Quantification of Shoulder Joint Passive Rotation Range of Motion *in Vivo*

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Abstract

Passive rotation range of motion (ROM) is an important factor in shoulder joint behavior. Previous work has shown shoulder joint rotation ROMs to be significantly dependent on arm position. However, the studies were either in vitro cadaver studies, or basically qualitative in vivo investigation on one plane of elevation. No research has investigated the quantitative relationships of internal and external rotations of the shoulder joint at multiple positions in normal subjects in vivo. Therefore, this study investigated quantitatively using an electromagnetic motion tracking system in vivo passive rotation ROM at a known rotational moment in multiple angles of arm elevation and planes of elevation. In 10 normal subjects, dominant arm was tested for humerus ROM for every 30 degree of elevation in various elevation planes under 4 N·m of moment. Internal rotation angle was found to decrease with arm elevation in most planes of elevation (r=0.4-0.6, p<0.05). External rotation decreased with arm elevation in forward flexion, in 30 degree anterior to the scapular plane, and in 60 degree posterior to the scapular plane (r=0.42, 0.46, 0.48, p<0.05), respectively. With humerus elevated at the 90 degree of arm elevation angle, range of internal rotation increased significantly as planes of elevation move backward, while the opposite trend was observed in the range of external rotation at the angles less than 90 degree of arm elevation angle.

Keywords: Shoulder rotation angle, Plane of scapula, Electromagnetic tracking system

Introduction

The glenohumeral (GH) joint is the most complex and commonly injured joint of human body. Patients with GH joint injury or even upper extremity impairment routinely undergo clinical assessment of passive shoulder rotation ROM. Prior to treatment planning, physical examination used to measure shoulder passive range of motions (PROMs) are implemented to assess impairment. However, the results of examinations have been determined at various testing positions of clinical interest. Some researchers use thorax as reference to humerus positioning [1,2,3], while others use scapular as reference [4,5]. It is recommended for both measurements that placement of the humerus and starting position (external or internal rotation) is noted and considered. Biomechanical researches [6,7] on effects of capsuloligament structure on glenohumeral joints may support the hypothesis that PROMs of glenohumeral joints is position dependent, because such researches have revealed that the level at which non-contractile tissues constrain the translation and rotation of humeral head varies with joint position.

Some studies have demonstrated that although incongruent humeral head translated greatly at the end of external/internal rotation, excessive translation might be restricted by joint capsule [8,9]. An et al. investigated contribution of joint position to elevation of glenohumeral joint in a vitro model [10]. They found that the maximal angle of elevation was achieved with external rotation of humerus head in all planes anterior to plane of scapula, while the maximal elevation was achieved with internal rotation of humerus head in the planes posterior to the plane of scapula. Lucas et al. indicated that the abduction ROM of GH joint lied in 60~90° if the humerus was kept at internal rotation [9]. But the range broadened with humerus positioned in the plane forward to frontal plane. If the humerus kept at external rotation in the frontal plane, the maximal angle of abduction will increase to more than 90°. The possible mechanism of the effect of humeral rotation on humeral elevation could be clearing of the tuberosity and relaxation of constraint of the capsular and ligament components.

From above, it is assumed that humeral elevation angles and planes of elevation play a key role on rotation ROMs of glenohumeral joints. However, the methods used to measure the rotational angle vary too. Sometimes, subjects were supine with humerus abducted through examinations [11,12]. But the

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Table 1. Basic data of the subjects

	Normal subjects (n=10)		
Variable	mean	SD	Range
Age (y)	25.9	1.79	24-29
Height (cm)	169.4	6.56	158-178
Weight (kg)	72.8	9.08	59-92

common process used currently is having subjects seated with elbow fixed at 90° of flexion and with inferior angle of scapular stabilized by examiners [13,14]. In addition, to further understand the knowledge of effects of upper arm positioning on rotational range is considerably important. As far as we know, few researches have investigated the relationship among rotational range of glenohumeral joint, starting angle of humeral elevation and multiple planes of elevation in vivo [13]. Therefore, the objective of the current study was to investigate amount of rotational range of glenohumeral joint in different starting positions, where humerus were elevated at different angles in various planes of elevation.

Materials and Methods

Subjects

Ten male healthy volunteers with no shoulder symptoms were recruited. Their demographic information was presented in Table 1. Inclusion criteria were no history of shoulder diseases such as limitation of range of motion in every direction, neurological disease, arthritis, dislocation (acromioclavicular joint or glenohumeral joint) or any surgery associated with shoulder girdle. All subjects read and signed informed consent forms before participated in this study.

Instrumentation

Flock of Birds (FoB, Ascension Technology. Inc., Burlington VT, USA), a 3-dimentional (3-D) tracking device with an extended distance transmitter and four wire receivers, was used to track the position and orientation of each subject's thorax and humerus in space. One receiver attached to the stylus was used to digitize anatomic landmark for definition of human anatomic coordinate. Previous investigators [6] proposed that the mental objects in the environment would cause the measurement errors by development of eddy currents around metals, which produce the secondary magnetic fields and interfere with the original filed omitted from the transducer. We moved the large mental objects away from this instrument to reduce measurement errors. The mean residual errors after calibration were 1.74 mm for x-coordinate, 2.79 mm for the y-coordinate and 3.18 mm for the z-coordinate. The accuracy of the Bird makes it suitable for this study.

A strain gauge (A033, Kwang-Hwa Electronic Material CO., Ltd. Taichung, Taiwan) with a load limit of 5 kg was used to detect the force by examiner, ensuring the given force was repeatable and reliable. Signal produced from the strain gauge was collected at a sampling rate of 20 Hz. Using a remote controller, a PC was used to collect arm kinematic data from Flock of Birds, while a control device of our design triggered strain signal in order to collect strain data synchronously.

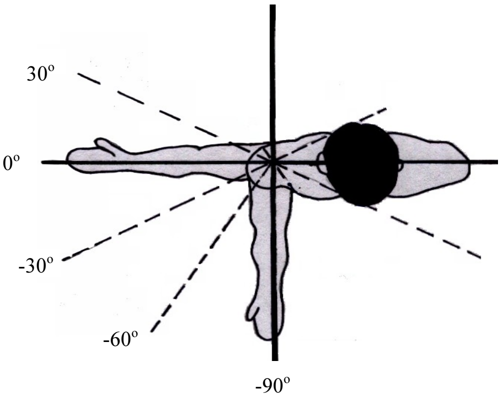


Figure 1. The same protocol was repeated at 30° and 60° anterior and posterior to the scapular plane, respectively. (scapular plane: -30°)

Experimental Procedure

The force sensor connecting to a handle was attached to the brace to detect applied force. Two electromagnetic sensors were used. With adhesive tape, one sensor was attached to the sternum notch and another to the upper portion of the brace secured to the distal humerus. All subjects were instructed to sit relaxed with their trunk stabilized with a pelvic and a chest belt. The GH joints at dominant side were going to be tested. An adjustable brace was used to stabilize elbow at 90° of flexion.

While subjects sat with their dominated arms relaxed in neutral position, six bony landmarks (suprasternal notch, 7th cervical vertebra, xiphoid process, medial epicondyle (EM), lateral epicondyle (EL), and acromioclavical joint) on thorax and humerus were palpated and digitized to determine the transformation matrix between receiver data and local anatomically based coordinate systems. Then an examiner applied a 30N of tensile load to humerus until a 4 N·m of external rotation moment was achieved. The humerus then returned to neutral position and reversed to internal rotation with the same peak moment of 4 N·m described above. These procedures were also applied for three repetitions while humerus was elevated at 30°, 45°, 60°, 90°, 120°, 135°, and 150°, respectively. The same protocol was repeated in planes at 30° and 60° anterior as well as posterior to the scapular plane (Fig. 1). Kinematic and force data were collected synchronously but stored in separate files for post processing.

Data Processing

Raw kinematic data were low pass filtered and processed with Matlab software. From the digitized data, the positions of six bony landmarkers were computed for setting anatomical coordinate systems of thorax and humerus. The rotation center of glenohumeral joint was defined with the method proposed by Paolo et al [15]. For thorax coordinate definition, the vertical Z_t axis of right-handed Cartesian coordinate system was directed inferiorly, defining from the suprasternal notch point to xiphoid process. The horizontal Y_t axis was directed medially and perpendicular to the plane formed by vector from suprasternal notch to C^7 and vector from suprasternal notch to xiphoid process. The X_t axis was calculated as the cross

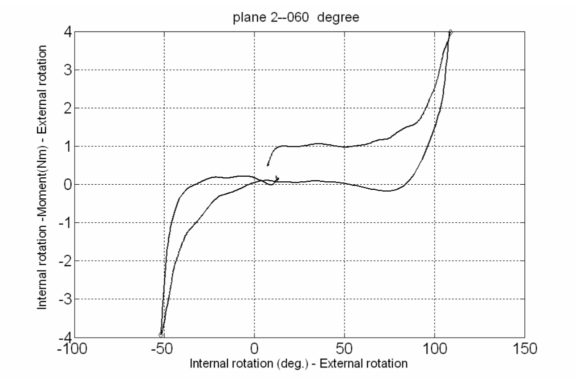
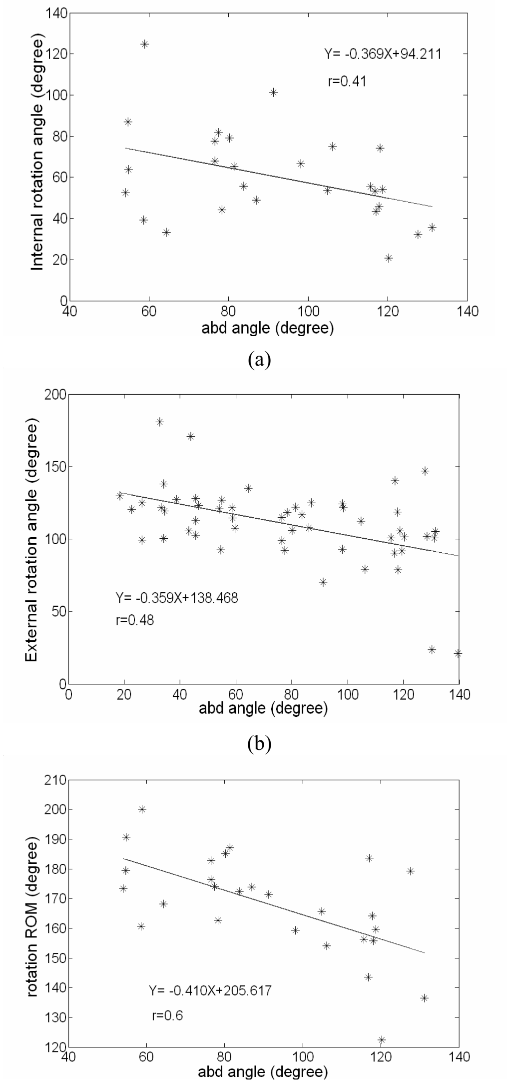


Figure 2. Internal-External moment-angle curve at 60 degree of arm elevation in the scapular plane of one human subject. The total rotation range of motion (ROM) was determined as the rotational angle between -4 Nm of IR and +4 Nm of ER.



(a)

(b)

(c)

Figure 3. Linear regressions of IR, ER and total rotation (TR) ROM (a-c). The solid line represents the derived IR, ER and TR ROM of all subjects as a function of arm elevation angles in 60° anterior to the frontal plane, respectively.

product of these two axes. For humeral coordinate definition, Y_h is the vector from EL to EM and directed medially. X_h is directed posteriorly and perpendicular to the plane formed by Y_h and a line from GH joint center to midpoint of EM and EL. Z_h is directed inferiorly perpendicular to X_h and Y_h. The recorded receiver orientation data during motion were transformed to describe relative positions of the local coordinate systems and were aligned with anatomically based and clinically meaningful coordinate system. The orientation of the humerus relative to the thorax was determined by the humerus and thorax local coordinate systems.

The change of the humeral orientation relative to trunk can be described as Euler angle, a sequence of three angles of rotation against the initial position [10]. The Z-X'-Z" rotation sequence of Euler angle was used to describe the 3-axis rotation angles. The first rotation about the Z axis represents plane of elevation (α). The second rotation about the X' axis represents arm elevation angle (β). The third rotation about the Z" axis stands for axial rotation (γ). The transformation matrix of the distal segment reference frame relative to the proximal reference frame is:

$$R_{xz}(\alpha,\beta,\gamma)=\lfloor\Gamma_{ij}\rfloor_{3\times3}\begin{bmatrix}-\sin\alpha\cos\beta\sin\gamma+\cos\alpha\cos\gamma & -\sin\alpha\cos\beta\cos\gamma-\cos\alpha\sin\gamma & \sin\alpha\sin\beta\\ \cos\alpha\cos\beta\sin\gamma+\sin\alpha\cos\gamma & \cos\alpha\cos\beta\cos\gamma-\sin\alpha\sin\gamma & -\cos\alpha\sin\beta\\ \sin\beta\sin\gamma & \sin\beta\cos\gamma & \cos\beta\end{bmatrix}$$

Three Euler angles of the humeral coordinate system relative to trunk coordinate system are calculated using the equations as follows:

$$\beta=\cos^{-1}(\Gamma_{33})$$
$$\alpha=-A\tan 2(\Gamma_{13},\Gamma_{23})$$
$$r=A\tan 2(\Gamma_{31},\Gamma_{32})$$

The measurement resulted from this procedure was passive rotation ROM of shoulder joint in response to a 4 N·m (external rotation) or -4 N·m (internal rotation) moment. Angle-moment curves were then obtained at multiple arm positions.

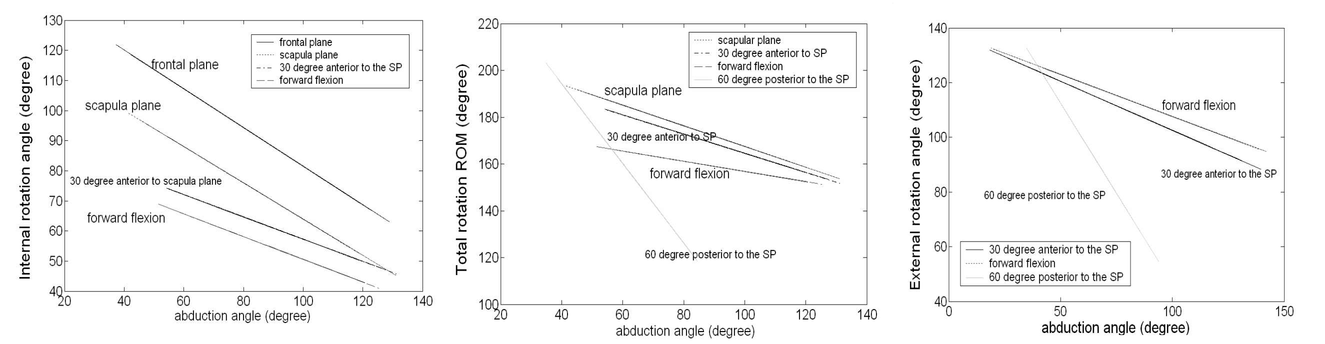
Statistical Analyses

To establish the relationships of passive range of rotation and angles of humeral elevation in multiple planes of elevation, a linear regression equation was calculated. Linear regressions were used in the analysis of relationship of external-internal PROMs and multiple humeral positions (plane of elevation vs. angles of arm elevation).

Results

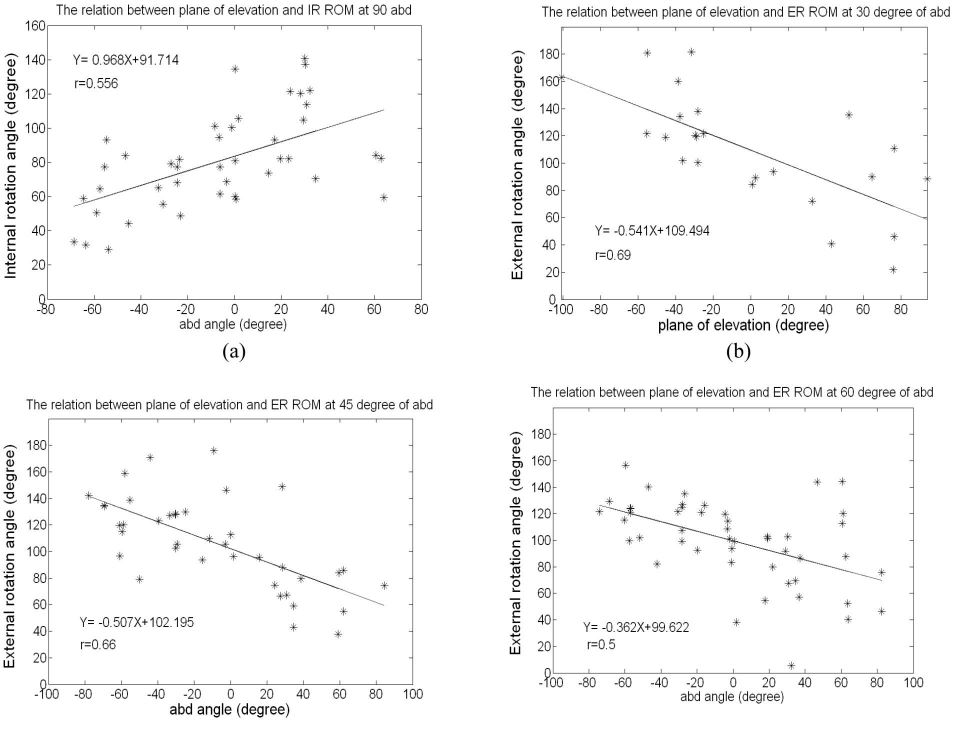
A representative curve of rotational moment and rotational range derived form one subject with humerus elevated at 60° in the scapular plane was shown in figure 2.

The range of external rotation, internal rotation, and range of internal-external rotation (TR, total range) were observed in figure 3 (a)-(c), as humerus was elevated at different angle in 60° anterior to the frontal plane.



(a) (b) (c)

Figure 4. The relationship between passive ROM (IR, TR, ER) and angles of elevation are shown for multiple elevation planes. (a): IR (b): TR (c): ER. SP: scapular plane



(a) (b)

(c) (d)

Figure 5. (a): The relationship between IR ROM and planes of elevation at 90 degree of arm elevation (r=0.556, p<0.05). (b-d): The relationship between ER ROM and planes of elevation at 30°, 45°, 60° of arm elevation (r=0.69, 0.66, 0.5, p<0.05, respectively.)

Effect of Angles of Humeral Elevation on Glenohumeral Rotation

The linear relationship between passive range of rotation and angles of humeral elevation in different planes of elevation was illustrated in figure 4(a)-(c), respectively. In figure 4(a), the declining tendency of range of internal rotation can be observed significantly as the angle of humeral elevation increased in frontal plane and 30°, 60°, 90° anterior to frontal plane (p<0.05). The similar trend took place in external rotation as humerus was positioned in planes of elevation of 60°, 90°anterior to frontal plane, and 30° posterior to frontal plane (p<0.05).

Effect of Planes of Elevation on Glenohumeral Rotation

The range of internal rotation measured with humerus elevated at 90°decreased significantly as planes of elevation move forward (Figure5(a), r=0.556, p<0.05). As to range of external rotation, greater ER occurs in the more anterior plane of elevation at 30°, 45°, 60° of arm elevation, respectively (r=0.69, 0.66, 0.5, p<0.05, Fig. 5(b)-(d)). However, there was a decrease in the influence of the plane of elevation on external rotation at angles larger than 90° of arm elevation.

Discussion

In the current study, we were primarily interested in variation of shoulder passive range of rotation as measured at different angles of elevation and in different planes of elevation. The non-contractile tissue such as capsule and ligament are believed to limit rotation by tightening of different portion as position of humerus changes. At the end range of elevation of humerus, the main constraints to rotation are assumed to be inferior band of glenohumeral ligament [7,16,17]. As the glenohumeral joint elevated and internally rotated, the posterior band of inferior glenohumeral joint ligament will become cordlike to support the humeral head [7,18]. In our investigation, the range of internal rotation decreased as humerus elevated higher in most planes of elevation (Fig. 4(a)). It can be assumed that as humerus elevated, ligamentum tissue, especially inferior glenohumeral ligament may get tensed and limit the further rotation of humeral head in internal direction. Thus, range of internal rotation decreased as humerus elevated progressively in most planes of elevation defined in the present study.

External rotation of the GH joint decreased with the angle of arm elevation anterior to the plane of scapula and 30° posterior to the frontal plane, as seen in Figure 4(c). It has been reported that the anterior band of inferior glenohumeral ligament and axillary pouch were primary resisters when the humeral head rotates externally with humerus elevated at 90° or even higher [7,19]. Moreover, the range of external rotation especially decreased rapidly when humerus moved in the plane 30° posterior to frontal plane (Fig. 4(c)), which could be explained by that the anterior band of inferior glenohumeral ligament become much more tense as humerus extend and elevated at the same time, therefore, restricted external rotation at greater level.

Larger IR motion is found in horizontal extension (0°) rather than in horizontal flexion relative to scapular plane (-60°, -90°) at 90° of arm elevation (Fig. 5(a)). This result is in agreement with that of O'Brien et al [7], who reported that in 90° glenohumeral elevation and internal rotation, the posterior band tension changes from being taught in horizontal flexion to being fully relaxed in horizontal extension relative to scapular plane. The posterior capsule may be loose and IR increases in the frontal plane compared with the planes anterior to frontal plane (-30°, -60°).

Greatest ER occurs in the sagittal plane (-90°) and decreases in the order -90° > -60° > -30° > 0°. According to O'Brien et al. [7], the anterior band progressively tightens with increasing GH joint horizontal extension and external rotation because the anterior band, running somewhat anteriorly to the vertical axis about which rotation occurs, checks external rotation and extension. The anterior capsule may be more relaxed in the sagittal plane than in other planes during ER movement with sequential arm elevation angles (30°,45°and 60°of arm elevation).

The mechanical responses of visicoelastic tissue around glenohumeral joint were influenced partly by rate of loading, number of load application, and inherently mechanical constraints [20]. The relation curve of rotation moments and angles (Fig. 2) founded in the current study might differ from the previous study [13]. The causal factors might be muscle activity, loading rate, and experimental design.

The baseline load in the present study did not offset the gravitational force caused by the weight of handle during each test. Future experimental design for related study should apply the load in a controlled manner in order to offset the handle weight. Further, although subjects were instructed to remain relaxed during testing, repeated trials may result in increasing spontaneous muscle contraction and tension of the subjects. Therefore, improved experimental design should include provision for electromyographic monitoring around the shoulder joint muscle to determine the state of muscle relaxation of the subject during all phases of testing. Further study to validate and improve this method of quantified measurement of in vivo passive ROM in multiple positions or to examine alternative measurement methodologies is needed.

Conclusions

Passive rotation ROM of the human shoulder joint was found to depend on arm elevation angles and planes of elevation. Testing position is a factor and should be routinely recorded and repeated measurement of passive ROM should be taken in a consistent position.

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