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Short communication

# The reliability of humerothoracic angles during arm elevation depends on the representation of rotations

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ABSTRACT

The reliability of joint rotation measurements is an issue of major interest, especially in clinical applications. The effect of instrumental errors and soft tissue artifacts on the variability of human motion measures is well known, but the influence of the representation of joint motion has not yet been studied. The aim of the study was to compare the within-subject reliability of three rotation formalisms for the calculation of the shoulder elevation joint angles.

Five repetitions of humeral elevation in the scapular plane of 27 healthy subjects were recorded using a stereophotogrammetry system. The humerothoracic joint angles were calculated using the $YX'Y''$ and $XZ'Y''$ Euler angle sequences and the attitude vector. A within-subject repeatability study was performed for the three representations. ICC, SEM and CV were the indices used to estimate the error in the calculation of the angle amplitudes and the angular waveforms with each method.

Excellent results were obtained in all representations for the main angle (elevation), but there were remarkable differences for axial rotation and plane of elevation. The $YX'Y''$ sequence generally had the poorest reliability in the secondary angles. The $XZ'Y'$ sequence proved to be the most reliable representation of axial rotation, whereas the attitude vector had the highest reliability in the plane of elevation.

These results highlight the importance of selecting the method used to describe the joint motion when within-subjects reliability is an important issue of the experiment. This may be of particular importance when the secondary angles of motions are being studied.



## 1. Introduction

The clinical applications of joint kinematic analysis are increasing, since they are more accurate and sensitive to small changes in the patient's state than conventional observational methods (Toro et al., 2003). But the minimal clinically important difference (MCID) is a critical aspect of that advantage, which is directly related to the reliability of the measuring procedure (Copay et al., 2007). If that reliability is not controlled, the results might be under or overestimated due to the measurement error, which could lead the clinicians to a wrong decision (McGinley et al., 2009).

According to the reliability theory, the observed motion can be considered the aggregation of a subject-specific "average" baseline gesture, plus some perturbations due to intra-subject variability and other causes, like instrumental errors and soft tissue artifacts (STA) (Duhamel et al., 2004). Therefore, the factors that influence such perturbations are likely to influence the reliability of the measurements.

One of these factors is how joint motion is described. Particularly for the shoulder, there are different standard Euler angle sequences, which are chosen depending on gimbal lock issues and the clinical interpretation of the results (Šenk and Chèze, 2006; Wu et al., 2005). However, the reliability of the results is seldom considered, although any source of variability, such as instrumental errors, STA or the natural intra-subject variability itself, are propagated by nonlinear functions that behave differently depending on the representation of the angle (Page et al., 2014).

This work analyzed the effect of joint angle representations on the reliability of shoulder kinematic measures. An experimental study of humeral elevation in the scapular plane was performed to test the reliability of kinematic measures in consecutive repetitions of the gesture.

To focus on the representation method and reduce other sources of error (e.g. STA) arm elevation was characterized as the motion of the humerus relative to the thorax. That motion was expressed by the Euler sequences $YX'Y''$ and $XZ'Y''$ and the attitude

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vector. The cycle-to-cycle error of each method was estimated with reliability and agreement metrics.

## 2. Material and methods

### 2.1. Subject sample

Twenty-seven asymptomatic, right-handed subjects participated in this study (14 male, 13 female, mean age 38.2 years, mean height 169.3 cm, mean weight 73.1 kg). All experiments were conducted in agreement with the principles of the World Medical Association's Declaration of Helsinki and approved by the Institutional Review Board. Participation was voluntary and the subjects signed an informed consent form before any data were collected.

This experiment was part of a larger study about shoulder functional assessment.

### 2.2. Description of the experiment

Each subject sat on a rigid seat, with their trunk upright. Their pelvis, trunk and left arm were fixed with straps, allowing only movement of the right arm (Fig. 1a).

The trunk reference frame was defined in the initial posture using two markers on the left and right acromion processes (LA and RA, respectively), with the $y$-axis in the vertical direction, the $x$-axis perpendicular to the plane formed by the $y$-axis and the LA-RA line, and the $z$-axis pointing to the right. The motion of the trunk was tracked by a technical cluster of markers located on LA, the second dorsal vertebrae (D2) and the medial third of the scapular spine (SC) (Fig. 1b).

The right arm was tracked by a rigid three-marker cluster attached to the splint in the region of the forearm. Elbow flexion was constrained by the splint itself to reduce the variability of motion. The marker cluster was parallel to the direction of the long axis of the humerus. The starting position of the arm was set to $\alpha = 37.5°$ anteriorly to the coronal plane of the trunk and $\beta = 45°$ down the transverse plane. An electronic inclinometer on the right arm and a table adjustable in height were used to set the humeral elevation. A line drawn on the table served as reference of the scapular plane.

The subjects were instructed to lift their arm as much as they could, at a self-determined comfortable speed, and maintain the maximum elevation for 3 s. This gesture was repeated 5 times, holding a 250 g mallet during the exercise.

## 3. Data processing

The motion of the markers was recorded by the Kinescan-IBV stereophotogrammetry system (Page et al., 2006). The rotations of thorax and humerus from the starting position at any instant $t$ were calculated as the Rodrigues vectors $\mathbf{\Omega}_{T0-t}$, $\mathbf{\Omega}_{H0-t}$, respectively (Page et al., 2009), which were transformed into the corresponding rotation matrices $\mathbf{R}_{T0-t}$, $\mathbf{R}_{H0-t}$ by the Rodrigues formula, considering the skew-symmetric matrix $\mathbf{S}\{\mathbf{v}\}$ associated with any vector $\mathbf{v} = (x, y, z)'$:

$$\mathbf{S}\{\mathbf{v}\} = \begin{pmatrix} 0 & -z & y \\ z & 0 & -x \\ -y & x & 0 \end{pmatrix}$$

$$\mathbf{R}_{i0-t} = \left( \mathbf{I}_3 + \frac{2}{1 + \mathbf{\Omega}'_{i0-t}\mathbf{\Omega}_{i0-t}} \left( \mathbf{S}\{\mathbf{\Omega}_{i0-t}\} + \mathbf{S}^2\{\mathbf{\Omega}_{i0-t}\} \right) \right) \tag{1}$$

where $\mathbf{I}_3$ is the identity $3 \times 3$ matrix. The orientation matrix of the thorax $\mathbf{R}_{Tt}$ was equal to the rotation $\mathbf{R}_{T0-t}$. The orientation of the humerus was obtained from $\mathbf{R}_{H0-t}$ by composition with its predefined orientation in the starting position:

$$\mathbf{R}_{Ht} = \mathbf{R}_{H0-t} \times \begin{pmatrix} \cos\alpha & \sin\alpha \sin\beta & \sin\alpha \cos\beta \\ 0 & \cos\beta & -\sin\beta \\ -\sin\alpha & \cos\alpha \sin\beta & \sin\alpha \cos\beta \end{pmatrix} \tag{2}$$

The resulting matrices were composed to obtain the humerothoracic relative pose:

$${}^{T}\mathbf{R}_{Ht} = \mathbf{R}'_{Tt} \times \mathbf{R}_{Ht} \tag{3}$$

This matrix was used to obtain the $YX'Y''$ and $XZ'Y''$ angles. The operations equivalent to (2) and (3) were applied to the Rodrigues vectors to obtain the humerothoracic pose in that notation, composing successive rotations around fixed axes like (Page et al., 2009):

$$\mathbf{\Omega}_{A\to C} = \frac{\mathbf{\Omega}_{A\to B} + \mathbf{\Omega}_{B\to C} - \mathbf{\Omega}_{A\to B} * \mathbf{\Omega}_{B\to C}}{1 - \mathbf{\Omega}'_{A\to B} \cdot \mathbf{\Omega}_{B\to C}} \tag{4}$$

${}^{T}\mathbf{\Omega}_{Ht}$ was then rescaled to represent the rotation as the attitude vector ${}^{T}\mathbf{\theta}_{Ht}$, considering that $|\mathbf{\Omega}| = \tan(|\mathbf{\theta}|/2)$ (Page et al., 2014).

The velocity of the elevation angle in the $YX'Y''$ sequence was used to split up the 5 repetitions of the ascent phase. For the statistical analysis, the movement cycles were normalized to 101 data points and the angle amplitudes (AA) were calculated (Table 1).

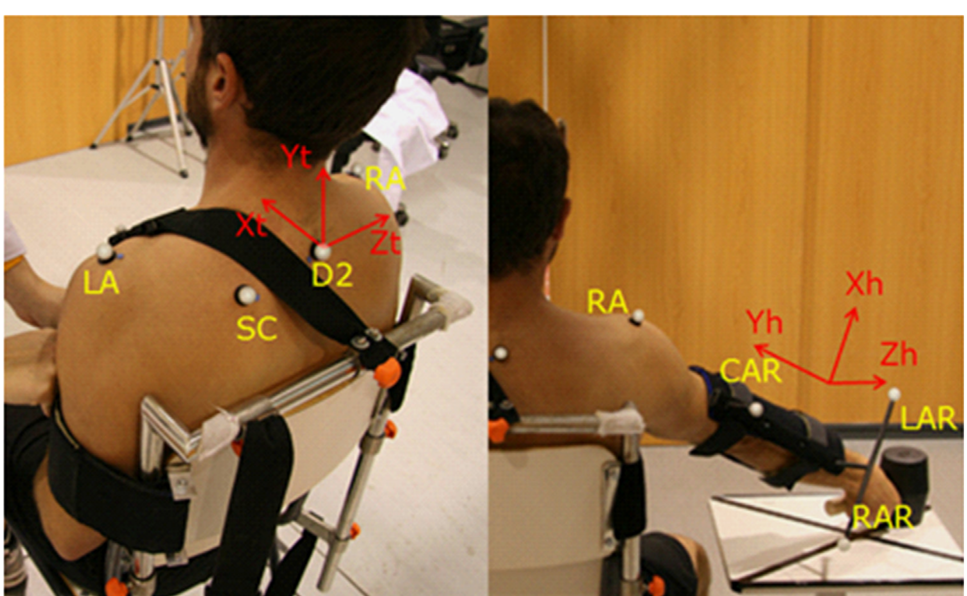


**Fig. 1.** (a) Experimental setup: subject seated, with trunk and left arm fastened to the chair. (b) Scheme of the markers and reference frames.

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