

## On the use of the rotation center of the glenohumeral joint for the local coordinate system of the humerus for in vivo motion recording studies

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**Abstract - For a proper assessment of the humeral local coordinate system, the longitudinal axis of the humerus is needed. Only two bony landmark can be discerned at the humerus: Epicondylus medialis and lateralis. A third landmark is desirable, preferably the rotation center of the glenohumeral joint. If it is assumed that the glenohumeral joint is a spherical joint, and no translations occur, the rotation center is fixed with respect to the scapular local coordinate system. In this cadaver study it is shown that the rotation center of the glenohumeral joint can be estimated using the position of five bony landmarks at the scapula. Since these bony landmarks can be recorded in vivo, the position of the glenohumeral joint and the local coordinate system of the humerus can be assessed. Errors result from the measurement accuracy of the bony landmarks, and the mean residual error of the regression equation. In vivo recordings showed that the estimated overall accuracy is  $2.86^\circ$ ,  $0.84^\circ$  and  $2.69^\circ$  standard deviation for the offset of the x-, y- and z-axis, respectively. It is concluded that the determination of GH from bony landmarks of the scapula adds an important step in the motion recording procedures of the shoulder.**

### INTRODUCTION

For motion recording and data processing of the upper extremity motions, local coordinate systems must be assessed for all segments: Thorax, clavicle, scapula, upper arm and forearm (Van der Helm & Pronk, 1995; Van der Helm, 1997). The motions can be recorded using tracking markers or an electromagnetic sensor attached to the segment. Then, the position and orientation of these tracking markers with respect to the local coordinate system of the segment must be determined before the actual measurements start. A local coordinate system is preferably defined with respect to three bony landmarks. For the humerus, only two bony landmarks can be discerned: Epicondylus medialis (EM) and epicondylus lateralis (EL). For a third 'bony landmark' the rotation center of the glenohumeral joint (GH) is the best choice. Firstly, because the line from the midpoint between both epicondyles to GH is a good approximation of the longitudinal axis of the humerus. Secondly, because rotations of the local coordinate system of the humerus with respect to the scapula, pivoting about GH, are an excellent representation of the glenohumeral joint rotations.

The glenohumeral joint consists of a small articular surface at the scapula, the cavitas glenoidalis or glenoid, and a much larger articular surface at the humerus, the caput humeri or humeral head. Some authors state that the radius of curvature of these articular surfaces are different. Poppen & Walker

(1976) used X-ray to determine the rotation center of the GH-joint from superimposed images using the method of Reuleaux (1963). Projection errors, scapular movement and the very high sensitivity of the Reuleaux method to measurement errors make their results very suspicious. Their suggestion that the humeral head is moving with respect to the *scapula*, and that therefore the radius of the humeral head must be smaller than the radius of the glenoid, is not supported by their analyzing methodology and results. Saha (1961) measured the radius very locally using a three-pin device, with an unknown accuracy. Saha (1961) distinguishes three cases for the curvature of the articular surfaces: A smaller humeral head with respect to the glenoid, even sized articular surfaces and a larger sized humeral head. A larger sized humeral head would mean the the humerus is only supported at the rim of the glenoid, thereby pressing at the labrum, and therefore unlikely. If the radius of the humeral head is smaller than the glenoid, then the rotation center of the glenohumeral head can shift its position with respect to the scapula. The contact 'point' between the two articular surfaces will be in the direction of the joint reaction force vector pointing from GH to the glenoid (Figure 1). Rozendaal (1997) showed that no particular instabilities are to be expected from this configuration, though there are no advantages as well. However, translations of the rotation center will cost energy, since the muscle force vectors will do additional work without much benefits because their points of application are displaced. In addition, a certain

'play' in the joint is disadvantageous from the viewpoint of motion control.

Van der Helm et al. (1989; 1992) and Soslowsky et al. (1992) found that both articular surfaces had a similar curvature, and can be regarded as two concentric spheres. Small incongruencies are likely to be dissolved by the visco-elastic properties of the articular cartilage. Hence, the rotation center of the glenohumeral joint will be at a fixed position with respect to the scapula.

The goal of this study is to investigate if the position of the GH rotation center can be estimated from the position and mutual distances of the bony landmarks at the scapula. These bony landmarks are recorded in a motion recording study anyway to determine the local coordinate system of the scapula. For the reliable assessment of this regression equation, data from many specimen are needed.

**METHODS**

Thirty-six sets of scapulae and humeri (17 left and right shoulder and two right shoulders) were used. The scapulae were defleshed, while the articular cartilage, labrum and coraco-acromial ligament remained intact. A large number of data points were measured on the articular surface of the glenoid and of the humeral head. Measurements were done using a 'palpator': a three-dimensional digitizer with an accuracy of 0.96 mm (standard deviation) per coordinate (Pronk & Van der Helm,

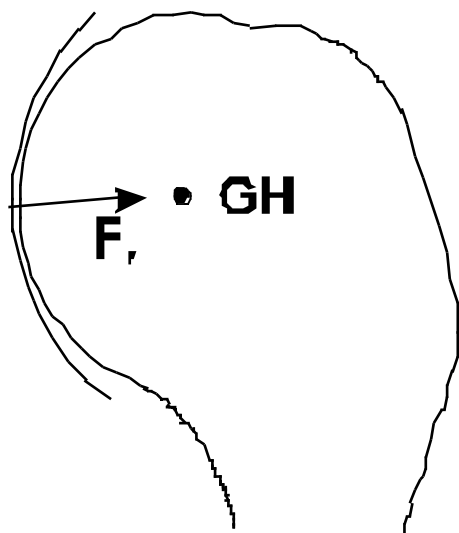


Figure 1 - The contact point between the humeral head and the glenoid is located on the same line along which the joint reaction force ( $F_r$ ) is acting. The joint reaction force points towards the (instantaneous) joint rotation center GH. If the radius of curvature of the humeral head is smaller than the radius of curvature of the glenoid (as shown), the joint rotation center GH shifts with respect to the scapula.

1991).

Five bony landmarks on the scapulae were measured:

1. AC: The most dorsal point on the acromioclavicular joint.
2. TS: Trigonum spinae, a point at the medial border in line with the scapular spine.
3. AI: Angulus Inferior, the most caudal point of the scapula.
4. AA: Angulus Acromialis, a sharp corner at the dorso-lateral side of the scapular spine.
5. PC: Processus Coracoideus, the most ventral point.

Since the retrieval of bony landmarks could be somewhat subjective, all measurements of the bony landmarks were repeated by two independent observers.

The local coordinate system of the scapula is defined as:

- $x_s$ :  $\frac{AC - TS}{|AC - TS|}$
- $z_s$ : Perpendicular to the plane through AC, TS and AI, pointing backwards.
- $y_s$ : Perpendicular to  $x_s$  and  $z_s$ .
- origin: AC

All data points were transformed to the local coordinate system of the scapula. Spheres were fitted to

**glenoid**

**humeral head**

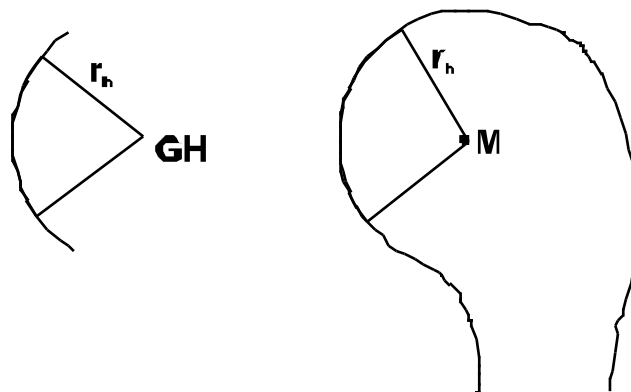


Figure 2 - A sphere is fitted to the glenoid with the radius of the humeral head as radius. M is the center of the sphere fitted to the humeral head, but its coordinates are not in the scapular coordinate system. The resulting center of the sphere fitted to the glenoid is the joint rotation center GH of the humerus with respect to the scapula, assuming that the glenoid and humeral head may be regarded as two concentric spheres.

Table 1 - Mean and standard deviation ( $N=36$ , values in mm) of the center and radius fitted to the glenoid, humeral head and glenoid with a fixed radius obtained from the humeral head. The mean residual error (mean  $\pm$  s.d.,  $N=36$ ) depicts the quality of the fit, and the Standard Error of the Mean (SEM), mean  $\pm$  s.d. ( $N=36$ ), depicts the accuracy with which the parameters could be estimated.

procedure	parameters	mean $\pm$ s.d.	mean residual error	SEM
sphere fitted to <b>glenoid</b>	Mx	9.8 $\pm$ 4.15	0.45 $\pm$ 0.26	1.40 $\pm$ 0.74
	My	-45.4 $\pm$ 4.73		0.39 $\pm$ 0.25
	Mz	-19.5 $\pm$ 7.33		0.33 $\pm$ 0.13
	r	25.5 $\pm$ 3.50		1.21 $\pm$ 0.61
sphere fitted to <b>humeral head</b>	Mx	-	0.93 $\pm$ 0.26	0.41 $\pm$ 0.21
	My	-		0.45 $\pm$ 0.14
	Mz	-		0.58 $\pm$ 0.27
	r	26.4 $\pm$ 2.26		0.50 $\pm$ 0.23
sphere fitted to <b>glenoid</b> using <b>radius humeral head</b>	Mx	10.0 $\pm$ 4.16	0.48 $\pm$ 0.28	0.48 $\pm$ 0.27
	My	-45.8 $\pm$ 4.88		0.24 $\pm$ 0.10
	Mz	-19.0 $\pm$ 7.56		0.14 $\pm$ 0.31

the datapoints on the humeral head and the glenoid using a least squares criterion. Estimated parameters are the center ( $MH_x, MH_y, MH_z$ ) and the radius ( $r_h$ ) of the humeral head, and the center ( $MG_x, MG_y, MG_z$ ) and the radius ( $r_g$ ) of the glenoid. A third sphere with center ( $GH_x, GH_y, GH_z$ ) was fitted to the glenoid using the radius  $r_h$  of the humeral head as a radius. The center of this latter sphere is the rotation center GH of the glenohumeral joint (Figure 2).

### RESULTS

Parameters of the spheres fitted to the humeral head and the glenoid are presented in Table 1. The mean radius of the sphere fitted to the glenoid was 25.5 ( $\pm$  3.5) mm, ranging from 16.5 to 33.4 mm. The mean radius of the sphere fitted to the humeral head was 26.4 ( $\pm$  2.26) mm, ranging from 22.1 to 31.5 mm. The mean difference between the spheres of the glenoid and the humeral head is  $-0.99 \pm 5.33$  mm, ranging from -7.43 to 5.34 mm. For the latter difference, 10 glenoids had a radius more than 1 mm larger than the humeral head, 16 glenoids had a radius more than 1 mm smaller than the humeral head, and the remaining 10 glenoidal radii were within 1 mm of the radius of the corresponding humeral head. The accuracy of the estimate is denoted by the Standard Error of the Mean (SEM), which is on average 1.21 mm for the glenoidal radius and 0.50 mm for the humeral head radius. This difference can be explained by the smaller surface of the glenoid which results in a less ‘informative’ data set, i.e. a smaller part of the sphere is covered.

If the radius  $r_h$  of the humeral head is used to estimate a sphere through the glenoidal surface, the mean residual error, averaged over 36 specimen, increases from 0.45 mm to 0.48 mm. In other words, the sphere through the humeral head is very close to the optimal sphere fitted through the glenoid. It is likely that the differences in curvature are small in respect to the compressibility of the articular cartilage.

The two articular surfaces of the glenoid and the humeral head may be regarded as two concentric spheres with the same radius of curvature  $r_h$ . Then, the center of the sphere fitted to the glenoid is the rotation center GH of the glenohumeral joint which has a fixed position with respect to the local coordinate system of the scapula. The rotation center GH is also a fixed point for the humerus, if it is assumed that no translations occur in the glenohumeral joint. The latter assumption is very likely, since the articular surfaces are almost congruent, and translation would mean a separation of the articular surfaces.

The position of GH is estimated in the scapular coordinate system (Table 1). The standard deviations of the x-, y- and z-coordinates are 4.16 mm, 4.88 mm and 7.56 mm, respectively. This standard deviation is considered unacceptably high for an estimate of the rotation center GH. However, many different scapular shapes were encountered during the dissection and recordings. The orientation of the local coordinate system and the position of the bony landmarks therein, provide information about the scaling and shaping of the scapulae. It is hypothesized that the position of these bony landmarks could improve the estimates of GH.

The following parameters were used to describe the scapular geometry:  $TS_x, AI_x, Ai_j, Aa_x, Aa_y, Aa_z,$

$PC_x, PC_y, PC_z$ . Using the five bony landmarks, ten distances could be calculated for each scapula. In total, 19 regressors were available for a regression analysis. The scapulae were divided into two groups: In a stepwise regression model selection procedure, the most significant regressors with their co-efficients were selected for the first group by minimizing the RMSE for the *second* group. In this procedure it is assured that these regressors have the maximal predictability for a second group. The following regression equations were derived:

$$GH_x = 18.97 + 0.24 * PC_x + 0.23 * AI_x + 0.16 * L_{AI-AA} + 0.05 * PC_y$$

$$GH_y = -3.88 + 0.17 * PC_y - 0.39 * L_{AC-AA} + 0.12 * AI_x - 0.1 * L_{AC-PC}$$

$$GH_z = -9.26 + 1.03 * PC_z - 0.24 * PC_y + 0.17 * L_{TS-PC}$$

where  $L_{AI-AA}$  is the distance between the bony landmarks AI and AA, etc. The RMSE for the first group in which the regressors were estimated was 2.81 mm, 3.39 mm and 3.45 mm for  $Gh_x, Gh_y, Gh_z$  respectively. The validity of these parameters is tested on the second group and resulted in a RMSE of 2.32 mm, 2.68 mm and 3.04 mm for  $Gh_x, Gh_y, Gh_z$  respectively. The reason that for the *second* group a lower RMSE was obtained is due to the fact that minimizing this RMSE was the criterion for inclusion of regressors in the *first* group.

### DISCUSSION

The first step in a motion recording study is the assessment of the local coordinate systems of the segments with respect to bony landmarks. At least three non-collinear bony landmarks are needed. At the humerus only two bony landmarks are available: Epicondylus Medialis (EM) and Epicondylus Lateralis (EL). Using the rotation center of the glenohumeral joint (GH), a local coordinate system of the humerus can be defined by:

- $y_h: \frac{GH - MI}{|GH - MI|}$
- $z_h$ : Perpendicular to the plane through GH, EM and EL, pointing backwards.
- $x_h$ : Perpendicular to  $y_h$  and  $z_h$ .
- origin: GH

where MI is the midpoint between EM and EL ( $MI = (\underline{EM} + \underline{EL})/2$ ). In this study it was shown that GH, being defined in the scapular coordinate system, can be estimated from bony landmarks of the scapula.

There are two important questions in this discussion:

- 1) Can the rotation center GH assumed to be fixed in the scapular coordinate system?
- 2) How reliable is GH as a ‘bony landmark’?

In the method of this study, it is implicitly assumed that the glenoid and humeral head can be regarded as two concentric spheres. If separate spheres are fitted to the glenoid and the humeral head, the radii are  $25.5 \pm 3.5$  mm and  $26.4 \pm 2.26$  mm, respectively. The difference in radii for all sets of scapulae and humeri range is  $-0.99 \pm 3.22$  mm, ranging from -7.43 to 5.34 mm. . It should at first be noted that we measured the labrum as well, which was in most cases protruding a little. This narrowed the radius of the glenoid. It can safely be presumed that in

vivo this protrusion vanishes, for the labrum is a deformable structure. Furthermore, it is important to note that the SEM of the glenoid radius is  $1.21 \pm 0.61$  mm, showing that the data set of the glenoid surface is not ‘informative’ enough to estimate a more accurate radius. Next, the radius of the humeral head is used to fit a sphere to the glenoid. This radius is the actual distance between the glenoidal surface and the center of the humeral head. The mean residual error of this fit only increases from  $0.45 \pm 0.26$  mm to  $0.48 \pm 0.28$  mm, showing that the new sphere is almost as good as an approximation. Now, two spheres with the same radius  $r_h$  have been fitted, justifying the assumption that the two articular surfaces of the glenohumeral joint can be approximated by two concentric spheres with the same radius.

Many authors have argued that the radius of the humeral head is smaller than the glenoid, and that the humeral head translates with respect to the glenoid. However, these arguments are not supported by data. Saha (1961) measured the radius very locally, but the accuracy of his measurement device is unknown. The studies of Soslowsky et al. (1992) and Van der Helm et al. (1989; 1992) both concluded that the humeral head and the glenoid had the same radius, which is in accordance with the current results. Therefore, it is concluded that the rotation center of the glenohumeral joint is fixed with respect to the scapula.

Errors in the estimation of GH will lead to an offset of the local coordinate system of the humerus, and to a systematic error in the rotations of the joint. Two types of errors are superimposed in the assessment of GH: The retrieval accuracy of the bony landmarks AC, TS, AA, AI and PC, and the residual error of the regression equation. A reproducibility study has been done in vivo on 10 subjects, measured 5 times by 2 observers. The effect of the first error was estimated to be 1.55 mm, 1.09 mm and 1.62 mm standard deviation for the x-, y-

and z-coordinate of GH, respectively, resulting in an orientation error of the local coordinate system of  $1.35\beta$ ,  $0.29\beta$  and  $1.26\beta$  of the x-, y- and z-axis of the humeral coordinate system. If the residual error of the regression equation is added, the orientation error increases to  $2.86\beta$ ,  $0.84\beta$  and  $2.69\beta$  of the x-, y- and z-axis of the humeral coordinate system. It is concluded that GH is an accurately measurable 'bony landmark', not largely affecting the assessment of the orientation of the humeral coordinate system.

It is concluded that the determination of GH from bony landmarks of the scapula adds an important step in the motion recording procedures of the shoulder.

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