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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 (m1e, m1i, m1n), in the sense of abduction: the maximal angular range of GH elevation is 90–100° (r1) (Inman et al., 1944; Kapandji, 1980). Forward elevations (m2e, m2i, m2n) in the sense of anterior flexion: the maximal angular range of GH elevation for these movements is 90–110° (r2) (Inman et al., 1944; Kapandji, 1980). Backward elevations (m3e, m3i, m3n)

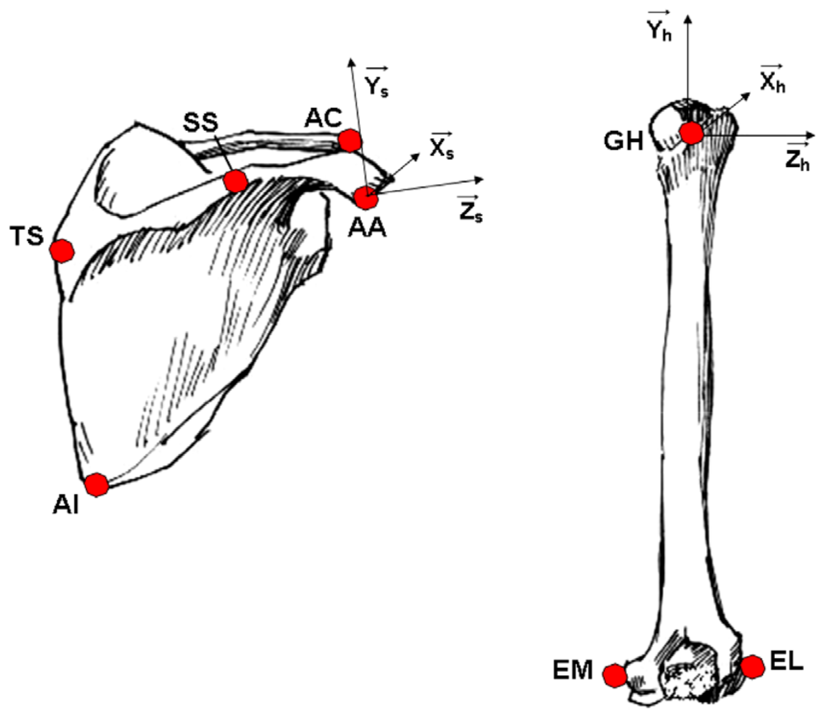

Fig. 1. Bone landmarks and local coordinate systems of humerus and scapula.

in the sense of extension: the maximal angular range of GH elevation for these movements is 35–45° (*r*3) (Kapandji, 1980). Movements in the horizontal plane from the starting position of 90° of arm abduction (m4*e*, m4*i*, m4*n*) in the sense of horizontal flexion or horizontal adduction: the maximal angular range for GH horizontal flexion is 65–80° (*r*4) (Kapandji, 1980). Last movements performed were the maximal GH circumductions (m5*e*, m5*i*, m5*n*) in the sense of maximal reachable workspace movements.

Five healthy subjects participated on the study (three men, two women, age 20–37, weight 55–85 kg). The experiment was performed on right shoulders; no subject had pathological history. Four surface markers were glued onto scapular landmarks and three onto the humeral landmarks according to ISB recommendation (Wu et al., 2005). The fifth scapular marker (SS) was added between AA and TS to ensure the LCS of scapula.

A motion analysis® tracking system (Motion Analysis Corporation, Santa Rosa, USA) with five digital Eagle cameras was used to record the motion. The scanning frequency was set to 100 Hz and the marker trajectories were processed in real-time mode by EVaRT 4.0 software. Raw data were low-pass filtered using a Butterworth filter ($F_c = 7$ Hz).

2.7. Data analysis

Glenohumeral movements were reconstructed from the spatial trajectories of the scapular and humeral markers according to the ISB recommendations. At each timestep, three angle values were produced, each corresponding to an instantaneous rotation value around a defined axis. Putting the instantaneous values together, three curves were obtained for every rotation sequence and every movement. These curves were analyzed to assess the occurrence of gimbal lock, and in the form of computed angle amplitudes (CAA) to assess the amplitude coherence.

2.8. Incidence of gimbal lock

The gimbal lock (GL) is a mathematical indetermination of angle values (α, γ) which are dependent on $\sin\beta$ (or $\cos\beta$) close to zero. In effect, to calculate α and γ, we are obliged to divide by $\sin\beta$ (or $\cos\beta$). As $\sin\beta$ tends towards zero, α and γ values are erroneous from the clinical point of view because they do not respect the expected values in the term of amplitudes. From the physical point of view, this situation can be observed when the first and the third axis quasi-coincide during the movement.

Incidence of GL is defined as follows: discontinuity of the curves α or γ that coincide with those of the β close to 0° or 180° (Euler) or β close to 90° or −90° (Cardan). The term 'close' for the β was set up in the interval of +20° or −20° (Euler) and in the interval +10° or −10° (Cardan). Incidence of GL was designated from all 15 movements. Incidence of GL is expressed for every movement as a number of GL incidences out of five subjects.

2.9. Amplitude coherence

Amplitude coherence is understood as a relation between the calculated angle amplitude (CAA) around the axis that corresponds to the performed movement and the maximal known angular range. The sequence is considered as coherent when the CAA corresponds to the expected maximal angular range. For example, for the GH elevation in the scapular plane, CAA of $\beta 1$ rotation (2nd rotation from YXY rotation sequence) and r1 scale (90–100°) as the expected GH amplitude were compared. The data were compared qualitatively, as the mean value of one movement from all subjects. Clinical coherence was designated from 12 movements, type m1–m4. These movements were considered to be clinically interpretable because they were performed in anatomical planes.

3. Results

3.1. Gimbal lock incidence

Table 1 presents the results for the incidence of gimbal lock (GL). For the *YXY* rotation sequence, GL was observed for all subjects (5/5) during all variations of elevation in the scapular plane, forward elevation, backward elevation and circumduction and for one subject (1/5) during the external rotation variation of horizontal flexion. Concerning the *YXZ* rotation sequence, GL was not observed in any movement in any of the subjects. For the *ZXY* rotation sequence, the GL was observed for all subjects only during variations of elevation in the scapular plane. GL was observed in four subjects during the internal and neutral rotation variations of circumduction, in three subjects during the internal and neutral rotation variations of forward flexion and in two subjects during the external rotation variation of circumduction and forward flexion. Concerning the *XZY* rotation sequence, the GL incidence was observed partially during the external, neutral rotation variations (two subjects) and internal rotation variation of horizontal flexion.

3.2. Amplitude coherence

The results for the qualitative comparison of GH joint movements and tested rotation sequences are shown in Table 2. From the relation between the computed angle amplitudes and expected maximal angular range in GH joint, *YXY* sequence was found to be coherent in none of the 12 movements. The sequence *YXZ* was found to be coherent for all three variations of GH backward elevation, for two variations of abduction and for neutral rotation variation of forward elevation. The sequence *ZXY* was found to be coherent for all variations of the backward elevation and external rotation variation of forward elevation. The *XZY* sequence was found to be coherent for all variations of elevation in scapular plane, backward elevation and horizontal flexion.

Table 2
Clinical coherence of rotation sequences for 12 movements and four rotation sequences

	Rotation axis	*r*1	m1*e*	m1*i*	m1*n*
		Range	Mean (SD)	Mean (SD)	Mean (SD)
YXY	*X*	90–100	82.6 (9.1)	86.5 (7.9)	86.4 (7.6)
YXZ	*Z*		97 (13.1)	97.9 (12.4)	
	X				37.3 (8.9)
ZXY	*X*		77.8 (4.0)	77.7 (8.2)	84.0 (5.3)
XZY	*X*		95.9 (13.6)	91.1 (10.6)	97.8 (10.2)
		*r*2	m2*e*	m2*i*	m2*n*
		Range	Mean (SD)	Mean (SD)	Mean (SD)
YXY	*X*	90–110	80.9 (8.1)	83.4 (11.9)	87.7 (11.6)
YXZ	*X*		20.3 (7.9)	49.6 (17.8)	
	Z				100.2 (10.7)
ZXY	*Z*		97.2 (9.0)	111.4 (31.9)	115.0 (11.0)
XZY	*Z*		39.8 (7.9)	31.6 (9.1)	34.1 (10.9)
		*r*3	m3*e*	m3*i*	m3*n*
		Range	Mean (SD)	Mean (SD)	Mean (SD)
YXY	*X*	35–45	12.7 (6.4)	10.1 (6.8)	8.3 (3.8)
YXZ	*X*		36.1 (4.0)	36.7 (11.3)	37.5 (7.0)
	Z				
ZXY	*Z*		40.2 (6.4)	35.7 (6.0)	37.1 (11.2)
XZY	*Z*		38.5 (4.4)	34.3 (6.0)	36.4 (10.8)
		*r*4	m4*e*	m4*i*	m4*n*
		Range	Mean (SD)	Mean (SD)	Mean (SD)
YXY	Y_s	65–80	98.2 (14.2)	84.5 (26.4)	86.4 (19.1)
YXZ	*Y*		90.0 (11.9)	n.e.	57.8 (20.0)
ZXY	*X*		25.6 (10.5)	23.4 (11.4)	30.3 (5.0)
XZY	*Z*		79.9 (3.4)	69.3 (8.0)	77.7 (10.1)

The results show the mean and SD values of computed angle amplitudes (CAA) for five subjects. The 'rotation axis' column shows the rotation used. 'n.e.' = values were not examined as a result of very small CAA and inconsistent curves.

Table 1
Comparison of gimbal lock incidence between different rotation sequences

	m1*e*	m1*i*	m1*n*	m2*e*	m2*i*	m2*n*	m3*e*	m3*i*	m3*n*	m4*e*	m4*i*	m4*n*	m5*e*	m5*i*	m5*n*
YXY	5/5	5/5	5/5	5/5	5/5	5/5	5/5	5/5	5/5	1/5	–	–	5/5	5/5	5/5
YXZ	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
ZXY	5/5	5/5	5/5	2/5	3/5	3/5	–	–	–	–	–	–	2/5	4/5	4/5
XZY	–	–	–	–	–	–	–	–	–	2/5	1/5	2/5	–	–	–

Gimbal lock incidence is shown out of five subjects.

4. Discussion

The ISB recommendation uses the Euler angle decomposing method and the rotation sequence has been chosen so that the first and third rotations define the orientation of the longitudinal axis or a bony ridge of the proximal and distal segment (Y_s and Y_h). We chose three other rotation sequences in the aim of evaluating them with respect to amplitude coherence and GL incidence. Theoretically, the YXZ sequence avoids GL as much as possible out of all Cardan sequences; however, the principle of different humeral rotations must be taken into account when analyzing the CAA. The ZXY sequence corresponds to the general ISB recommended rotation sequence (Grood and Suntay, 1983; Wu and Cavanagh, 1995). The XZY sequence was used in previous experimental studies (Rundquist et al., 2003; Rundquist and Ludewig, 2004).

The angle computations are very complicated from a numerical point of view. When GL occurs, changes are observed in the angle values, with the largest changes occurring for rotations around the first and third axes. As a result of these changes, when GL occurs, none of the three CAA of three consecutive rotations can be accepted. In YXY sequence, both Y-axes are in static position with the arm alongside the trunk orientated vertically. Thereby the axes' coincident situation appears in almost every case when the subject is sitting or standing and the arm is alongside the trunk. In our experiment GL was observed in all subjects during 12 out of the 15 movements tested, principally in the starting/ending position.

In the present study, the amplitude coherence measurement was designed to evaluate the principle movement amplitude. Other amplitudes, such as humeral rotations amplitudes, were not compared. The protocol was made in two steps, (i) the starting value of the chosen rotation, and (ii) the development of the rotation angle around the chosen axis. The difference between the maximal angle value and its starting value was considered as the CAA. Nine movements out of 12 were evaluated as coherent for the XZY rotation sequence. In contrast, for the recommended sequence YXY, no movement was judged as coherent. This is mainly due to the alterations resulting from the GL that causes the inconsistent form of the calculated curves. According to our observations, application of the YXY rotation sequence should not be altered for the flexion and/or abduction movements (forward elevation and/or elevation in the scapular plane) starting from 30° of arm elevation. However, this principle does not apply to movements of backward flexion.

3D angle computation from three consecutive rotations about mobile axes has two major disadvantages: gimbal lock errors and sequence dependence. Another problem is posed by the amplitude coherence, which completes the restricting factors of the method in general. Nevertheless, the method of consecutive rotations remains the principal tool for the clinical analysis of movements in complex articulations such as GH joint (Van der Helm, 1996; Meskers et al., 1998; Rundquist et al., 2003; Rundquist and Ludewig, 2004). In order to obtain the complete clinical interpretation of the method, the more detailed humeral rotation analysis should be tested. In addition, the aims of each individual experiment should be taken into consideration when choosing the sequence.

Looking to the results of horizontal flexion movements, the XZY sequence is the only one which assesses the amplitude coherence; nevertheless, we observed one or two GL incidence out of five subjects. This impossibility to find a correct clinical interpretation for all sequences should be explained by the situation in the GH joint that is far from the basic anatomical position of the segments. Actually, this anatomical reference position is the origin for the three elementary movements description.

Recommended sequence YXY can be convenient as far as the movements neither go through a singular position (i.e. the arm alongside the trunk), nor reach the maximal range of movements. This sequence actually presents a particular interest whenever the movement is performed out of an anatomical plane.

We tried to ensure the accurate representation of glenohumeral motion, though there remain several possible sources of error. The main problem is the sliding of the scapula under the skin which remains a topical problem for the capture systems using the surface markers. Our protocol uses the additional marker, SS, on the middle of the spina scapulae in the goal of recalculation procedure of TS and AI markers that do not follow the real TS and AI landmarks of the bone. The real advantage in the scapula motion recordings using the surface markers remains the non-invasive and dynamic approach in vivo. The interpretation is based on important differences in the angular amplitudes, so experimental errors due to the skin artifacts may not influence the conclusions.

The results of GL appearance and the amplitude coherence in the present study should be interpreted together. Thus, the best rotation sequence for the elevation in the scapular/frontal plane (abduction) appears to be the XZY and for the backward elevation (extension) all three tested Cardan sequences give comparable results. We did not find any satisfactory rotation sequence for all movement variations of forward elevation (flexion) and horizontal flexion.

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