superior–inferior translation ($p < 0.01$, Fig. 2). However, no difference in superior–inferior translation was detected between repaired and contralateral shoulders ($p = 0.74$, Fig. 2). During external rotation, no statistically significant difference in anterior–posterior translation was detected due to either rotation angle ($p = 0.77$, Fig. 3) or shoulder condition, i.e. repaired vs. contralateral ($p = 0.16$, Fig. 3).

4. Discussion

Previous techniques for measuring glenohumeral joint motion have relied upon cadaveric simulations, 2D imaging, static 3D imaging, conventional motion measurement systems, and bone pins. There are significant limitations associated with each of these approaches. Cadaveric experiments can provide accurate measures of joint position or motion, but are unable to duplicate the complex motions or forces associated with in-vivo conditions. 2D imaging of glenohumeral joint position using fluoroscopy (Werner et al., 2004) or radiography (Poppen and Walker, 1976) cannot sufficiently characterize the motion of a six degree-of-freedom joint. 3D imaging of the glenohumeral joint position has been performed with MRI (Graichen et al., 2000), CT (Baeyens et al., 2001), or biplane radiography (Paletta et al., 1997), but these techniques are currently limited to static analyses. Conventional motion measurement systems can track the position of surface markers or sensors during dynamic activities (Ludewig and Cook, 2002), but these systems are susceptible to skin movement artifact and in-vivo accuracy assessment is difficult and rarely performed. Tracking of bone pins has also been used, but this invasive approach

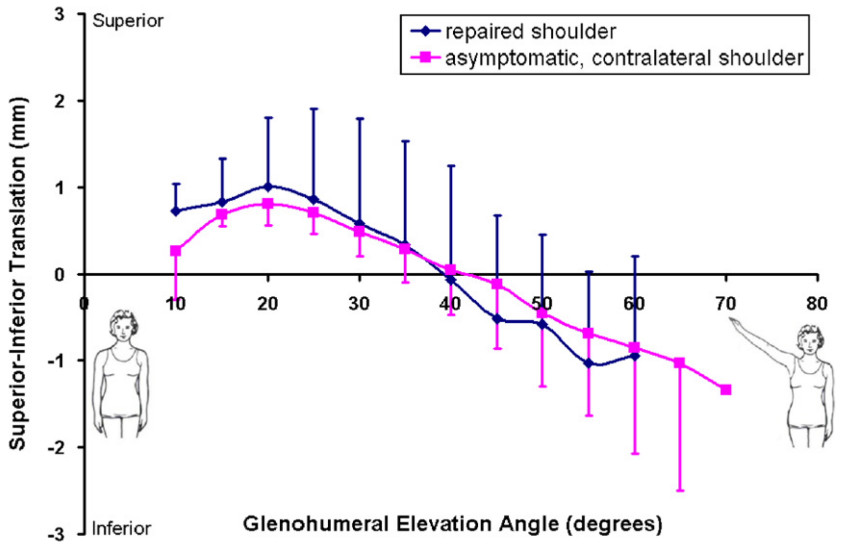

Fig. 2. Superior–inferior glenohumeral translation of the repaired and contralateral shoulders during coronal-plane elevation. Data for three trials for each subject were averaged, and the averages and standard deviations across the five patients are plotted here. Positive values indicate superior translation of the humerus relative to the glenoid. Data are reported relative to glenohumeral elevation angle (i.e., the angle between the humerus and scapula) and not humerothoracic angle (i.e., the angle between the humerus and torso). Assuming a scapulohumeral rhythm of 2:1, these data are presented over a range that corresponds to humerothoracic angles of approximately 15–105°.

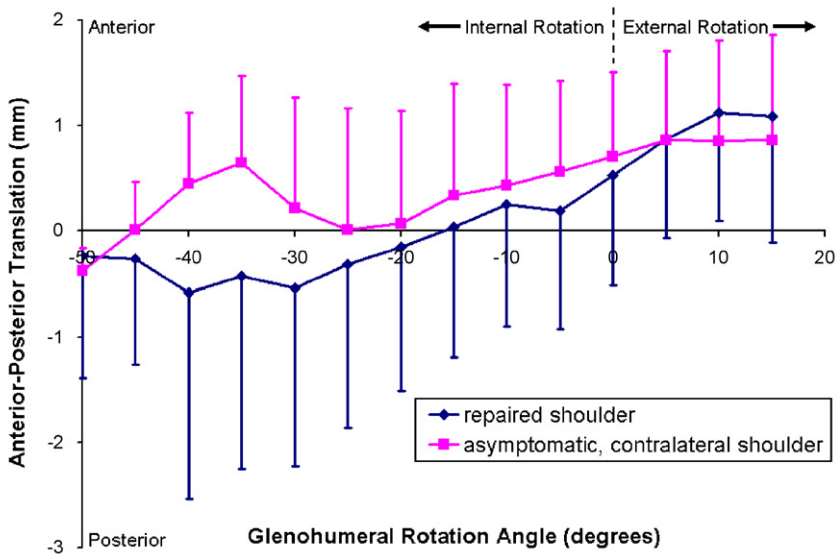

Fig. 3. Anterior–posterior translation of the repaired and contralateral shoulders during external rotation. Data for three trials for each subject were averaged, and the averages and standard deviations across the five patients are plotted here. Positive values indicate anterior translation of the humerus relative to the glenoid.

limits the number of willing volunteers and makes serial studies over time impractical (McClure et al., 2001). In contrast, the technique described here overcomes many of the limitations associated with conventional motion measurement techniques by providing non-invasive, accurate, 3D measures of in-vivo glenohumeral joint motion during dynamic activities.

Although direct comparisons between research studies are difficult due to differences in techniques and testing conditions, the glenohumeral joint translations reported in this study are consistent with previous research. The data from our study indicated an overall range of superior–inferior translation during elevation of approximately 2.6 mm (Fig. 3). This range is in agreement with the work of Graichen and colleagues, who have consistently reported superior–inferior translation ranges of 1–2 mm during elevation in subjects with healthy, uninjured shoulders (Graichen et al., 2000, 2005). Our data further demonstrate that the anterior–posterior translation range during external rotation (repaired shoulder: 1.5 mm, contralateral shoulder: 2.1 mm, Fig. 4) is similar to that in a previously reported study that reported anterior–posterior translations in the range of 1–2 mm during external rotation (von Eisenhart-Rothe et al., 2002).

This study demonstrated in-vivo application of a model-based tracking technique for measuring dynamic glenohumeral joint motion. Although the data failed to detect any statistically significant differences in glenohumeral joint translations between repaired and contralateral shoulders, our interpretation of these findings is currently limited by small sample size and early post-operative time points. Additional patients are currently being tested. We note that it may be inappropriate to assume that a patient's contralateral shoulder is "normal", since previous research has reported a significant incidence of rotator cuff tears in the asymptomatic, contralateral shoulder of patients with a symptomatic rotator cuff tear (Yamaguchi et al., 2001). Furthermore, it is plausible that differences in motion patterns between dominant and non-dominant shoulders may exist in subjects with "normal" shoulders. Accordingly, future research will measure glenohumeral joint motion in a group of normal control subjects.

In summary, the technique described here of using biplane X-ray images and model-based tracking provides non-invasive, accurate, dynamic, 3D measures of in-vivo glenohumeral joint motion during shoulder motion. On-going research is using the techniques described here to assess the effects of conservative and surgical treatment of rotator cuff tears. It is anticipated that this approach will allow clinicians and researchers to optimize the treatment of rotator cuff tears, thereby decreasing medical costs and improving function, comfort, and quality of life in patients with this common condition.

Conflict of interest

The authors disclose that there are no financial or personal relationships with other people or organizations that could inappropriately influence (bias) this work.

Acknowledgments

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