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Technical Note

In vivo estimation of the glenohumeral joint rotation center from scapular bony landmarks by linear regression

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Abstract

In this paper, a method is described for *in vivo* prediction of the glenohumeral joint rotation center (GH-r), necessary for the construction of a humerus local coordinate system in shoulder kinematic studies. The three-dimensional positions of five scapula bony landmarks as well as a large number of data points on the surface of the glenoid and humeral head were collected at 36 sets of cadaver scapulae and adjacent humeri. The position of GH-r in each scapula was estimated by mathematically fitting spheres to the glenoid and humeral head. GH-r prediction from scapula geometry parameters by linear regression resulted in a RMSE between measured and predicted GH-r of 2.32 mm for the x-coordinate, 2.69 mm for the y-coordinate and 3.04 mm for the z-coordinate. Application *in vivo* revealed a random humerus orientation error due to measurement inaccuracies of 1.35, 0.29 and 1.26° standard deviation per rotation angle. The estimated total humerus orientation error including the offset error due to the regression model inaccuracy was 2.86, 0.84 and 2.69° standard deviation. As these errors were about 15 and 20% of, respectively, the intra- and inter-subject variability of the humerus orientations measured, it is concluded that the method described in this paper allows for an adequate construction of a humerus local coordinate system.

Keywords: Shoulder kinematics; Glenohumeral joint; Rotation center; Bony landmarks; Linear regression

1. Introduction

In order to measure three-dimensional shoulder kinematics, palpation techniques were developed to obtain three-dimensional bony landmark positions on the shoulder bones (Johnson et al., 1993; Meskers et al., 1997; Pronk, 1987; Van der Helm and Pronk, 1995). On each bone, at least three non-collinear markers are required. On the humerus however, only the epicondylus medialis and lateralis are suitable. For definition of the longitudinal axis of the humerus, the glenohumeral joint rotation center (GH-r) would be a desirable third landmark, but its position has to be estimated. To our knowledge, no methods are described so far for the estimation of GH-r *in vivo*, though various methods have been described for the hip joint rotation center. Crowninshield et al. (1978) used radiographs. Others used Moiré fringe patterns (Ellis et al., 1979), intercepts of helical axes (Blankevoort et al., 1990) and sphere centers (Cappozzo, 1984). Several authors investigated the relationship between aspects of the pelvic geometry and the hip joint rotation center (Andriacchi et al., 1980; Bell et al., 1989, 1990; Tylkowski et al., 1982; Seidel et al., 1995). Measurements of GH-r from radiographs are susceptible to projection errors and the application of other techniques is hampered by the relative inaccessibility of the scapula. Using the relationship between scapular geometry to estimate GH-r, however, would be easily applicable within the palpation technique, in which the three-dimensional positions of scapular bony landmarks are already obtained. The present study was therefore undertaken to obtain a relationship between GH-r and geometric parameters based on the three-dimensional position recordings of scapular bony landmarks.

2. Materials and methods

2.1. Cadaver measurements

Thirty-six sets of scapulae and humeri of 19 embalmed cadavers (34 left–right and two left shoulders) were used.

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No gross pathology was present. No further selection took place. Mild osteoarthrosis was allowed. The bones were defleshed. The labrum was left intact. Three-dimensional position measurements were performed using a spatial linkage digitizer with an estimated accuracy of 0.96 mm standard deviation per coordinate and 1.43 mm in absolute distance (Pronk and Van der Helm, 1991). Five bony landmarks on the scapula were measured:

1. AC, the most dorsal point of the acromioclavicular joint.
2. TS, the trigonum spinae, at the medial scapular border in line with the spina scapulae.
3. AI, the angulus inferior, the most caudal point of the scapula.
4. AA, the angulus acromialis at the dorsolateral curvature of the scapular spine.
5. PC, the most ventral point of the processus coracoideus.

Each bony landmark was measured five times by two observers. The mean of the recordings of the two observers was used for further calculations. Data of left shoulders were mirrored in the measurement coordinate system ($x = -x$). Scapular data points were then translated and rotated to a scapula fixed coordinate system, defined as

origin: AC.
x_s: $AC - TS/\|AC - TS\|$.
z_s: perpendicular to the plane through AC, TS and AI, pointing backwards.
y_s: perpendicular to x_s and z_s, pointing upwards.

2.2. GH-r estimation

About 40 data points were measured on the surface of the glenoid including the labrum, and on the caput humeri. Spheres were fitted in a least-squares sense to the data points on glenoid and humeral head by minimizing

$$J = \sum_{i=1}^{n} e_i^2, \tag{1}$$

where

$$e_i = \sqrt{(x_i - M_x)^2 + (y_i - M_y)^2 + (z_i - M_z)^2} - r, \tag{2}$$

with the estimated parameters, r being radius, and M_x, M_y, M_z the coordinates of the sphere center.

A Levenberg–Marquardt algorithm was applied (Ljung, 1987). GH-r was regarded to be the center of a new sphere fitted to the glenoid using the radius of the sphere fitted to the humeral head as a fixed parameter (Van der Helm et al., 1992)

2.3. GH-r prediction

Both the x-, y- and z-coordinates of the positions of AC, TS, AI, AA and PC and all 10 distances between the bony landmarks were used as potential regressors in a multiple regression procedure to predict GH-r. The scapulae were randomly divided in two data sets. One set was used for construction of linear regression models, and the other was used for validation of the models. The actual regression and a first selection of the parameters included in the models was performed using a stepwise regression model selection procedure based upon minimization of the root mean-square error (RMSE) as implemented in the NCSS statistical software package. The RMSE from the validation set was used as the final criterion for the composition of the models.

2.4. *Error estimation* in vivo

GH-r position variability due to position recording inaccuracies of the bony landmarks as well as GH-r position inaccuracies due to regression model errors were estimated in an *in vivo* study. The regression model error was estimated as the RMSE from the *in vitro* validation procedure. Position-recording accuracy was established by performing five repeated measurements of the scapular bony landmarks of 10 volunteers using a 6 DOF electromagnetic tracking device and a stylus (Meskers et al., 1997). Using a first-order Taylor series expansion (Jenkins and Watts, 1969) the variance of the humerus orientation expressed in Euler angles was estimated as a function of the variability of GH-r (De Groot, 1997). The orientation variance was calculated and averaged over the total elevation range of the humerus. The Euler angles were calculated from rotations with respect to a thorax fixed global coordinate system (y-axis pointing cranially, x-axis pointing to the right and z-axis pointing dorsally). In this way, humerus orientation errors evolving from the position recording inaccuracy were calculated as well as total orientation errors evolving from the position recording variance added up with the regression model variance.

3. Results

The *in vitro* intra-observer accuracy of the bony landmark measurements was 0.96, 1.02 and 1.0 mm for the x-, y- and z-coordinate, respectively. The inter-observer accuracy was 1.73, 1.90 and 1.57 mm. The results of the sphere fitting procedures are summarized in Table 1.

Table 2 presents the final composition of the regression models and the values of the coefficients. The reconstruction of GH-r in the validation scapula set resulted in a RMSE between measured and reconstructed GH-r of 2.32 mm for the x-coordinate (range -5.66 to $+4.22$), 2.68 mm for the y-coordinate (range -4.47 to $+4.69$) and 3.04 mm for the z-coordinate (range -4.68 to $+4.72$). Application of the regression model to the fitting scapula set resulted in errors of 2.81, 3.39 and 3.45 mm, respectively.

Table 1
Mean and standard deviation of the parameters describing GH-r ($n = 36$, all values are in mm). CH = caput humeri. S.E.M. = standard error of the mean calculated within the Levenberg- Marquardt algorithm as the square root of the covariance matrix (Ljung, 1987). Blanks were entered because M^{CH} was expressed in the global coordinate system and its coordinates are therefore meaningless

Procedure	Parameter	Value	Mean res. error	S.E.M. parameter
Sphere fitted to glenoid				
	M_x glenoid	9.83 ± 4.15	0.45 ± 0.26	1.40 ± 0.74
	M_y glenoid	-45.4 ± 4.73		0.39 ± 0.25
	M_z glenoid	-19.5 ± 7.33		0.33 ± 0.13
	r glenoid	25.5 ± 3.5		1.21 ± 0.61
Sphere fitted to CH				
	M_x CH	—	0.93 ± 0.26	0.41 ± 0.21
	M_y CH	—		0.45 ± 0.14
	M_z CH	—		0.58 ± 0.27
	r CH	26.4 ± 2.26		0.50 ± 0.23
Sphere fitted to glenoid using r CH(= GH-r)				
	M_x GH	9.98 ± 4.16	0.48 ± 0.28	0.48 ± 0.27
	M_y GH	-45.8 ± 4.88		0.24 ± 0.10
	M_z GH	-19.0 ± 7.56		0.14 ± 0.31

Table 2
The derived regression models and their *in vitro* fitting and validation errors

x-Coordinate		y-Coordinate		z-Coordinate	
Regressor	Coefficient	Regressor	Coefficient	Regressor	Coefficient
Offset	18.9743	Offset	−3.8791	Offset	9.2629
PC_x	0.2434	L_{AC-AA}	−0.3940	PC_z	1.0255
AI_x	0.2341	PC_y	0.1732	PC_y	−0.2403
L_{AI-AA}	0.1590	AI_x	0.1205	L_{TS-PC}	0.1720
PC_y	0.0558	L_{AC-PC}	−0.1002		
S.D. fitting error (first data set, $n = 18$)			2.81 mm (x)	3.39 mm (y)	3.45 mm (z)
S.D. validation error (second data set, $n = 18$)			2.32 mm (x)	2.68 mm (y)	3.04 mm (z)

The mean *in vivo* GH-r position recording accuracy was 1.55, 1.09 and 1.62 mm standard deviation per coordinate. The evolving random humerus orientation variability was estimated as 1.35, 0.29 and 1.26° standard deviation, respectively for rotations of the humerus around the global y- and z-axis and the local humeral y-axis. The mean total humerus orientation variability was estimated as 2.86, 0.84 and 2.69° standard deviation.

4. Discussion

4.1. Assumptions and limitations

Both the low residual errors and SEMs justified the fitting of spheres to humeral head and glenoid. The mean residual error increased only slightly when the radius of the humeral head was used to estimate GH-r which indicates that the GH-r estimation is valid. GH-r will not translate with respect to the scapula in case of perfect ball-and-socket joint behavior. The latter will be very likely when glenoid and humeral head have equal radii. We found a slightly larger humeral head, which can be explained by the fact that we measured the labrum as well, which was protruding a little. This does however not prevent an intimate contact between humeral head and glenoid *in vivo*. Almost equal radii were also found by Soslowsky et al. (1992). Rozendaal (1996) calculated the translation stiffness of the glenohumeral joint and found it to be considerable, even when the humeral head was up to 3 mm smaller than the glenoid. The influence of the embalming process on the cartilage is unknown, but any error evolving from this will be small compared to, e.g. the palpation inaccuracy of the bony landmarks. For accurate GH-r estimation *in vivo*, a normal scapular geometry is required.

4.2. Regression procedure

A large variability in the position of GH-r with respect to AC justified this procedure. The problem of constructing valid regression models without fitting noise is well known. Therefore, the final choice of the regression models was made dependent on the residual error of the validation procedure. Automatic parameter selection procedures could not be trusted fully in this respect because of the non-zero covariances between the variables. Eventually, we found RMSEs lower than the lowest values reported in literature for the hip joint, viz., 5.8, 3.0 and 3.5 mm (Seidel et al., 1995).

4.3. Errors in vivo

The estimated orientation errors of the humerus evolving from the position-recording inaccuracy are random errors and will add to both the intra- and inter-individual variance of recorded humerus orientations in vivo. The regression model error will result in offset orientation errors and only adds to the inter-individual variance. The orientation errors were calculated over the full elevation range of the humerus. In the resting position as well as (near) maximal elevation, the first and third rotations are susceptible to the gimbal lock effect, causing the variability to be higher than the second rotation (De Groot, 1997). Compared to the total intra- and inter-individual variability of the humerus orientations measured, the GH-r position recording error as well as the total error were low: about 15 and 20% of, respectively, the intra- and inter-individual variability. It is therefore concluded that the method of *in vivo* GH-r prediction described in this paper allows for an adequate construction of a humerus local coordinate system.

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