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The effect of axis alignment on shoulder joint kinematics analysis during arm abduction

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Abstract

Background. A joint coordinate system allows coherence between the performed movement, its mathematical representation and the clinical interpretation of the kinematics of joint motion. In 2005, the International Society of Biomechanics (ISB) defined a joint coordinate system for the shoulder. To improve kinematics interpretation, the ISB suggested aligning the coordinate systems of the humerus and the scapula. Therefore, the aim of this research project was to determine how the alignment of the joint coordinate system axes can influence the interpretation of shoulder joint kinematics. More precisely, we wanted to investigate if mathematical alignment of the reference and moving coordinate system axes could facilitate the kinematic interpretation of a simple abduction movement without introducing additional coupled motion.

Methods. An experiment was carried out on eight shoulder cadaveric specimens. Elevation of the arm in the scapular plane (abduction) was recorded using an electromagnetic tracking device. Three-dimensional angular displacements of the arm during elevation in the scapular plane were described using the standard ISB joint coordinate system, and using a modified joint coordinate system for which the axes were mathematically aligned.

Findings. The results obtained revealed a difference in the interpretation of the starting angles between the ISB joint coordinate system and the aligned coordinate system. No difference was found in the interpretation of the angular range of motion ($P < 0.01$).

Interpretation. The aligned coordinate system provided a standardized starting angle of elevation that allows an easier clinical interpretation of shoulder kinematics.

Keywords: Shoulder; Joint coordinate system; Three-dimensional kinematics; Clinical interpretation

1. Introduction

In 2005, the International Society of Biomechanics (ISB) proposed a Joint Coordinate System (JCS) for the shoulder composed of two coordinate systems, a reference one and a moving one (Fig. 1) (Wu et al., 2005). This recommendation aimed at encouraging all authors to "(i) use the same set of bony landmarks, (ii) use identical local coordinate systems and (iii) to report motions according to this recommended standard" (Wu et al., 2005). This recommendation has resulted in the standardization of shoulder joint motion description and provides better communication among researchers.

The ISB recommendation describes shoulder joint motion as a succession of three rotations of the humerus

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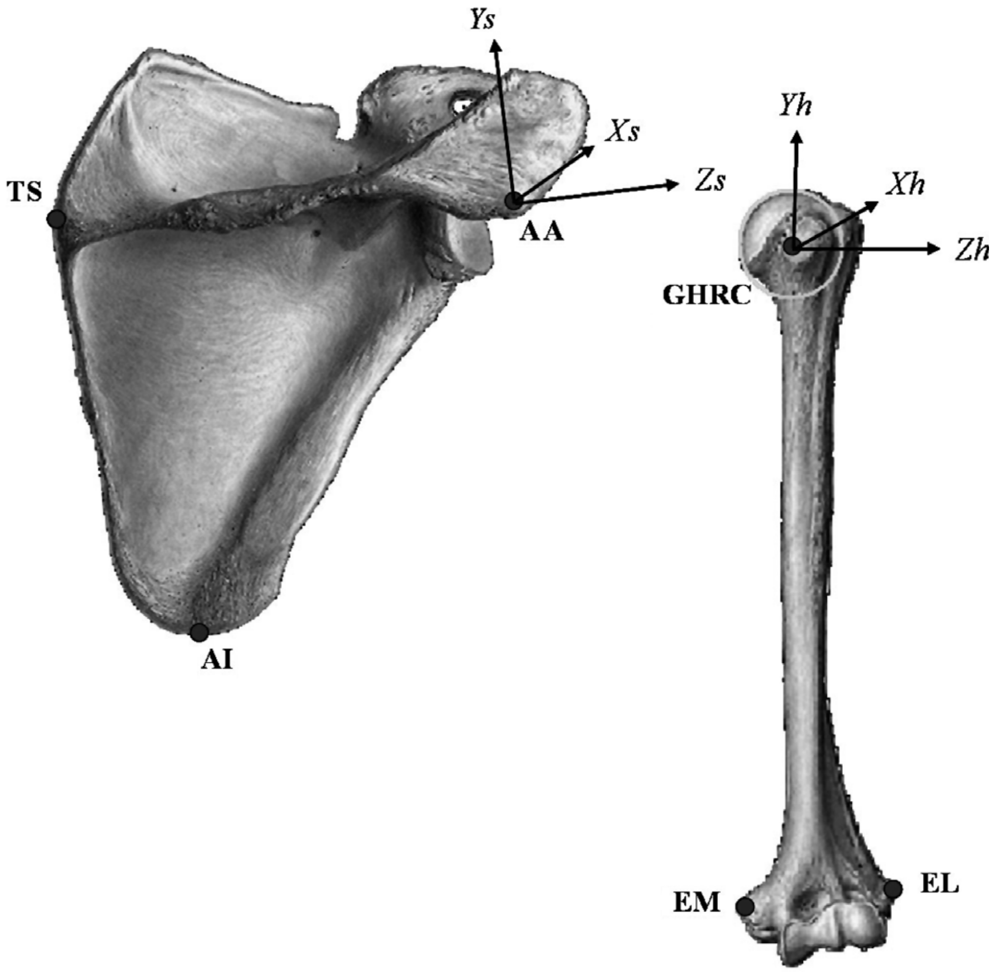

Bone	Anatomical Landmark	Description
Humerus (h)	GHRC	GlenoHumeral rotation center
	EL	Most caudal point on Lateral Epicondyle
	EM	Most caudal point on Medial Epicondyle
Scapula (s)	TS	Triogonum Spinae Scapulae, midpoint of triangular surface on medial border of the scapula in line with the scapular spine
	AI	Angulus Interior, most caudal point of the scapula
	AA	Angulus Acromialis, most latero-dorsal point of the scapula

Fig. 1. Representation of the ISB JCS and description of the bony landmarks used to define the humerus and scapula coordinate systems.

coordinate system relative to the scapula coordinate system (Y–X–Y in Euler angles). However, two major disadvantages arising from using three consecutive rotations about mobile axes have recently been reported (Šenk and Chèze, 2006). The first one is a "mathematical indetermination of angle values close to 0° or 180°", which is commonly called gimbal lock (Šenk and Chèze, 2006). The second disadvantage concerns the sequence dependence, that is, that movement description is dependent on the order in which the rotation occurs (Grood and Suntay, 1983; Skalli et al., 1995). This can produce inconsistencies in the kinematics representation of the movement performed, which can make motion analysis interpretation questionable and doubtful. The use of consecutive rotations indeed remains the principal tool to represent 3D angular displacement in clinical movement analysis (Šenk and Chèze, 2006).

Recently Šenk and Chèze (2006) demonstrated that with the ISB JCS, no rotation sequence was found to be clinically interpretable for all tested movements. When applying the ISB recommendation, inconsistency between the movement performed and its corresponding calculated range of motion were reported because of gimbal lock incidence. They showed that for an abduction movement from 0° up to 90–100°, the calculated range of motion varies from 37.3° (SD 8.9°) to 97.8° (SD 10.2°). These findings were mainly attributed to the choice of the rotation sequence used. According to these authors, the best rotation sequence to describe elevation in the scapular plane (abduction) is XZY, because it produced no incidence of gimbal lock in their experimental setup. Nevertheless the interpretation of the described movement still remains unsatisfactory in their view. The rotation sequence XZY was adequate for elevation in the scapular plane, but not necessarily convenient for other movements.

For a clearer interpretation of shoulder joint motion, the ISB suggests starting by aligning the x-, y-, and z-axes of the coordinate systems of the humerus and the scapula (Wu et al., 2005). To our mind, two different methods can be used to align both coordinate systems. The first method would be to position the upper arm so that both coordinate systems are initially aligned (anatomical alignment). The second would be to modify the JCS orientation without adjusting the upper arm position (mathematical alignment).

To the best of our knowledge, there is no *in vitro* or *in vivo* study that compares the effect of coordinate system alignment on shoulder joint kinematics. Therefore, the aim of this study was to investigate, using cadaveric shoulder specimens, how the alignment of both coordinate systems influence the kinematics interpretation of a simple abduction movement. To our mind, anatomical alignment has the disadvantage of forcing the arm in a position which is not necessarily corresponding to the real initial upper arm reference position. A mathematical alignment would therefore seem to be a more interesting approach. Three-dimensional (3D) angular displacements of the arm during elevation in the scapular plane (abduction, mainly a planar movement) will be described. Two joint coordinate systems will be used: ISB JCS (standard JCS), and the modified ISB JCS for which the axes of the local (reference and moving) coordinate systems have been mathematically aligned (aligned JCS).

2. Methods

2.1. Specimen preparation

Eight fresh-frozen shoulder cadaveric specimens including entire arm were used (four lefts and four rights, age range 59–87 years). The specimens were stored in a freezer at −20 °C and thawed at room temperature for approximately 8 h before the dissection. All soft tissues around the shoulder were removed except for the rotator cuff muscles, the capsule, the anterior and posterior deltoid. The forearm and the hand were left intact. The cadaver specimens did not show any musculoskeletal pathology as assessed by a senior orthopaedic surgeon. Two aluminium triangles were fastened with plastic screws on the scapula and on the humerus for calibration purpose. After dissection, the specimens were refrozen and then sent for a CT scan (computer-assisted tomography). From the CT images, an individual 3D reconstruction was realized using a commercial software (SliceOmatic, Tomovision, Montréal, Canada). The 3D reconstruction is used thereafter to estimate the rotation center of the proximal humerus, to define the joint coordinate system and to visualize the recorded motion.

2.2. Experimental set-up

A testing device made of an abduction guide and two mounting blocks was designed in our research laboratory to reproduce *in vitro* an abduction movement of the arm (Fig. 2A). Prior to the experiment, the shoulder specimens were thawed again for a period of 12 h at room temperature. To immobilize the relative motion between the humerus and the forearm, the elbow was fixed with a brass screw. The scapula was screwed by an orthopaedic surgeon to the main mounting block of the testing device in a manner to visually reproduce the anatomical position of the scapula (Fig. 2B). The initial position of the arm was consequently perpendicular to the ground, in 0° abduction and 0° horizontal abduction. The arm was hanging freely between the guiding boards, to ensure abduction in the plane YZ of the scapula. The middle deltoid was replaced by a strip of non-elastic fabric to simulate its function as main abductor of the arm (Fig. 2B). One extremity of the fabric strip was fixed to the deltoid tuberosity and the other to a pulling mechanism (Fig. 2A). The pulling mechanism (Fig. 2C) consisted of an electric cylinder (NV-D Series, Industrial Device Coorporation, Rockford, USA), which was used to simulate a continuous abduction movement of the arm at constant speed (≈10°/s). To prevent slipping of the fabric strip over the acromion during traction of the electric cylinder, a guiding device was attached on top of the scapula (Fig. 2D). This device also helped reproduce the line of action of the middle deltoid muscle.

3D shoulder joint motion was recorded using an electromagnetic tracking device (Fastrak, Polhemus, Colchester, USA) (Fig. 2A). The accuracy of the system is 1 mm for linear displacement and 0.1° for angular displacement. Sensors were screwed on plastic plates which were directly fixed on the scapula and humerus (Fig. 2B). The sensor on the scapula served as a control for possible movement of the scapula on the testing device in spite of it being rigidly fastened. A personal computer with custom-design software recorded in real time the 3D displacement of the arm at 60 Hz.

The experimental session was divided in six stages (Fig. 3). Prior to data acquisition, the effect of metal on the accuracy of the tracking device was evaluated. Acquisition error was around ±1 mm. Thereafter, a calibration procedure was realized. The calibration procedure consisted in digitalizing the extremity of both triangles fastened on the scapula and the humerus using a Fastrak pointer. This procedure allowed to establish a transformation matrix between the motion of the specimen recorded by the Fastrak

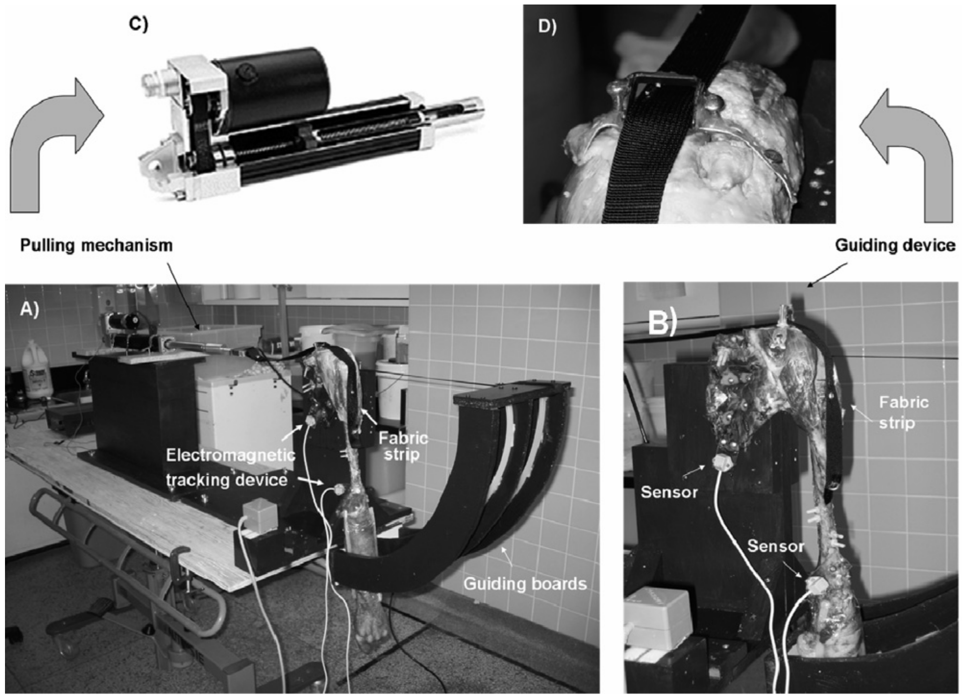

Fig. 2. (A) *In vitro* testing device; (B) position of the scapula on the main mounting block of the testing device; (C) electric cylinder; (D) guiding device.

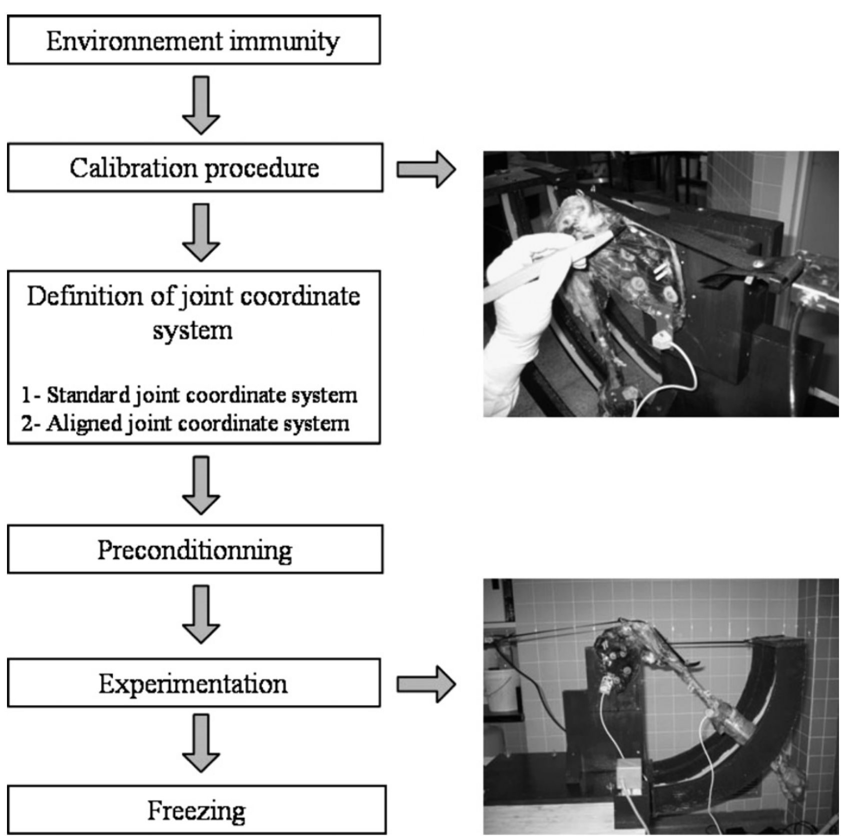

Fig. 3. Summary of the experimental procedure.

sensors and the individual 3D reconstruction. The standard JCS and the aligned axes of the aligned JCS were then defined.

2.2.1. Standard JCS definition

The standard shoulder JCS recommended by ISB, is based on scapular and humeral anatomical bony

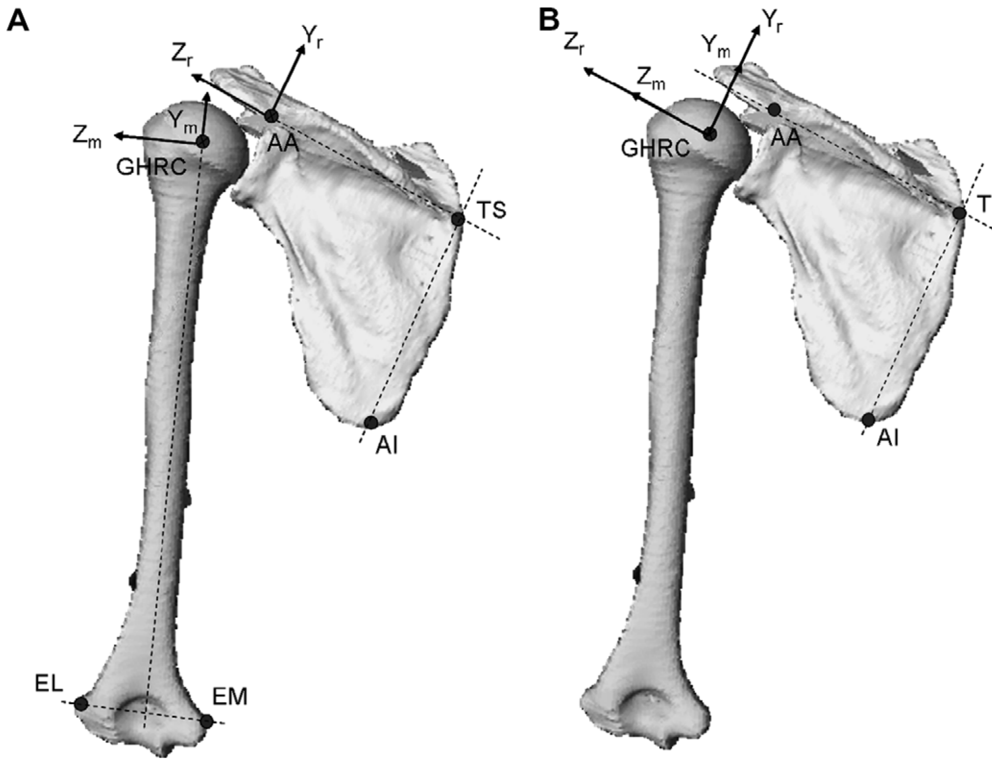

Fig. 4. Definition of (A) the standard joint coordinate system and (B) the aligned joint coordinate system where 'r' and 'm' denotes reference JCS and moving JCS, respectively.

landmarks (table in Fig. 1). This ISB recommendation requires the definition of two local coordinate systems: one for the scapula (reference coordinate system) and one for the humerus (moving coordinate system) (Fig. 4A).

The reference coordinate system ($_r$) origin is positioned at the angulus acromialis of the scapula (AA) and its axes oriented according to scapular bony landmarks listed in Fig. 1. The Z_r-axis is defined as the line connecting TS and AA, pointing towards AA. The X_r-axis is defined as the line perpendicular to the plane formed by AI, AA and TS, pointing forward. The Y_r-axis is the common line perpendicular to X_r and Z_r and pointing upward (Fig. 4A).

The moving coordinate system ($_m$) origin is positioned at the glenohumeral rotation center (GHRC) (Fig. 4A) and its axes oriented according to humeral bony landmarks (Fig. 1). The GHRC is the only landmark to be estimated. According to the ISB recommendation, the choice of the method used to estimate the GHRC is left to the discretion of the author (Wu et al., 2005). In the present study, the GHRC corresponds to the center of a sphere fitted by a least square method to the articular surface of the humeral head (Helm et al., 1992). The Y_m-axis is defined as the line connecting GHRC and the midpoint of EL and EM pointing to GHRC. The X_m-axis is defined as the line perpendicular to the plane formed by EL, EM and GHRC and is directed forward. The Z_m-axis is the common line perpendicular to Y_m and X_m pointing to EL.

The moving coordinate system is described relative to the reference coordinate system. The transformation matrix between the reference coordinate system ($_r$) and the moving coordinate system ($_m$) is calculated as follows:

$$T_{r}^{m} = \left[T_{G}^{S1} * T_{S1}^{r}\right]^{-1} * \left[T_{G}^{S2} * T_{S2}^{m}\right] \tag{1}$$

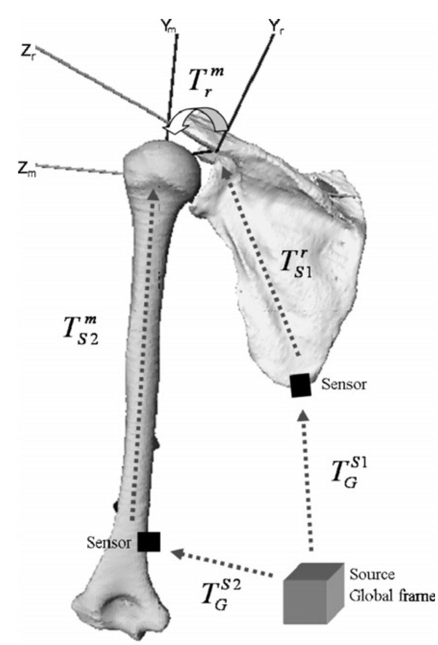

Fig. 5. Representation of the transformation matrix used to express the motion of the moving coordinate system relatively to the reference coordinate system using the standard JCS.

As shown in Fig. 5, T_{G}^{S1} defines the transformation matrix between the global frame ($_{G}$) and the sensor on the scapula ($_{S1}$), T_{S1}^{r} the transformation matrix between the sensor on the scapula and the reference JCS, T_{G}^{S2} the transformation matrix between the global frame and the sensor on the humerus ($_{S2}$) and T_{S2}^{m} the transformation matrix between the sensor on the humerus and the moving coordinate system, respectively. Rotations are described using Cardan angles. The rotation sequence XZY was used.

2.2.2. Aligned axes of JCS

Similar to the ISB JCS, two local coordinate systems are defined. One difference between the ISB JCS and the aligned JCS is the location of the origin of the reference coordinate system ($_{r}$).The reference coordinate system ($_{r}$) is defined according to scapular bony landmarks listed in Fig. 1, and the origin is positioned at the GHRC on the humerus instead of the angulus acromialis. As previously mentioned, the GHRC is estimated as the center of a sphere fitted by a least square method to the articular surface of the humeral head (Helm et al., 1992). The Z_r-axis is defined as the line connecting TS and AA, pointing towards AA. The X_r-axis is defined as the line perpendicular to the plane formed by AI, AA and TS, pointing forward. The Y_r-axis is the common line perpendicular to X_r and Z_r and pointing upward (Fig. 4B).

The moving coordinate system ($_{m}$) origin is positioned at the GHRC (Fig. 4B). Instead of orienting the axes of the system with the humerus bony landmark, the axes X_m, Y_m, Z_m are parallel and coincident to axes X_r, Y_r, Z_r of the reference coordinate system ($_{r}$) when the arm is in resting position (i.e. 0° abduction, horizontal abduction and rotation). Thus, the moving coordinate system is defined according to scapular bony landmarks.

Similar to the standard JCS, the moving coordinate systems is described relatively to the reference coordinate systems by Eq. (1). The rotations are described using Cardan angles and the rotation sequence is XZY.

2.3. Abduction movements

First, preconditioning of the specimen was performed. Twenty five movements of abduction up to the maximum range of motion were carried out using the pulling mechanism (Debski et al., 1995; Parsons et al., 2002; Thompson et al., 1996). The maximum range of motion was considered to be reached when the arm stopped moving. After preconditioning, 10 abduction movements of maximum range of motion were completed using the pulling mechanism and recorded. The pulling mechanism was controlled in displacement and the generated force was recorded. The arm was elevated at continuous speed until it reached its maximal range of motion. The recorded force corresponded approximately to 575 N (538–578 N) depending on the specimen weight (1.7–2.8 kg). Each trial lasted 10 s. During experimentation, the specimens were kept moist with saline solution. Afterwards, the specimen were restored in the freezer at −20 °C.

The initial angular position of the arm was defined as the angle between the moving and reference coordinate system around the three axes when the arm was at rest (Fig. 6A). Movement range of motion around the X_r-, Y_r-, Z_r-axes, was defined as the angle difference between the final and the initial position of the arm (Fig. 6B).

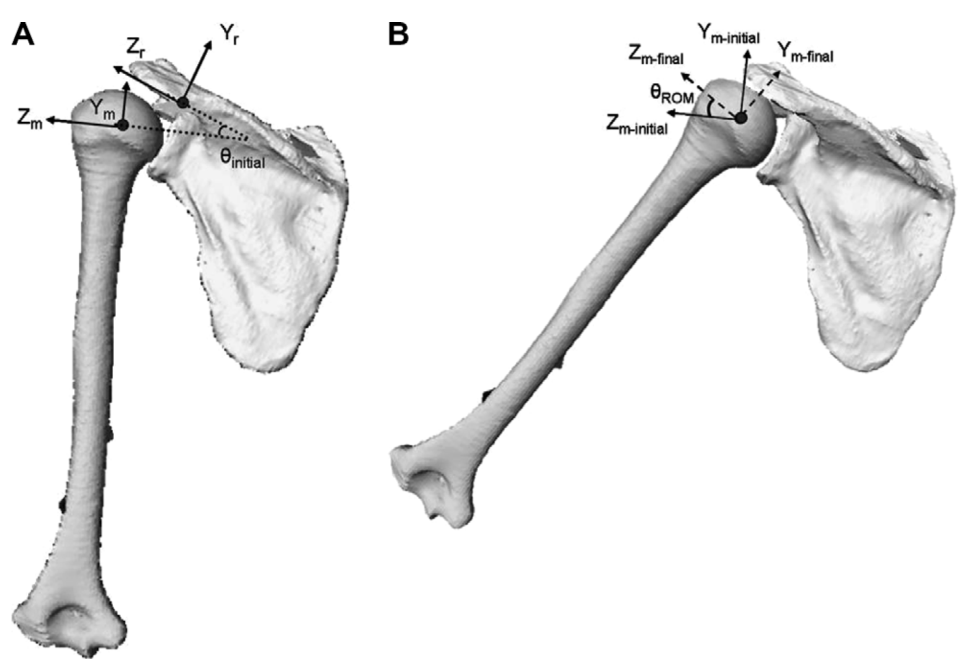

Fig. 6. Representation of (A) the initial abduction angle when the arm is at rest and (B) the abduction range of motion where 'r' and 'm' denotes reference JCS and moving JCS, respectively.

2.4. Statistical analysis

A two-way ANOVA for repeated measurements was used to determine whether a difference could be found in the abduction range of motion, the horizontal abduction and the rotation range of motion determined using the standard JCS and the aligned JCS. A two-way ANOVA for repeated measurements was also used to determine whether there was a difference between the initial angular position of the arm around the three axes when measured using the standard JCS and the aligned JCS. Statistical significance was set at $P < 0.01$. All analyses were performed using the SPSS software.

3. Results

Fig. 7 presents the mean and standard deviations for the range of motion and the initial angular position of the arm obtained from eight specimens. It is interesting to note that for the magnitude of range of motion evaluated in the present study, no discontinuity (gimbal lock) in the kinematics curves representation was reported when using the standard JCS or the aligned JCS. This observation was valid for all trials and all specimens.

3.1. Range of motion

The mean abduction range of motion measured on all eight specimens varied between 28.1° (SD 0.2°) and 45.4° (SD 0.3°) for the standard JCS and between 28.8° (SD 0.1°) and 44.9 (SD 0.3°) for the aligned JCS. For horizontal abduction (movement parallel to the ground), the range of motion varied between 1.4° (SD 0.4°) and 24.0° (SD 0.5°) for the standard JCS and between 1.4° (SD 0.4°) and 25.2° (SD 0.5°) for the aligned JCS. As for rotation, range of motion varied between 2.8° (SD 0.0°) and 24.2° (SD 0.1°) for the standard JCS and between 0.8° (SD 0.0°) and 24.2° (SD 0.1°) for the aligned JCS.

For abduction and horizontal abduction, there was no statistically significant difference between the magnitude of the ranges of motion measured using the standard JCS and aligned JCS respectively. Rotation was the only range of motion when standard JCS and aligned JCS showed a statistically significant difference ($P = 0.002$). However, the mean difference between standard JCS and aligned JCS was only 1.4° (SD 0.8°).

3.2. Initial angular position of the arm

For abduction, the initial angular position of the arm varied between 5.6° (SD 0.0°) and 28.8° (SD 0.2°) for the standard JCS and between 0.0° (SD 0.0°) and 0.6° (SD 0.4°) for the aligned JCS. For horizontal abduction, the initial angular position of the arm varied between 0.1° (SD 0.1°) and 30.8° (SD 0.0°) for the standard JCS and between 0.0° (SD 0.0°) and 0.3° (SD 0.1°) for the aligned JCS. As for rotation, the initial angular position varied between 0.1° (SD 0.1°) and 8.1° (SD 0.0°) for standard JCS and between 0.0° (SD 0.0°) and 0.1° (SD 0.1°) for aligned JCS.

For abduction ($P = 0.005$) and horizontal abduction ($P = 0.002$), there was a statistically significant difference between the initial angular position of the arm computed with standard JCS and aligned JCS. For rotation, there was no statistically significant difference between standard JCS and aligned JCS. The mean difference between the initial angular position computed with the standard JCS and aligned JCS for rotation was 3.4° (SD 2.6°).

4. Discussion

Cross-talk effect (coupled motion) is a concern when describing joint motion as a succession of rotations.

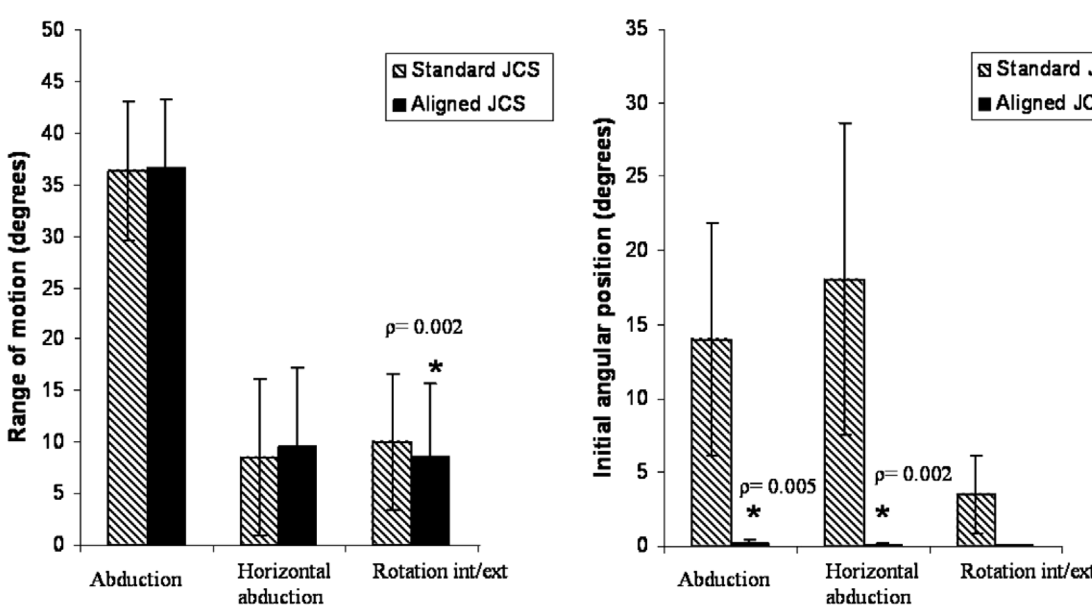

Fig. 7. Mean range of motion (SD) and mean initial angular position of the arm (SD) in degrees computed with the standard JCS and the aligned JCS.

Cross-talk effect usually results from an ill-defined JCS. For example, abduction can cross-talk into horizontal abduction and into rotation. No additional cross-talk effect was reported for the aligned JCS since no significant difference was observed between the range of motion computed with the standard JCS and the aligned JCS. Our finding also showed that standard JCS and aligned JCS did not cause any incidence of gimbal lock for the magnitude of ROM evaluated. This confirms Šenk and Chèze findings (2006). The latter did not observe any gimbal lock when using the rotation sequence XZY to compute elevation of the arm in the scapular plane. The skin artefact was identified by Senk and Chèze as a possible experimental source of error affecting theirs results. In the realisation of the present study, similar results were obtained while this source of error was eliminated with the used of markers directly fastened on the bones. Thus, the XZY rotation sequence is an appropriate means of describing elevation of the arm in the scapular plane.

We did not expect to find any difference between the magnitude in the range of motion calculated with standard JCS and aligned JCS because it is calculated as the amplitude between the final and initial position. A statistical difference was observed only for rotation but it was not considered significant from a clinical point of view (1.4°).

The interpretation of the initial angular position of the arm was influenced by the JCS used. It must be noted that care was taken at the beginning of the experiment, to position the arm perpendicular to the ground, so that its resting position was at 0° of abduction, horizontal abduction and rotation. However, with the standard JCS, interpreting the initial angular position of the arm led to the conclusion that most specimens were in negative abduction, positive or negative horizontal abduction and positive or negative rotation. This was due to the relative orientation of the moving and reference coordinate system. In addition, when using standard JCS, the initial angular position of the arm around the three axes varied between specimens. This inter-specimen variability complicated the task of comparing specimens.

Using the aligned JCS, interpretation of the initial angular position of the arm was facilitated because of its standardization. At rest, the arm was in fact at 0° of abduction, horizontal abduction and rotation which was more meaningful from a clinical point of view. Furthermore, the alignment of the JCS was found to reduce inter-specimen variability and consequently facilitate comparisons between specimens. However, before aligning the JCS, it should be ensured that the arm is properly positioned.

We expected to find a difference between the initial angular position of the arm calculated with the standard JCS and the aligned JCS, because the initial orientation of the aligned JCS was voluntarily modified in a manner to standardize it at 0° of abduction, horizontal abduction and rotation. The absence of any significant difference for rotation initial angular position could be explained by two specimens for which the difference between the standard and aligned JCS was lower than 1.1°. This small difference between the initial position of the standard JCS and the aligned JCS can be attributed to the position of the scapula, which made the JCS Y-axes already aligned.

In our *in vitro* study, the scapula was positioned on the testing device in such a way that it reproduced its *in vivo* anatomical orientation in a resting position (Culham and Peat, 1993; Della Valle et al., 2001). To obtain this anatomical position, the scapula was slightly rotated in the coronal plane, which did not necessarily make the two coordinate systems (scapular and humeral) parallel to each other. To align the JCS without changing bone orientation, the idea of using a mathematical approach thus seemed interesting. However, the mathematical approach has the disadvantage of making the moving coordinate axis no longer coincident with the anatomical longitudinal axis of the humerus.

It is difficult to compare our findings with those of previous studies because of the recent publication (2005) of the standard JCS. To the best of our knowledge, Šenk and Chèze (2006) were the first to report problems related to using ISB JCS. Mathematical alignment of the JCS axes appeared to us to be a way of enhancing standardization of shoulder joint motion description so that it would foster better communication among researchers.

The use of the aligned JCS could demonstrate major benefits for future kinematics analysis. Since the aligned JCS is built on scapula bony landmarks only, it could eventually be used to analyze the shoulder joint motion of humerus amputed at the level of the epicondyle or of humerus with deformities (i.e. axial torsion of the humerus causing misalignment of the epicondyle). Moreover, using only scapula bony landmarks decreases the quantity of landmarks that have to be localized. Indeed, "the in vivo localisation of external anatomic landmarks is known to be difficult and subjective" (Marin et al., 2003). Precision errors related to anatomical landmark localisation may lead to mislocation and misorientation of the JCS that would ultimately affect kinematics motion analysis (Marin et al., 2003).

The limitations of this study can mainly be related to the testing device used. Firstly, this device was designed to simulate the elevation of the arm in the scapular plane only. Therefore, the influence of coordinate system axis alignment on other movements such as flexion, extension or circumduction could not be evaluated. Secondly, the scapula was rigidly fixed to the testing device. The influence of coordinate system axis alignment for *in vivo* motion when the scapula is moving could also not be evaluated. More over, our testing device was designed to simulate only the action of the middle deltoid. Constraints for the horizontal abduction had to be imposed (guiding board) to ensure elevation of the arm in the scapular plane. Nevertheless, it is important to mention that this device was the first one to simulate a continuous motion of the arm. The main advantage of using that kind of device was the possibility to record motion of the arm in a continuous way. Unlike previous testing devices used to study *in vitro* shoulder joint kinematics, this device also has the advantage of reproducing the line of action of the deltoid muscle and allowing the use of entire arm which helps preserving the inertial property of the entire upper limb. Finally, the sensitivity of the electromagnetic tracking device to the presence of metal in the environment could be another limitation and potential source of error in this study. LaScalze et al. (2003) showed that the metal located in the work field influenced the accuracy of electromagnetic tracking device. Therefore, before data acquisition, the effect of the small aluminium triangles on the accuracy of the tracking device was evaluated. The Fastrak sensors were rigidly fixed together and moved in the experimental environment. Their position, one compared to the other, was recorded and the computed error was below 1 mm and 1°. Therefore, the size of the aluminium triangles was small enough to minimally interfere with the electromagnetic tracking device.

5. Conclusion

The JCS definition recommended by the ISB is a major improvement in shoulder joint motion analysis. This recommendation encourages researchers to use standards that stimulate communication and discussion in the biomechanical field. To avoid representation and interpretation problems, the ISB suggests aligning both JCS. We have investigated here the effect of aligning the axes of the moving coordinate system with the axes of the reference coordinate system on shoulder kinematics. We proposed a mathematical approach for alignment of the coordinate system and demonstrated that an aligned JCS can provide a clearer interpretation of the initial angular position of the arm without introducing additional cross-talk. By starting at 0°, the aligned JCS reduced inter-specimen variability and made interpretation of kinematics easier. Future kinematics studies must be realized to determine if the aligned JCS can prove useful for the analysis of more complex movements such as circumduction which is a multiplanar motion.

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