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Rotation sequence as an important factor in shoulder kinematics

Miroslav Šenk *, Laurence Chèze

LBMH—UCB Lyon I., Bât. Oméga, 2è étage, 43 Bd. du 11 novembre 1918, 69 622 Villeurbanne Cedex, France

Abstract

Background. The International Society of Biomechanics has proposed a standardization recommendation for motion recordings of the upper extremity defining the set of bony landmarks, local coordinate systems and joint coordinate systems. The aim of our study was to verify the clinical interpretation of the proposed rotation sequence for the glenohumeral joint and to compare it with other sequences.

Methods. Fifteen glenohumeral movements in their maximal ranges were tested on five healthy subjects. The movements were separated into five groups (flexion, extension, abduction, horizontal flexion and circumduction) with three humeral rotation positions (full external, full internal and neutral). Four glenohumeral rotation sequences were constructed using YXY, YXZ, ZXY and XZY orders and angle amplitudes were examined in terms of gimbal lock and amplitude coherence.

Findings. The results of the gimbal lock incidence and amplitude coherence should be taken into account together. Therefore, the suitable rotation sequences for all rotation variations of abduction and extension were found and no tested rotation sequence was found to be clinically interpretable for *all* tested movements.

Interpretation. Before glenohumeral three-dimension experiments the choice of the rotation sequence should be made in agreement with the no-gimbal lock incidence and amplitude interpretability of the performed movements.

Keywords: Shoulder; Glenohumeral; Rotation sequence; Gimbal lock; 3D kinematics; Angle

1. Introduction

The large range of motion in the glenohumeral joint complicates three-dimensional (3D) kinematic analyses. As a consequence, despite recent recommendations on the description of motion (Wu et al., 2005) the issue (i) what rotation sequence could better describe the joint motion and (ii) how to prevent from gimbal lock in particular motions, still exists.

The International Shoulder Group (ISG) with the Standardization and Terminology Committee of International Society of Biomechanics (ISB) has proposed recommendations on definitions of Joint Coordinate System (JCS) of various joints for the reporting of human joint motion (Wu et al., 2005). This recommendation was developed based on the paper by Van der Helm (1996) and modified with respect to the ISB notation (Wu and Cavanagh, 1995). The aim of the recommendation is to encourage every author to use (i) the same set of bone landmarks, (ii) identical local coordinate systems (LCS) and (iii) the same definition of JCS and rotation sequence. For the glenohumeral joint, the standardized rotation sequence is $Y_s - X'_f - Y''_h(YXY)$.

When applying the ISB recommendation during preliminary experimental study of glenohumeral motions, gimbal lock is often observed (Šenk and Chèze, 2004). Therefore, the choice of the most suitable rotation sequence in the glenohumeral joint in this study was designed on two reflections; firstly, the avoidance of gimbal lock and, secondly, easy interpretation of reconstructed movements from the computed angle amplitudes' point of view. Therefore, two aims of the

* Corresponding author.
E-mail address: miroslav.senk@univ-lyon1.fr (M. Šenk).

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present study are amplitude coherence and the determination of the incidence of gimbal lock. These objectives are the key to the clinical interpretation of the full range motions in the glenohumeral joint.

2. Material and methods

2.1. Rotation sequences

We first used the proposed Euler $Y_s - X'_f - Y''_h(YXY)$ sequence (Wu et al., 2005). Then we tested three other sequences that correspond to Cardan angle representations: $Y_s - X'_f - Z''_h(YXZ), Z_s - X'_f - Y''_h(ZXY)$ and $X_s - Z'_f - Y''_h(XZY)$.

The decomposition of the orientation of the LCS of the humerus relative to that of the scapula was done as follows:

2.2. YXY sequence

$\alpha 1$: Direction of the elevation of the Y_h-axis relative to the scapula *Y–Z* plane. Rotation ($\alpha 1$): GH plane of elevation.

$\beta 1$: Rotation around the rotated humerus X_h-axis parallel to the scapula *X–Z* plane. Rotation ($\beta 1$): GH elevation (negative).

$\gamma 1$: Rotation around the twice rotated Y_h-axis of the humerus. Rotation ($\gamma 1$): GH-axial rotation.

2.3. YXZ sequence

$\alpha 2$: Rotation around the Y_s-axis of the scapula, identical for $\alpha 1$ rotation. Rotation ($\alpha 2$): GH plane of elevation.

$\beta 2$: Rotation around the rotated *X*-axis perpendicular to the scapula *Y–Z* plane. Rotation ($\beta 2$): GH elevation I. (GH abduction when humerus in neutral rotation, GH flexion/extension when humerus in external/internal rotation.)

$\gamma 2$: Rotation around the twice rotated Z_h-axis of the humerus. Rotation ($\gamma 2$): GH elevation II. (GH flexion/extension when humerus in neutral rotation, GH abduction/adduction when humerus in external or internal rotation.)

2.4. ZXY sequence

$\alpha 3$: Rotation around the Z_s-axis of the scapula. Rotation ($\alpha 3$): GH flexion/extension.

$\beta 3$: Rotation around the rotated *X*-axis parallel to the scapula *X–Y* plane. Rotation ($\beta 3$): GH abduction/adduction.

$\gamma 3$: Rotation around the twice rotated Y_h-axis of the humerus. Rotation ($\gamma 3$): GH-axial rotation.

2.5. XZY sequence

$\alpha 4$: Rotation around the X_s-axis of the scapula. Rotation ($\alpha 4$): GH abduction/adduction.

$\beta 4$: Rotation around the rotated *Z*-axis parallel to the scapula *Y–Z* plane. Rotation ($\beta 4$): GH flexion/extension.

$\gamma 4$: Rotation around the twice rotated Y_h-axis of the humerus. Rotation ($\gamma 4$): GH-axial rotation.

2.6. Experimental setup

The bony landmarks of the scapula and humerus (Fig. 1) were chosen according to the ISB recommendation (Wu et al., 2005).

Segments of the humerus and scapula were constructed according to the ISB recommendation, see Fig. 1, and were assumed to be rigid. More precisely, four landmarks are important for the construction of the scapula LCS: AC, AA, TS and AI. Due to the sliding effect of the scapula under the skin, only AC and AA markers can be considered as having a stable position with respect to their corresponding landmark during movement. Consequently, we added the SS marker; glued in the middle of the AA–TS distance on the spina scapulae, see Fig. 1. The marker SS was added to recalculate the TS and AI marker trajectories. First, the trajectories of stable LCS (AC, AA and SS) were solidified using the algorithm of Veldpaus and colleagues (Veldpaus et al., 1988). The scapular LCS was then recalculated following the ISB recommendation.

The humerus LCS was defined using EL, EM and GH. GH, the centre of the humeral head, was estimated on the basis of three relative marker trajectories of the humeral and scapular segments using the circumduction movements on small amplitudes in 30° of arm abduction.

Five different groups of arm movements were examined in their full range with the elbow in full extension. Every group of movements was performed in three variations of humerus rotation during the movement: maximal external rotation (*e*), maximal internal rotation (*i*) and neutral (free) rotation (*n*). In total, 15 glenohumeral movements were examined.

Twelve GH movements were designated as movements in anatomical planes and three GH movements were designated as movements of maximal arm reachable workspace. The more detailed description of the movements is as follows: Elevations in the scapular plane (m1*e*, m1*i*, m1*n*), in the sense of abduction: the maximal angular range of GH elevation is 90–100° (*r*1) (Inman et al., 1944; Kapandji, 1980). Forward elevations (m2*e*, m2*i*, m2*n*) in the sense of anterior flexion: the maximal angular range of GH elevation for these movements is 90–110° (*r*2) (Inman et al., 1944; Kapandji, 1980). Backward elevations (m3*e*, m3*i*, m3*n*)