Glenohumeral translation during active and passive elevation of the shoulder — a 3D open-MRI study

Heiko Graichen*, Tobias Stammbergerb, Harald Bonelc, Karl-Hans Englmeierb, Maximilian Reiserc, Felix Eckstein

*Muskuloskeletalk Research Group, Anatomische Anstalt, Ludwig Maximilians Universität München, Pettenkoferstr. 11, D 80336 München, Germany
bInstitut für Medizinische Informatik und Systemforschung, GSF Forschungszentrum Neuherberg, Ingolstädter Landstr. 1, 85764 Oberschleißheim, Germany
cInstitut für Radiologische Diagnostik, Klinikum Großhadern, Marchioninistr. 15, D 81377 München, Germany

Accepted 28 August 1999

Abstract

Despite its importance for the understanding of joint mechanics in healthy subjects and patients, there has been no three-dimensional (3D) in vivo data on the translation of the humeral head relative to the glenoid during abduction under controlled mechanical loading. The objective was therefore to analyze humeral head translation during passive and active elevation by applying an open MR technique and 3D digital postprocessing methods. Fifteen healthy volunteers were examined with an open MR system at different abduction positions under muscular relaxation (30°–150° of abduction) and during activity of shoulder muscles (60°–120°). After segmentation and 3D reconstruction, the center of mass of the glenoid and the midpoint of the humeral head were determined and their relative position calculated. During passive elevation, the humeral head translated inferiorly from −1.58 mm at 30° to −0.36 mm at 150° of abduction, and posteriorly from −1.55 mm at 30° to −0.07 mm at 150° of abduction. Muscular activity brought about significant changes in glenohumeral translation, the humeral head being in a more inferior position and more centered, particularly at 90° and 120° of abduction (p < 0.01). In anterior/posterior direction the humeral head was more centered at 60° and 90° of abduction during muscle activity. The data demonstrate the importance of neuromuscular control in providing joint stability. The technique developed can also be used for investigating the effect of muscle dysfunction and their relevance on the mechanics of the shoulder joint. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Shoulder; Humeral head translation; MR imaging; Virtual reality

1. Introduction

Shoulder joint stability joint requires adequate coordination of all passive and active stabilizers (Bowen and Warren, 1991; Warner et al., 1992; Pagnani et al., 1995; Walch, 1996) and pathologic changes of them can lead to unphysiologic translation of the humeral head relative to the glenoid cavity. Quantitative assessment of glenohumeral translation has so far been performed in vitro in cadaveric shoulder specimens (Harryman et al., 1990; McMahon et al., 1995; Wülker et al., 1995) or with finite element models (van der Helm and Pronk, 1995), but the elimination of the natural shoulder girdle motion, and the unknown force relationship between the different shoulder muscles make it problematic to transfer these in vitro data to the situation in the living. In vivo analyses with conventional radiography (Howell et al., 1988; Pal et al., 1997; Poppen and Walker, 1976) are of limited value due to projectional artifacts and to the restriction to two planes (van der Helm and Pronk, 1995). In CT and high-field MR systems (Kiss et al., 1997) the arm cannot be investigated in the clinically relevant positions (Kessel and Watson, 1977; Hawkins and Hobeika, 1983).

These problems can be potentially overcome by using an open MR system, which allows to investigate the shoulder joint in functional positions during abduction (Graichen et al., 1998) and under the influence of muscle activity (Graichen et al., 1999). The objective of this study was to analyze 3D humeral head translation relative to the glenoid cavity during passive and active elevation in healthy volunteers by applying specific 3D imaging and postprocessing techniques. The specific
questions to be answered were: (1) Is there a reproducible pattern of superior-inferior or anterior–posterior glenohumeral translation during passive elevation (30°–150°) in healthy volunteers. (2) Is the position of the humeral head relative to the glenoid altered by the action of abducting muscle forces.

2. Material and methods

An open MR scanner (Magnetom Open, Siemens, Erlangen, Germany) was used and an optimized T1-weighted, 3D gradient recalled echo-sequence (TR = 16.1 ms, TE = 7.0 ms, FA = 30°) at a spatial resolution of 1.88 × 0.86 × 1.56 mm³ (FOV = 220 mm², acquisition time of 4 min and 26 s) was applied. Fifteen healthy volunteers were first examined without muscle activity (passive elevation), positioning the arm at five different abduction angles (30°–150°). In a second step, the influence of muscle activity on glenohumeral translation was investigated by examining the volunteers at 60, 90 and 120° of arm abduction, a 1 kg mass with an adducting load direction being applied perpendicular to the distal humerus during imaging, and the abductor muscles of the shoulder being contracted isometrically. All parts of the study were approved by the local ethic committee.

The 3D image data sets were then transferred to a multiprocessing computer (ONYX, Silicon Graphics Inc., Mountain View, CA), semiautomatic segmentation of the humerus, and the scapula being performed with a region-growing algorithm. After 3D reconstruction, the articular surface of the glenoid was seperated interactively from the body of the scapula, and its center of mass (CM) calculated. Finally, a plane was fitted to the glenoid which served as a local reference system, the upper edge of the articular surface defining the superior direction. The reproducibility of the CM determination was tested by performing this step six times on one scapula.

For determining the center point (CP) of the humeral head, the data were transferred into a virtual reality (VR) environment (Haubner et al., 1997) in which a sphere was fitted to the central part of the articular surface of the humeral head. The size of the transparent sphere was adapted interactively to the size of the humeral head (VR-matching) and used as a starting point for an automatic matching algorithm (computational matching), which computes the least-squares distance between the sphere and the articular surface of the humerus head as a measure of similarity (s (m_x, m_y, m_z, r);

$$S(m_x, m_y, m_z, r) =$$

$$\sum_i g(h_i) \left( (h_i^x - m_x)^2 + (h_i^y - m_y)^2 + (h_i^z - m_z)^2 - r \right)$$

(1)

where \(h_i = (h_i^x, h_i^y, h_i^z)\) are the sampled points on the surface of the humeral head and \(g\)

$$g(Z, Z_{cm}) = e^{-\frac{(z-z_{cm})^2}{2s^2}}$$

(2)

is a Gaussian weighted function, to reduce the influence of partial volume effects in the anterior and posterior parts of the humeral head. The function \(S(m_x, m_y, m_z, r)\) was then minimized, the parameter space being restricted to a close neighborhood of the starting parameters \(m\) and \(r\):

$$S((m, r) = \text{min}$$

$$with (m, r) \in \{ (m, r) | |m - m_s| < \delta m, |r - r_s| < \delta r \}$$

(3)

The accuracy of the VR- and the computational matching was compared by calculating the least-squares distance of both methods in 20 positions. In the remaining 100 positions, the computational matching was only applied when the degree of similarity was lower than 0.017 mm. The reproducibility of the VR- and the computational matching was tested by performing the measurement on one shoulder six times.

Finally, the CP of the humeral head was projected perpendicularly onto the plane that had been fitted to the glenoid, its location relative to the CM of the glenoid being computed in all dimensions (Fig. 1).

3. Results

During passive elevation (30°–150°), the humeral head showed a slightly superior position relative to the glenoid, which decreased significantly from +1.58 ± 1.2 mm at 30° of abduction to +0.36 ± 1.6 mm at 150° (Fig. 2).

With muscle activity, the humeral head was in a superior position at 60° of abduction (+1.0 ± 1.3 mm) (Fig. 2), but at 90° (+0.04 ± 1.3 mm) and at 120° (−0.02 ± 1.4 mm) of abduction it was centered (Fig. 2). Direct comparison of values obtained at muscular activity with those at muscular relaxation showed an inferior translation of 0.8 ± 1.5 mm (p < 0.05) at 60°, of 0.8 ± 1.5 mm (p < 0.01) at 90° and of 1.0 ± 1.4 mm (p < 0.01) at 120° of abduction.

During passive elevation, the midpoint of the humeral head showed a significant anterior translation from 30° (1.55 ± 2.2 mm) to 90° (2.38 ± 1.8 mm) of abduction (Fig. 3), but from 90° to 150° (−0.07 ± 1.4 mm) it translated posteriorly (Fig. 3).

With muscle activity, the humeral head was localized between 1 and 1.8 mm anterior relative to the CM of the glenoid (Fig. 3). Direct comparison of the values obtained at muscular relaxation with those obtained at muscular relaxation showed a posterior translation of 0.88 ± 2.6 mm (p < 0.05) at 60°, of 1.22 ± 2.0 mm (p < 0.01) at 90°, and an anterior translation of 0.37 ± 2.0 mm at 120° (p = n.s.).
The determination of the CM of the glenoid and that of the CP of the humeral head by the VR method were shown to be highly reproducible (Table 1), the computational optimization improving the mean least-squares distance only slightly (0.015–0.012 mm).

4. Discussion

The objective of this study was to three-dimensionally analyze the translation of the humeral head relative to the glenoid during elevation of the shoulder in vivo during passive elevation and under isometric muscle activity.

In previous studies, the importance of passive stabilizers (O’Brien et al., 1990; Pagnani et al., 1995; Warner et al., 1992; Habermayer and Schuller, 1990; Lazarus et al., 1996; Matsen et al., 1994) have been examined with in vitro shoulder models. However, the assumptions regarding the force relationship of the shoulder muscles in those
models are difficult to justify (van der Helm and Pronk, 1995; Wülker et al., 1995), and most biomechanical models have been restricted to the analysis of glenohumeral motion (Poppen and Walker, 1976; van der Helm and Pronk, 1995). These problems could be overcome in the present study by investigating healthy volunteers in vivo, in whom the physiologic neuromuscular activation patterns were preserved and the scapula free to move. Some limitations arise from the fact that the scapula touched the table during imaging, but the positioning of the arm was not carried out in the imaging device, but in a sitting position outside the scanner. In a previous study (Graichen et al., 2000) could confirm that the abduction angle taken outside are highly reproducible, and that a normal scapulo-humeral rhythm is preserved with the MR method employed. The problems involved in the analysis of glenohumeral translation with conventional radiography (Deutsch et al., 1996; Howell and Galinat, 1989; Poppen and Walker, 1976) were overcome by developing a three-dimensional postprocessing method.

Poppen and Walker (1976) observed from X-rays that the humeral head moved upward relative to the glenoid between 0 and 30° of abduction and translated inferiorly by 2–3 mm throughout the rest of abduction. In our study, the inferior translation observed from 30 to 150° was only 1.2 mm. Deutsch et al. (1996) described a more centered position of the humeral head in healthy volunteers, showing no significant change of the position during abduction. In their radiographic study, the volunteers held a weight equal to 2.5% of body weight. In our analysis we also find a more centered position of the humeral head under muscle activity, but systematic differences are observed between the different arm positions, however, the difference of positioning the volunteers in this study and other conventional radiographic studies should be mentioned. While at 60° of abduction the humerus is still 1 mm superior to the glenoid, it is more centered at 90 and 120°. The superior position at 60° may be caused by the dominance of the deltoid with its cranial force direction, while at 90° and 120° the rotator cuff muscles with their centralizing effect are more active (Graichen et al., 1999; Kronberg et al., 1990; Sporrong et al., 1996).

In another radiographic study, Howell et al. (1988) described a nearly centered position of the humeral head in anterior/posterior direction at full extension, this being in agreement with our data. In all other positions during abduction, we found an anterior position of the humeral head during passive elevation, but again a centralizing effect of muscle activity. The technique described here can be readily extended to other positions of the joint and with other external force directions, its advantage being that the neuromuscular control mechanisms of each individual are preserved. It should be noted that the study was performed under isometric and not under isotonic muscle activity, which may yield different results, but it is currently not possible to obtain three-dimensional information in real time.

In conclusion, we have developed a MR-based technique that makes it possible to investigate humeral head translation three dimensionally in functionally important arm positions with and without muscle activity. The study demonstrates the relevance of neuromuscular control in providing joint stability and can be used as a basis for investigating the effect of muscle dysfunctions and their relevance for joint mechanics in shoulder patients.

Acknowledgements

We would like to express our thanks to the Deutsche Forschungsgemeinschaft (DFG) for their support (GR 1638/1-2).

References

