In vivo three-dimensional motion analysis of the shoulder joint during internal and external rotation

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Abstract

Purpose The purpose of this study was to assess accurately the three-dimensional movements of the scapula and humerus relative to the thorax during internal/external rotation motion with abduction of the shoulder joint.

Methods Ten right shoulders of ten healthy volunteers were examined using a wide-gantry open magnetic resonance imaging (MRI) system. MRI was performed every 30° from 90° external rotation to 90° internal rotation of the shoulder joint.

Results The contribution ratio of the scapulothoracic joint was 12.5% about the long axis of the humerus during internal/external rotation motion. With arm position changes from 90° external rotation to 60° internal rotation, most movement was performed by the glenohumeral joint. Conversely, at internal rotation of $\geq 60^\circ$, the scapula began

to markedly tilt in the anterior direction. At 90° internal rotation, the scapula was significantly tilted anteriorly ($p < 0.05$) when compared with the other positions.

Conclusions We clarified the existence of a specific scapulohumeral motion pattern, whereby the glenohumeral joint moves with internal rotation and the scapulothoracic joint moves with anterior tilt together with internal rotation motion of the shoulder joint.

Introduction

The shoulder joint has the largest range of motion of any of the major diarthrodial joints in the human body. Motion in the shoulder involves the glenohumeral joint and the scapulothoracic joint. Simultaneous analysis of these movements is important for the identification of variable clinical conditions and the planning of treatment methods. Analysis of shoulder joint motion during internal and external rotation of the shoulder joint, with the humerus in 90° of abduction, has already been performed by McClure et al. [1]. In that study, using bone pins in the scapula, and using skin markers on the humerus and thorax, three-dimensional (3-D) motion of the shoulder joint was analysed. However, large discrepancies are said to exist between skin markers and bones, and a lack of accuracy has been noted in studies using skin markers [2–6]. The insertion of bone pins directly into bones is clearly invasive [1, 7, 8], and this added invasiveness may result in movements that are not necessarily physiological in nature. Furthermore, in studies that utilise both skin markers and bone pins, obtaining accurate information on where the bony landmark being used has been placed on the humerus or the glenoid fossa is impossible. Although the 3-D positions and kinematics of bony landmarks can be analysed relative to each other, the positions and kinematics of the component bones overall cannot be analysed. The purpose of

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this study was to assess accurately the 3-D movements of the scapula and humerus relative to the thorax during internal/external rotation motion with abduction of the shoulder joint. We performed magnetic resonance imaging (MRI) in multiple limb positions during internal and external rotation of the shoulder joint with the humerus in 90° of abduction. After extracting the 3-D position data, by calculating the rotation angle and movement distance between each position for each bone, we analysed 3-D motion of each joint.

Materials and methods

Subjects

The right shoulders of ten healthy adults (two men and eight women; mean age 27.8 ± 3.5 years; range 22–32 years) were examined. None of the subjects had shoulder pain or a medical history of shoulder joint disorders. All study protocols were approved by the Ethics Committee of our institution, and informed consent was obtained from all subjects prior to enrolment.

Methods

Image acquisition of 3-D MRI

Three-dimensional MRI images were acquired using a wide-gantry open MRI scanner (1.5 T MAGNETOM Espree, Siemens, Erlangen, Germany) with an open-bore system (internal bore 70 cm, length 125 cm). MRI scanning was performed using the 3-D FLASH method [repetition time (TR) 12 ms, echo time (TE) 5.8 ms, flip angle 20°, thickness 0.8 mm, field of view (FOV) 240×240 mm², 452×512 matrix]. Each subject was examined in a supine position, wearing a soft coil around the shoulder. Fixation of the arm and body without any restriction of scapular motion was required to minimise motion artefacts when acquiring images. The arm was fixed with Velcro tape using urethane wedges at 30° intervals. A wooden board was made with the area in the region of the scapula removed, to avoid obstructing physiological movements of the scapula. The design allowed free movement of the scapula while preserving a comfortable position for the volunteer. MRI was performed every 30° from 90° external rotation to 90° internal rotation of the shoulder joint at 90° abduction of the shoulder. Scan time was five minutes and 25 seconds for each arm position (Fig. 1).

Creation of a surface model by segmentation

The images were transferred to a computer running Virtual Place M® software (AZE, Tokyo, Japan), which was

Fig. 1 Image acquisition for 3-D MRI. **a** We created a special device designed to allow free movement of the scapula while maintaining a comfortable posture for the volunteer. **b** Scanning images at the neutral position

developed at our institution. Segmentation was defined as extracting bone contours and associating each contour with the individual bone. Contours of the humerus, scapula and thoracic cage including the lungs were automatically segmented from MR volume images in the neutral position, and contours were then manually modified including the cortical bones. For each subject, 3-D surface bone models were reconstructed from the segmented area using the marching cubes algorithm [9]. The bone model was visualised using original software based on the Visualization Toolkit (Kitware, Clifton Park, NY, USA).

Image matching (voxel-based registration)

The voxel-based registration technique is a method for superimposing images by minimising the sum of squared intensity differences for segmented voxels [10]. Using this

technique, a segmented bone in the neutral position was superimposed on an image of the same bone in another position. Transformation matrices (registration matrices) from the neutral position to other positions were calculated for each bone in the MR scanner coordinate system. Using this method, we can analyse six degrees of freedom in vivo kinematics of the bones respectively at the shoulder joint. The original validation study for this voxel-based registration technique using phantoms revealed that rotational error was 0.43° and translational error was 0.52 mm [11].

Definition of the local coordinate systems (LCSs)

To evaluate the scapula motion about the long axis of the humerus, the LCSs of the thorax at the neutral position were defined according to the definitions in Fig. 2. The LCS matrices were defined in the global coordinate system (GCS), which was the MR scanner coordinate system at the neutral position. The X_g axis was the lateral-medial direction, the Y_g axis was the posterior-anterior direction and the Z_g axis was the cranial-caudal direction. The LCS of the thorax was defined as having its origin at the apical portion of the lung (O_t). The direction of the axis was the same with the GCS.

Motion analysis

Using our system, any bone can be selected as a standard and the relative motions of its surrounding bones can be analysed. The relative motions of the scapula and humerus relative to the thorax from the neutral position to other positions were calculated from the registration matrices of each bone, which were obtained by superimposition of MR images from the neutral position to other positions using the voxel-based registration technique. For instance, when analysing the transformation of motion of the scapula relative to the thorax from the neutral position to 30° external rotation, the relative matrix can be calculated as follows:

$${}^tR_s = R_t^{-1} \times R_s$$

Fig. 2 Definition of the local coordinate system (LCS) of the thorax and rotational description of the scapula. The LCS of the thorax was defined as having its origin at the apical portion of the lung (O_t). To express movement of the scapula around each axis, the X_t axis was used for anterior/posterior tilt, the Y_t axis for adduction/abduction and the Z_t axis for internal/external rotation

In this equation R_s is the registration matrix of the scapula created by superimposition of MR images from the neutral position to 30° external rotation, R_t is the registration matrix of the thorax created by superimposition of MR images from the neutral position to 30° external rotation and ${}^tR_s$ is the matrix of the scapula relative to the thorax from the neutral position to 30° external rotation. We analysed the movements of the scapula and humerus relative to the thorax using the LCS of the thorax. To express movement of the scapula around each axis, the X_t axis was used for anterior/posterior tilt, the Y_t axis for adduction/abduction and the Z_t axis for internal/external rotation. The decomposition order of the scapula relative to the thorax was Z-Y-X in Euler angles [12]. To express movement of the humerus, the X_t axis was used for rotation. The decomposition order of the humerus relative to the thorax was Z-Y-X in Euler angles [12]. We investigated the following points, which were evaluated during internal and external rotation motion:

1. The contribution ratio of the scapulothoracic joint in internal/external rotation motion, which was calculated from the mean rotation angles of the scapula and the humerus relative to the thorax respectively around the X_t axis.
2. The incremental contribution ratio of the scapulothoracic rotation to humerothoracic rotation between each position. This quantity, known as the scapulohumeral rhythm [15], was defined as the ratio of the mean rotation angles of the scapulothoracic joint to the mean humerothoracic rotation angles. In this section, we calculated the amount of change of the scapulothoracic rotation around the X_t axis (Fig. 2). Then, for each amount of change between positions, we expressed the incremental contribution ratio of the scapulothoracic rotation to humerothoracic rotation as a percentage. Thereby we measured the scapulohumeral rhythm between the scapula and humerus during internal/external rotation motion.
3. Movements of the scapula relative to the thorax for (a) anterior/posterior tilt, (b) adduction/abduction and (c) internal/external rotation.

Statistical analysis

For each rotation of the scapula and humerus, one-way repeated measures analysis of variance (ANOVA) and post hoc tests (Bonferroni-Dunn test) were performed to compare mean rotation angles among the arm positions. A difference of $p < 0.05$ was considered statistically significant. Statistical analysis was conducted using the Statcel2® software package for personal computers (OMS Publishing Inc., Saitama, Japan). Using data from a pilot study, sample size requirements were determined by a power calculation. The sample size for this study was selected to provide adequate power to detect a statistically significant difference.

Results

Contribution ratio of the scapulothoracic joint during internal/external rotation

During internal/external rotation at 90° abduction of the humerus, the mean total range of internal/external rotation of the shoulder joint was 157.0°, which included a mean 19.7° rotation of the scapulothoracic joint. The total contribution ratio of the scapulothoracic joint was 12.5% during total rotation motion from 90° internal rotation to 90° external rotation (Fig. 3).

Incremental contribution ratio of the scapulothoracic rotation to humerothoracic rotation between each position (scapulohumeral rhythm)

Except for the incremental contribution ratio from 90° internal rotation to 60° internal rotation, the contribution

Fig. 3 The mean rotation angles of the scapula and humerus relative to the thorax around the X_1 axis during internal/external rotation. The horizontal axis indicates rotational arm positions and the vertical axis indicates mean rotation angles

ratios of the scapulothoracic rotations were very low, ranging between 0.8 and 12.8%. The incremental contribution ratio from 90° internal rotation to 60° internal rotation was 50.1% and the highest for the others. Overall, the change in the contribution ratio was not constant and did not increase in a uniform pattern (Fig. 4).

Relative movement of the scapula over the thorax

Anterior/posterior tilt

The scapula was slightly tilted anteriorly from 90° external rotation to the neutral position. It increased from $-3.1 \pm 3.8^\circ$ at 90° external rotation to 0° at neutral rotation; between these positions the scapula tilted 3.1° anteriorly (Fig. 5a). From the neutral position to 60° internal rotation, the scapula was gradually tilted anteriorly and then rapidly tilted anteriorly from 60° internal rotation to 90° internal rotation. It increased from 0° at the neutral position to $16.5 \pm 6.7^\circ$ at 90° internal rotation; between these positions the scapula tilted 16.5° anteriorly.

At 30° internal rotation, the scapula was significantly tilted anteriorly when compared with 90° external rotation, 60° external rotation and 30° external rotation ($p < 0.05$).

At 60° internal rotation, the scapula was significantly tilted anteriorly when compared with 90° external rotation, 60° external rotation, 30° external rotation and the neutral position ($p < 0.05$).

Fig. 4 The ratio of the mean rotation angles of the scapulothoracic joint relative to the mean rotation angles of the humerothoracic around the X_1 axis for each position. There was no constant ratio across the range of positions

Fig. 5 **a** The mean rotation angles of anterior/posterior tilt of the scapula. Asterisks indicate a significant difference. There was a significant effect of the rotation position on the anterior-posterior tilt angle of the scapula. At 90° internal rotation, the scapula was significantly tilted anteriorly when compared with the other positions ($p<0.05$). At 60° internal rotation, the scapula was significantly tilted anteriorly when compared with 90° external rotation, 60° external rotation, 30° external rotation and the neutral position ($p<0.05$). At 30° internal rotation, the scapula was significantly tilted anteriorly when compared with 90° external rotation, 60° external rotation and 30° external rotation ($p<0.05$). **b** The mean rotation angles of adduction/abduction of the scapula. Asterisks indicate a significant difference. At 90° internal rotation, the scapula was significantly adducted when compared with 60° external rotation, 30° external rotation, the neutral position and 60° internal rotation ($p<0.05$). **c** The mean rotation angles of internal/external rotation of the scapula. No significant differences were observed

At 90° internal rotation the scapula was significantly tilted anteriorly when compared with the other positions ($p<0.05$).

Adduction/abduction

At 90° internal rotation, the scapula was significantly adducted compared with 60° external rotation, 30° external rotation, neutral position and 60° internal rotation ($p<0.05$). Adduction increased from 0° at the neutral position to $7.2\pm 7.4^\circ$ at 90° internal rotation; the scapula rotated 7.2° between these positions (Fig. 5b).

Internal/external rotation

For scapular movement relative to the thorax, no consistent trend was seen, and no significant differences were observed. External rotation increased from $-1.3\pm 3.9^\circ$ at 90° external rotation to $1.2\pm 2.1^\circ$ at 60° internal rotation; the scapula rotated 2.5° between these positions (Fig. 5c).

Discussion

Various methods have previously been used for kinematic analysis of the shoulder joint. However, each of these methods has limitations and disadvantages that have not yet been resolved. Cadaveric experiments possess several limitations in terms of methodology [13, 14]. In addition to skin and soft tissues, outer muscles are excised, as are the clavicle and ribs, but these muscles may exert major influences on the kinematics of the shoulder joint. Little evidence has suggested that physiological arm positions and movements can be analysed in cadaveric studies. Movements of the humerus and scapula are not in the 2-D plane but are instead 3-D; hence, X-ray studies are not feasible [15–18]. Meanwhile, studies using biplane fluoroscopy combined with computed tomography (CT) [19, 20] or MRI [21] images provide extremely accurate analysis, but in the shoulder joint it is impossible to depict the glenohumeral and scapulothoracic joints simultaneously because of limits on the region of interest. Such procedures would not have enabled the simultaneous depiction of the 3-D kinematics of the scapula and humerus relative to the thorax. Fluoroscopy also raises issues regarding radiation exposure. Studies using skin markers are highly susceptible to skin movement artefacts [2–6]. In particular, the scapula moves substantially beneath the skin during internal/external rotation of the arm; thus, calculating the movement of the scapula by means of skin markers placed on the skin is regarded as problematic. Studies using bone pins are clearly invasive and pin insertion may restrict physiological joint motion [1, 7, 8].

To overcome these problems, we have developed our own accurate, noninvasive in vivo joint 3-D kinematic

analysis system and have used this to perform various joint analyses [11, 22–25]. This method enables the computation of parameters such as angles of rotation of each bone and transformation distances, by performing MRI in different arm positions and using the voxel-based registration method on the resulting data to superimpose images of the same bone in different arm positions. Use of our method enables detailed, highly accurate 3-D kinematic analysis of the shoulder joint in vivo in a noninvasive manner. In order to carry out kinematic analysis of the scapula and humerus with respect to internal/external rotation motion during arm abduction, it is important to elucidate the kinematics of both the scapula and humerus relative to the thorax, but this requires a wide-gantry MRI to scan the part of the thorax alongside the scapula and humerus. Only with this method does it become possible to accurately evaluate the movements of the scapula and humerus relative to the thorax in different arm positions. Conversely, a disadvantage of our study is that these measurements were taken under sequential static conditions, which may not accurately represent what actually occurs during dynamic activities. We also used a custom-made device to remove as much restraint on the scapula as possible, but the study was performed with the subject in a supine position, and the results of kinematic analysis may therefore differ from those involving load-bearing in the upright position. The results of this study showed that in a position of 90° abduction of the shoulder joint, from 90° external rotation to 60° internal rotation, the scapula changed position slightly to an anterior tilt relative to the thorax. Meanwhile, from 60° internal rotation to 90° internal rotation, however, the position changed drastically to an anterior tilt. At 90° internal rotation, the scapula showed significant adduction to the position at 60° internal rotation, whereas other arm positions showed no significant changes in position observed, toward either adduction or abduction. No significant changes in position in terms of internal/external rotation were observed in any arm position. McClure et al. [1] used bone pins and skin markers in a report on shoulder joint internal/external rotation with the humerus in 90° of abduction. In that study, the scapula moved with anterior tilt, adduction and internal rotation during the movement from 80° external rotation to 50° internal rotation. Our analysis revealed similar results despite the fact that different axes were used, with changes in position in the anterior/posterior tilt and adduction/abduction directions. However, with arm position changes from 50 to 90° of internal rotation, the scapula clearly began to markedly tilt in the anterior direction. In addition, we found that in this position, movement of the glenohumeral joint was minor and barely perceptible. From 90° external rotation to 60° internal rotation of the shoulder joint, laxity

of the articular capsule and the glenohumeral ligaments meant that most movement was performed by the glenohumeral joint. Meanwhile, at internal rotation of $\geq 60^\circ$, tension on the articular capsule and the glenohumeral ligaments increased, decreasing the movement of the glenohumeral joint and resulting in increased movement of the scapulothoracic joint. We clarified the existence of a specific scapulohumeral motion pattern, whereby the glenohumeral joint moves with internal rotation and the scapulothoracic joint moves with anterior tilt together with internal rotation motion of the shoulder joint. We believe that an analysis of normal scapular and humeral kinematics in healthy people could provide extremely important information for future research on various shoulder disorders.

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