

A standardized protocol for motion recordings of the shoulder

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Abstract - The comparison and exchange of motion data is hampered by the lack of a standardized description. A standard is proposed for the description of three-dimensional motions of the shoulder. It is shown how the known 3-D motion recording methods (roentgen, palpation and video) can adapt to the proposed protocol. Three steps are involved: Determination of local co-ordinate systems using bony landmarks, use of tracking markers to measure rotations of the local co-ordinate systems and choice of reference frame and order of Euler angles for motion description.

INTRODUCTION

The shoulder mechanism consists of three synovial joints, i.e. the sternoclavicular (SC) joint, the acromioclavicular (AC) joint and the glenohumeral (GH) joint. The medial border of the scapula is pressed against the thorax by the combined action of the m. serratus anterior and m. rhomboideus. This connection, the so-called scapulothoracic gliding plane, turns the shoulder girdle into a closed-chain mechanism. If small joint translations are neglected, the SC-joint can be represented by three rotational Degrees-of-Freedom (DOF), commonly referred to as pro-/retraction, elevation/depression and axial rotation. The AC-joint adds another three rotational DOF, which have no common names. The scapulothoracic gliding plane decreases the number of DOF with two (line connected to a surface). If it is considered that the axial rotation of the clavicle has no effect on the scapular orientation, three DOF remain for the scapula. This means that the scapula is subjected to forced rotations and translations. In other words, not every combination of orientation and position can be attained.

The complex motion constraints of the shoulder girdle result in a three-dimensional (3-D) motion pattern. Two-dimensional recordings have been shown to be very sensitive to projection errors (Groot, 1996). Hence, 3-D motion recording and description is necessary. Additional problems result from the motions of the clavicle and scapula underneath the skin: video-recordings using markers attached to the skin are not feasible, and the rotation axes of the AC-joints are not 'visible'.

Few 3-D motion recording techniques have been published. Högfors et al. (1991) used a 3-D roentgen technique with two roentgen cameras and implanted markers. Apparent problems are the difficult localization of the markers with respect to bony landmarks, the small field of view and low sample frequency. Advantage is the high accuracy and capacity to record dynamic motions. Other

authors used a palpation technique in which bony landmarks were retrieved and subsequently digitized using a palpator (Pronk, 1987; Van der Helm & Pronk, 1995) or electromagnetic devices like 3-Space or Flock-of-Birds (Johnson et al., 1993). Advantages are the non-invasive methodology and the direct retrieval of the bony landmarks. However, it is a static method: Only positions can be measured, not motions. 3-D video recordings (VICON, Optotrack, etc.) of the thorax and humerus are widely used. However, due to the large bone-to-skin displacements, no clavicular or scapular motions can be recorded using external markers. Advantages of the method are the fully dynamic capacity and high sampling frequency.

Motions recorded in the various studies are difficult to compare, since the local co-ordinate systems and rotation order are different. A standardized protocol for motion description is lacking, and due to the recording methodology some data sets are incomplete, i.e. in video techniques scapular and clavicular motions are missing, and bony landmarks have been missing in the roentgen technique. The goal of this paper is the proposition of a standardized protocol for 3-D motion description and the incorporation of the various recording methods into the same protocol.

The following steps will be shown:

- Definition of global and local co-ordinate systems with respect to *bony landmarks*.
- The choice of tracking markers.
- Motion description by choice of reference frame and order of rotation

Since the shape of bones and joints are different between individuals, it must be acknowledged that an absolute reference frame for comparing motions does not exist. Bony landmarks are well retrievable references in a bone, and are preferred above bony ridges like the scapular spine or humeral shaft. Bony ridges require additional definition since a straight line must be fitted through them. Bony landmarks are used to define local co-ordinate systems of the bones (Table 1). For comparison of

Table 1 - Description of bony landmarks

Bone segment	Bony landmark	Description
Thorax	IJ	Incisura Jugularis (suprasternal notch)
	PX	Processus Xiphoideus, most caudal point on sternum
	C7	Processus Spinosus of 7th cervical vertebra
	T8	Processus Spinosus of 8th cervical vertebra
Clavicle	SC	Most ventral point on Sternoclavicular joint
	AC	Most dorsal point on Acromioclavicular joint
Scapula	AC	Most dorsal point on Acromioclavicular joint
	TS	Trigonum Spinae, point on medial border in line with the scapular spine
	AI	Angulus Inferior, most caudal point of scapula
	AA	Angulus Acromialis, most latero-dorsal point of scapula
humerus	PC	Most ventral point of processus coracoideus
	GH	Glenohumeral rotation center, estimated by regression
	EM	Most caudal point on Medial Epicondyle
	EL	Most caudal point on Lateral Epicondyle

motions between studies, at least the same bony landmarks must be used, otherwise the results can not even be calculated in another co-ordinate system.

Definition of global and local co-ordinate systems with respect to bony landmarks.

In the definition of co-ordinate systems the following principles are considered:

- The global co-ordinate system and the local co-ordinate systems of the bones are as much aligned as possible in the initial (resting) position.
- Rotations about intuitively recognizable axes

- are better interpretable.
- Gimbal lock orientations somewhere in the range of motion must be avoided.

Global co-ordinate system:

- \underline{X}_g : horizontal, pointing from left to right.
- \underline{Y}_g : vertical, pointing upward.
- \underline{Z}_g : horizontal, pointing backward.

The global co-ordinate system is more or less aligned with the body. However, this is task dependent. Sitting and standing tasks do not pose a big problem, but in e.g. discus throwing the throwing direction can be used as the forward-backward direction. If motions of the left side of the body are recorded, it is advised to *start* data processing with mirroring the *raw* data in the *measurement co-ordinate system* ($X = -X$), in order to avoid left-handed co-ordinate systems or changes of definition.

Thorax

The local co-ordinate system ${}^G T$ (see footnote¹) is defined as:

$$\bullet \quad {}^G \underline{v}_t: \frac{\left\{ \left({}^g \underline{IJ} + {}^g \underline{C7} \right) / 2 - \left({}^g \underline{PX} + {}^g \underline{T8} \right) / 2 \right\}}{\left\| \left({}^g \underline{IJ} + {}^g \underline{C7} \right) / 2 - \left({}^g \underline{PX} + {}^g \underline{T8} \right) / 2 \right\|}$$

(vector from the midpoint between PX and T8 to the midpoint between IJ and C7, approximately vertical in the initial position)

¹For notation is referred to Craig (1985). The prefix of vectors or local co-ordinate systems defines the co-ordinate system in which the vector or local co-ordinate system is defined, e.g. ${}^G \underline{v}_t$ defines the y-axis of the thorax with respect to the global co-ordinate system. The two prefixes of rotation matrices define the first and second co-ordinate system between which the rotation is defined, e.g. $A \overset{A}{R} B = B$.

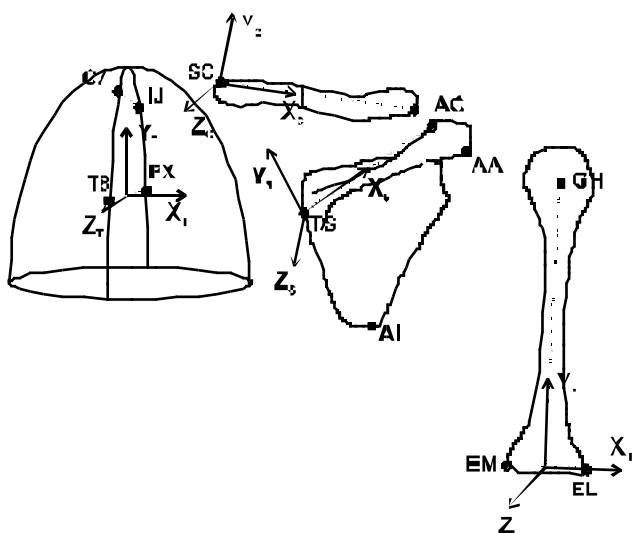


Figure 1- Bony landmarks and local co-ordinate systems of thorax, clavicle, scapula and humerus

- ${}^G\mathbf{x}_i$: Perpendicular to the plane fitted to the points ${}^G\mathbf{IJ}$, ${}^G\mathbf{C7}$ and $({}^G\mathbf{PX} + {}^G\mathbf{T8})/2$, pointing to the right.
 - ${}^G\mathbf{z}_i$: Perpendicular to ${}^G\mathbf{x}_i$ and ${}^G\mathbf{y}_i$.
 - Origin: ${}^G\mathbf{IJ}$
 - and ${}^G\mathbf{T} = [{}^G\mathbf{x}_i \quad {}^G\mathbf{y}_i \quad {}^G\mathbf{z}_i]$.
- ${}^G\mathbf{IJ}$ is the position vector of bony landmark IJ (Incisura Jugularis), etc. The thorax co-ordinate system is defined such that in the resting position it is approximately aligned with the global co-ordinate system G.

Clavicle

The local co-ordinate system ${}^G\mathbf{C}$ is defined as:

- ${}^G\mathbf{x}_c$: $({}^G\mathbf{AC} - {}^G\mathbf{SC}) / \|({}^G\mathbf{AC} - {}^G\mathbf{SC})\|$
- ${}^G\mathbf{z}_c$: Perpendicular to ${}^G\mathbf{x}_c$ and ${}^G\mathbf{y}_c$ (!!), pointing backward.
- ${}^G\mathbf{y}_c$: Perpendicular to ${}^G\mathbf{z}_c$ and ${}^G\mathbf{x}_c$.
- Origin: ${}^G\mathbf{SC}$.
- and ${}^G\mathbf{C} = [{}^G\mathbf{x}_c \quad {}^G\mathbf{y}_c \quad {}^G\mathbf{z}_c]$.

NB., only two bony landmarks can be identified on the clavicle. Therefore, the thorax ${}^G\mathbf{y}_c$ axis is used for definition of the initial orientation of the clavicle. Once the orientation of the initial position of the clavicle has been defined, subsequent rotations can be found by the displacement of tracking markers (Högfors et al., 1991) or e.g. by minimizing AC-joint rotations (Van der Helm & Pronk, 1995). Pronk (1987) and Johnson et al. (1993) used the bony landmark AA instead of bony landmark AC. Here, AC is preferred since it is a common point with the clavicle, and the rotation between the clavicular and scapular local co-ordinate systems closely approximates the AC-joint rotations.

Scapula

- ${}^G\mathbf{x}_s$: $({}^G\mathbf{AC} - {}^G\mathbf{TS}) / \|({}^G\mathbf{AC} - {}^G\mathbf{TS})\|$.
- ${}^G\mathbf{z}_s$: Perpendicular to $({}^G\mathbf{AI} - {}^G\mathbf{AC})$ and ${}^G\mathbf{x}_s$, pointing backward, i.e. perpendicular to the scapular plane.
- ${}^G\mathbf{y}_s$: Perpendicular to ${}^G\mathbf{z}_s$ and ${}^G\mathbf{x}_s$.
- Origin: ${}^G\mathbf{AC}$.
- and ${}^G\mathbf{S} = [{}^G\mathbf{x}_s \quad {}^G\mathbf{y}_s \quad {}^G\mathbf{z}_s]$.

Humerus

- ${}^G\mathbf{y}_h$: $({}^G\mathbf{GH} - {}^G\mathbf{E}) / \|({}^G\mathbf{GH} - {}^G\mathbf{E})\|$.
- ${}^G\mathbf{z}_h$: Perpendicular to ${}^G\mathbf{y}_h$ and $({}^G\mathbf{EL} - {}^G\mathbf{EM})$, pointing backward.
- ${}^G\mathbf{x}_h$: Perpendicular to ${}^G\mathbf{y}_h$ and ${}^G\mathbf{z}_h$.
- Origin: ${}^G\mathbf{GH}$.
- and ${}^G\mathbf{H} = [{}^G\mathbf{x}_h \quad {}^G\mathbf{y}_h \quad {}^G\mathbf{z}_h]$.

GH is *not* a bony landmark. It can be obtained by a regression equation using AC, AA, TS, AI and PC (Meskers et al., 1997: standard deviation of the residual error between 2-5 mm. per co-ordinate).

GH provides a useful operationalization of the longitudinal axis of the humerus. It can also be operationalized in another way, e.g. by a cuff mounted to the upper arm.

The choice of tracking markers

Tracking markers are markers which can be retrieved during the motion under study. The tracking markers can be used to calculate the position and orientation of the local co-ordinate system in each recorded position. For the various recording methods different tracking markers are used. In a 3-D roentgen study tantalum balls implanted to the bones are used. In a palpation study the bony landmarks serve both for the definition of the local co-ordinate systems, but also as tracking markers, since they are recorded in each position. A Flock-of-Bird system provides a direct recording of the position and orientation of the local co-ordinate system, the sensor replaces the set of tracking markers. In a 3-D video recording marker trees mounted to the segments are used as tracking markers.

The calculation procedure contains the following steps:

- Before the start of the experiment, the position of the tracking markers (or sensor) are recorded with respect to the local co-ordinate system, i.e. the bony landmarks are recorded simultaneously: recording of Initial Position.
- The position of the marker tree is recorded during the experiment.
- The rotations of the marker tree with respect to marker tree in the Initial Position can be calculated using an algorithm provided by Veldpaus et al. (1988).
- The orientation of the local co-ordinate system during the experiment can be calculated using the rotation of the marker tree and the Initial Position of the local co-ordinate system.

The first step is especially important for 3-D roentgen recordings. It must be attempted to record the position of the bony landmarks together with the position of the tantalum balls. Otherwise the results can not be generalized to non-invasive situations. If no tracking markers can be used for the clavicle and scapula (i.e. in 3-D video measurements), the orientation of these bones can be calculated by a regression equation using the humeral orientation, a marker at AC and the initial position of the scapula as regressors (Groot, 1997^a). Groot (1997^b) found that there were no major effects of movement velocity and external forces of the scapulo-humeral rhythm. This allows for extrapolation of static (palpation) measurements to dynamic situations (3-D video).

Table 2 - Calculation of rotation matrices for joint rotations

	Joint	Rotation matrix
Clavicle w.r.t. Thorax	Sternoclavicular joint	${}^G T . R_{c_i} = {}^G C \Rightarrow R_{c_i} = {}^G T^T . {}^G C$
Scapula w.r.t. Clavicle	Acromioclavicular joint	${}^G C . R_{s_i} = {}^G S \Rightarrow R_{s_i} = {}^G C^T . {}^G S$
Humerus w.r.t. Scapula	Glenohumeral joint	${}^G S . R_{h_i} = {}^G H \Rightarrow R_{h_i} = {}^G S^T . {}^G H$

Motion description by choice of reference frame and order of rotation

An important distinction in the definition of rotation is the difference between rotations with respect to the *global* co-ordinate system and with respect to a *local* co-ordinate system. A general description of rotations with respect to the global co-ordinate system is given by:

• ${}^G A . {}^A_B R = {}^G B \Rightarrow {}^A_B R = {}^G A^T . {}^G B$

where R denotes the rotation from local co-ordinate system ${}^G A$ to local co-ordinate system ${}^G B$ and is defined as a rotation about the axes of the global co-ordinate system. Postfix T means the transposed matrix. Pre-multiplying with a rotation matrix means rotations about the axes of the global co-ordinate system. Post-multiplying with a rotation matrix means rotations about the axes of the (first) local co-ordinate system as is usually the case in biomechanical definitions.

Choice of reference frame

There are two ways to describe the orientation of a bone, with respect to the proximal bone (*joint rotations*) and a ‘global’ orientation (*bone rotations*). A global orientation would mean the orientation with respect to the global co-ordinate system. However, if for example the throwing motion of a discus thrower is considered, the orientation of the clavicle with respect to the track does not make much sense. Therefore, for the ‘global’ orientation the thorax is chosen as a reference. It is very common to describe the humerus orientation with respect to the thorax (the virtual ‘thoraco-humeral’ joint, often referred to as shoulder joint!). But also for the interpretation of the scapular motions over the scapulothoracic gliding plane the thorax is very useful as a reference frame.

Joint rotations (Table 2)

The thorax is defined with respect to the Global Co-ordinate System (GCS), since there is no proximal bone. Next, the SC-joint rotations are defined as rotations of the clavicle with respect to the thorax, AC-joint rotations of the scapula with respect to the clavicle and GH-joint rotations of the humerus with respect to the scapula. It is important to note that these rotations are calculated using the rotations of local co-ordinate systems based on bony landmarks. For true joint rotations the location of the (sometimes moving) joint rotation center with respect to the local co-ordinate system is needed. However, since the bony landmarks SC and AC are close to the joint rotation centers, and GH is actually an approximation of the joint rotation center, the deviations will be small.

Bone rotations (Table 3)

The thorax is defined with respect to the GCS, similar as in the definition of joint rotations. The clavicle, scapula and humerus are defined with respect to the thorax. For the clavicle the rotations are also similar as in the joint rotations, since the thorax is the proximal bone.

Euler angles

A rotation matrix is a 3 x 3 matrix consisting of the cosines between the axes of the first and second local co-ordinate system between which the rotation is defined. These nine numbers contain only three independent variables. One way to decompose the three independent variables is the choice of Euler angles. Euler angles can be interpreted as subsequent rotations around axes of the (local or global) co-ordinate system:

$$R_x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\alpha) & -\sin(\alpha) \\ 0 & \sin(\alpha) & \cos(\alpha) \end{bmatrix}$$

Table 3 - Calculation of rotation matrices for bone rotations

	Rotation matrix
Thorax w.r.t. Global co-ordinate system	${}^G R_{t_i} = {}^G T \Rightarrow R_{t_i} = {}^G T . {}^G T$
Clavicle w.r.t. Thorax	${}^G T . R_{c_i} = {}^G C \Rightarrow R_{c_i} = {}^G T^T . {}^G C$
Scapula w.r.t. Thorax	${}^G T . R_{s_i} = {}^G S \Rightarrow R_{s_i} = {}^G T^T . {}^G S$
Humerus w.r.t. Thorax	${}^G T . R_{h_i} = {}^G H \Rightarrow R_{h_i} = {}^G T^T . {}^G H$

Table 4 - Definition of rotation order of the SC-, AC- and GH-joint rotations. Axes denoted with single and double quotes are rotated with respect to the initial aligned orientation of local co-ordinate systems.

	Rotation order	Description
Sternoclavicular joint	Y Z' X''	Pro/retraction about the <i>thoracic</i> ${}^G\mathbf{y}_t$ axis elevation/depression about the local \mathbf{z}_c axis axial rotation about the local \mathbf{x}_c (longitudinal axis)
Acromioclavicular joint	Y Z' X''	Pro/retraction about the <i>clavicular</i> ${}^G\mathbf{y}_c$ axis lateral/medial rotation about the local \mathbf{z}_s axis perpendicular to the scapular plane tipping forward/backward about the local \mathbf{x}_s axis through the scapular spine
Glenohumeral joint	Y Z' Y''	Plane of elevation with respect to the <i>scapular</i> ${}^G\mathbf{y}_s$ axis Elevation/depression about the local \mathbf{y}_h axis axial rotation about the local \mathbf{y}_h axis

$$R_y = \begin{bmatrix} \cos(\beta) & 0 & \sin(\beta) \\ 0 & 1 & 0 \\ -\sin(\beta) & 0 & \cos(\beta) \end{bmatrix}$$

$$R_z = \begin{bmatrix} \cos(\gamma) & -\sin(\gamma) & 0 \\ \sin(\gamma) & \cos(\gamma) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

for rotations α , β and γ about the x-, y- and z-axis respectively. Successive rotations α , β and γ result in

- $R = R_x(\alpha) \cdot R_y(\beta) \cdot R_z(\gamma)$

N.B. the second and third rotation occur about rotated axes redirected by one (R_x) or two ($R_x \cdot R_y$) previous rotations. The rotation order is very important: x-y-z result in different angles than e.g. y-z-x. The following was considered in the choice of rotation order:

The definitions are more or less according to medical terminology, though the latter only refers to the anatomical position and often misplaces rotations by translations.

The last rotation is about the ‘longitudinal’ axis. The advantage is that the first two rotations determine the orientation of this axis.

Since in the initial (resting) position the local co-ordinate systems of the bones are not aligned, the rotations do not start with zero-zero-zero. Often, the zero-zero-zero position can even not be obtained (e.g. alignment of the clavicular and scapular co-ordinate systems is physically impossible).

Gimbal lock orientations should be avoided. The gimbal lock orientation occurs if the second rotation is $\pm 90^\circ$ (when three different axes are used, like x-y-z, etc.) or if the second orientation is 0° or 180° (when two different axes are used, like y-z-y, etc.). Then, in the gimbal lock position the first and third rotation axis co-incide, and no solution can be

found for the decomposition into Euler angles. Close to the gimbal lock position the rotations becomes very sensitive to measurement errors, resulting in large intra- and interindividual standard deviations.

Choice of order of rotations

In Tables 4 and 5 the proposed order of rotations using Euler angle decomposition is shown. The rotation axes are shown in Figure 1. Euler angles are defined about axes of the first co-ordinate system (where it should be kept in mind that the second and third rotation are about displaced axes). The description of the rotations in anatomical terms is also given.

The rotations should be interpreted as follows. To start, imagine that the second local co-ordinate system (e.g. the scapula) is aligned with the first local co-ordinate system (e.g. the thorax: ${}^G\mathbf{T}$). The first rotation occurs about the common axis, e.g. the ${}^G\mathbf{y}_t$ (and thus ${}^G\mathbf{y}_s$ axis). After this first rotation the x- and z-axis are not aligned any more. Then the second rotation occurs about the displaced \mathbf{z}_s axis, and the third rotation about the twice displaced \mathbf{x}_s axis. Then the resulting scapular orientation is equal to the recorded position ${}^G\mathbf{S}$. The magnitude of the first, second and third rotation can be uniquely solved from the rotation matrix R^{*2} .

DISCUSSION

Until now, three methods for recording the three-dimensional motion of the shoulder mechanism have been published: using 3-D roentgen, using a palpation technique and 3-D video. In the current

*²There are two solutions to determine Euler angles from a rotation matrix. However, if the second rotation is constrained between -90° and 90° (x-y-z, etc.) or between 0° and 180° (y-z-y, etc.), the best interpretable solution remains.

Table 5 - Definition of rotation order of the thorax, clavicle, scapula and humerus rotations. Axes denoted with single and double quotes are rotated with respect to the initial aligned orientation of the local co-ordinate systems.

	Rotation order	Description
Thorax	X	Forward/backward rotation about the <i>global</i> \underline{Y}_G axis
	Z'	Lateral flexion about the local \underline{z}_t axis
	Y''	Torsion about the local \underline{y}_t axis
Clavicle	Y	Pro/retraction about the <i>thoracic</i> \underline{y}_t axis
	Z'	elevation/depression about the local \underline{z}_c axis
	X''	axial rotation about the local \underline{x}_c (longitudinal axis)
Scapula	Y	Pro/retraction about the <i>thoracic</i> \underline{y}_t axis
	Z'	lateral/medial rotation about the local \underline{z}_s axis perpendicular to the scapular plane
	X''	tipping forward/backward about the local \underline{x}_s axis through the scapular spine
Humerus	Y	Plane of elevation with respect to the <i>thoracic</i> \underline{y}_t axis
	Z'	Elevation/depression about the local \underline{y}_h axis
	Y''	axial rotation about the local \underline{y}_h axis

paper a standardized protocol is proposed for a similar description of motions irrespective which method is used. Main problems are that in the 3-D roentgen technique the bony landmarks must be recorded with respect to the tracking markers (tantalum balls), and that for the 3-D video measurements regression equations are needed for determining the scapular and clavicular rotations. The glenohumeral rotation center (GH) can be estimated using a regression equation with the position of the bony landmarks of the scapula as regressors. When the local co-ordinate systems are defined with respect to the bony landmarks, tracking markers (or a sensor in case of an electromagnetic device) are used to determine the rotations. Subsequently, rotations can be uniquely described with respect to the proximal bone (joint rotations) or with respect to the thorax (bone rotations) using an Euler angle decomposition of the rotation matrix.

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