A standardized protocol for the description of shoulder motions.

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Introduction

Standardization of joint motions is very important for the enhancement of the study of motion biomechanics. The International Shoulder Group (ISG) supports the efforts of the ISB on this item, and recommends that authors be required to:

- use the same set of bony landmarks;
- use identical Local Coordinate Systems (LCS);
- report motions according to a standardized protocol.

Next to the standardized report, the authors are free to define their own convention, which may be more appropriate for demonstrating their arguments.
The ISG has nominated a committee for the standardization of the motion description of the shoulder. Members are:

- Mohsen Makhsous
- Peter van Roy
- Carolyn Anglin
- Jochem Nagels
- Andrew Karduna
- Frans van der Helm
- DirkJan Veeger
- Kevin McQuade
- Xuguang Wang

More information can be obtained at: http://www.internationalshouldergroup.org.
The starting point for the standardization protocol is a paper by Van der Helm (1996). However, in some points the final proposal deviates from this paper.

Three principles are essential for standardization of the motions of any musculoskeletal system:

1. The use of an unambiguous set of bony landmarks for all studies.
   This will enhance the data exchange between cadaver studies, X-ray studies, 3D motion recording studies, musculoskeletal model simulations, etc.
2. The Local Coordinate System (LCS) should be defined in a standard fashion with respect to these bony landmarks. The initial orientation of the LCS should be close to the orientation of the Global Coordinate System. Motions are recorded using 'tracking markers', which can be optical markers for a camera system, or receivers for an electromagnetic device. The relation between the LCS (i.e. the bony landmarks) and the tracking markers should be determined in an initial measurement at the start of the experiment.
3. Rotations are defined as the rotation of a LCS with respect to a more proximal LCS. In this way, bone rotations (osteo-kinematics) are defined. For the motions of the articular surfaces (arthro-kinematics), the shape and position of the articular surfaces with respect to the LCS is needed. Arthro-kinematic definitions are beyond the scope of this proposal.

Proposal

1. *Definition of bony landmarks.*
   In Fig. 1 the bony landmarks of the thorax, clavicle, scapula and humerus are shown. In Table 1 the definitions of the bony landmarks are given to allow them to be located in vivo. For the clavicle only two bony landmarks can be discerned: SC and AC. Hence, the axial rotation of the clavicle cannot be determined through (non-invasive) palpation measurements, but can be calculated on the basis of optimization (Van der Helm & Pronk, 1995). In contrast to Van der Helm (1996), the use of the landmark Angulus Acromialis (AA) is proposed instead of Acromio-Clavicular joint (AC). This choice will

reduce the occurrence of complications due to gimbal lock (based on results by de Groot, 1998). The glenohumeral joint (GH) is strictly speaking not a bony landmark, but is needed to define the longitudinal axis of the humerus. GH can be estimated by regression analysis (Meskers et al., 1998[b]) or by calculating the pivot point of helical axes (IHA) of glenohumeral motions (Stokdijk et al., 2000; Veeger et al, 1996). The latter method is preferred since it is more accurate, and is also valid for patients in whom it is likely that the GH rotation center is changed due to degeneration of the articular surfaces, or due to implants. In some pathological cases it is likely that the GH center can not accurately be estimated with the IHA method due to translations in the joint. It is, however, questionable whether the regression method will be an acceptable alternative, or whether different methods should be used.

2. *Motion recording methods*
   A number of three-dimensional motion recording methods have been used for the shoulder, based on X-ray, optical camera systems, electromagnetic receivers and palpation techniques. In these recording techniques a cluster of tracking markers (Helm & Veeger, 1996) or electromagnetic receivers (Karduna et al, 2000; Meskers et al., 1998[a]) is used to track the bony motions. The positions of these tracking markers or receivers with respect to the LCS are needed for data processing, and should be measured separately in a static calibration trial.
3. *Definition of Global Coordinate System (GCS)*
   The definition of the Global Coordinate System (GCS) is arbitrary, and subject to personal preferences and field of education. In this proposal the convention of Van der Helm (1996) is used, with a horizontal X-axis (pointing left to right), vertical Y-axis (pointing upwards) and horizontal Z-axis (pointing backwards). There is, however, no principal objection against other conventions. It is proposed that the above extension be used unless the ISB decides on a different standardized GCS (Wu & Cavanagh, 1995).
4. *Definition of Local Coordinate Systems (LCS)*
   In Table 2 the Local Coordinate Systems are defined with respect to the bony landmarks. The rotation center of the glenohumeral joint (GH) is not a bony landmark, but can be reconstructed by either regression equations using AC, AA, TS, AI and PC (Meskers et al., 1998[b]) or by determining the pivot point through multiple helical axes (Stokdijk et al., 2000; Veeger et al, 1996). For the humeral LCS two options are given: Using the bony landmarks EL and EM, or using the normal to the plane through the upper arm and forearm (see Wang, 1996).
5. *Definition of rotations*
   Rotations are described as the rotation of a bone LCS relative to the LCS of another bone, or the GCS. In the shoulder, it is useful to report two types of rotations:
   - Rotations with respect to the proximal bone ('Joint rotations'): These are the thorax relative to the GCS, clavicle relative to thorax (sternoclavicular joint), scapula relative to clavicle (acromioclavicular joint), humerus relative to scapula (glenohumeral joint), see Table 3.
   - Rotations of the scapula and humerus relative to the thorax ('Bone rotations'): Scapula relative to thorax, Humerus relative to thorax (the non-existent thoraco-humeral joint, often loosely described as the shoulder joint), see Table 4.
6. *Definition of sequence of Euler angles*
   Tables 5 and 6 show the proposed sequence of Euler angles to decompose the rotation matrices as defined in section 5). The sequence of Euler angles has been chosen such that the first two rotations define the orientation of the longitudinal axis of the bone (clavicle and humerus) or a bony ridge (scapular spine), and the third rotation is about this axis (axial rotation). The main problem is to avoid gimbal lock problems as much as possible. Gimbal lock describes the situation when the first and third axes of rotation coincide when the second rotation is $+90^o$ or -90^o (for any order of three different rotation axis, e.g. X-Y-Z) or 0^o or 180^o (for any order of rotations with the first and third rotation about the same initial axis, e.g. Y-Z-Y). Near the gimbal lock position (roughly within 20^o) measurement errors will be amplified and large inaccuracies of the first and third rotations

will result. Given the large rotations of the shoulder bones, gimbal lock problems will appear unavoidably. In the current definitions, gimbal lock problems might appear when the lateral rotation of the scapula approaches 70^{o}, and/or the humeral elevation is 0^{o} (vertically downward) or 180^{o} (vertically upward).

Concluding remarks

1. Standardization of motion description facilitates the exchange of data, and will improve the interpretation of results.
2. Results from all types of motion recording studies can be described by the same methodology.
3. Choice of an identical set of bony landmarks is essential for comparisons.
4. Proper definition of local coordinate systems and rotation sequence is needed to enhance the physical interpretation of the rotations (e.g. axial rotation as last rotation), avoidance of gimbal lock problems.

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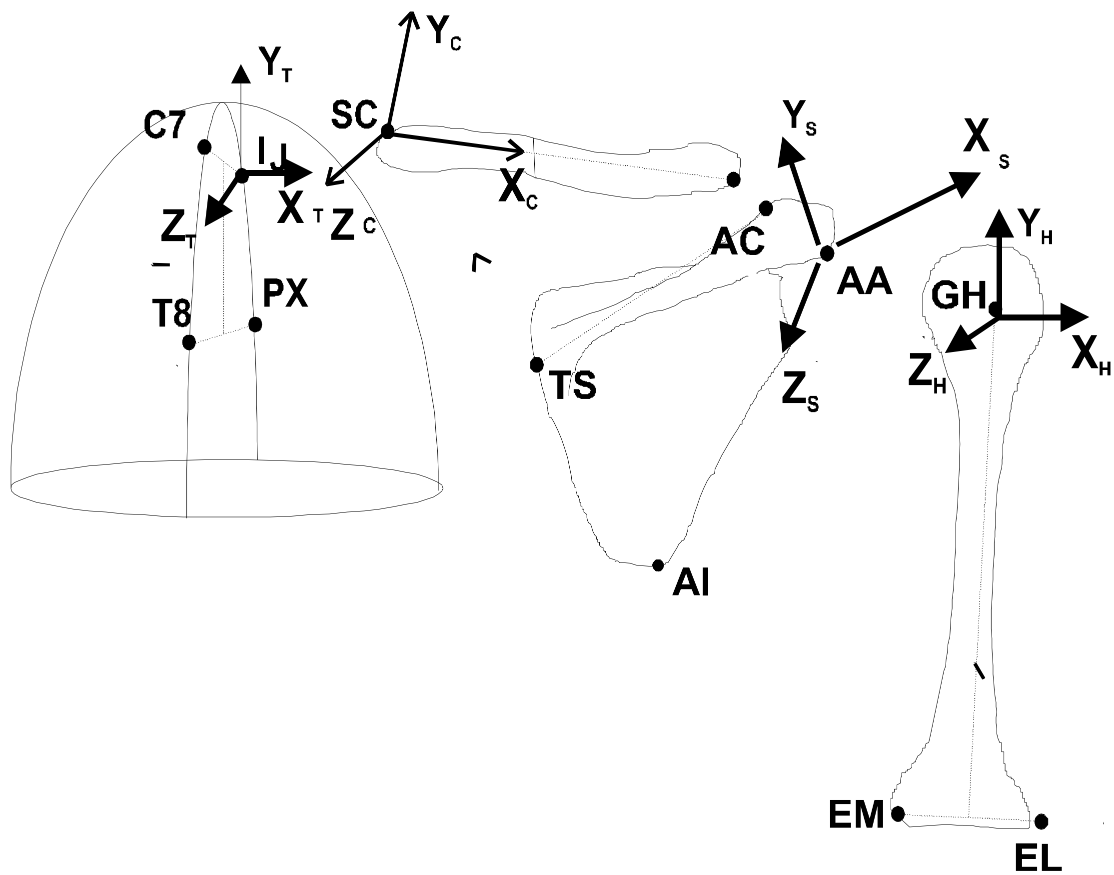

Figure 1: *Local coordinate systems of the thorax, clavicle, scapula and humerus are defined with bony landmarks.*

Table 1: Description of bony landmarks

Bone segment	Bony landmark	Description
Thorax	IJ	Deepest point of Incisura Jugularis (suprasternal notch)
	PX	Processus Xiphoideus, most caudal point on sternum
	C7	Processus Spinosus of 7th cervical vertebra
	T8	Processus Spinosus of 8th thoracic vertebra
Clavicle	SC	Most ventral point on Sternoclavicular joint
	AC	Most dorsal point on Acromioclavicular joint (shared with scapula)
Scapula	AC	Most dorsal point on Acromioclavicular joint (shared with clavicula)
	TS	Trigonum Spinae Scapulae, mid point of triangular surface on medial border of the scapula in line with the scapular spine
	AI	Angulus Inferior, most caudal point of scapula
	AA	Angulus Acromialis, most latero-dorsal point of scapula
	PC	Most ventral point of processus coracoideus
humerus	GH	Glenohumeral rotation center, estimated by regression or motion recordings
	EM	Most caudal point on Medial Epicondyle
	EL	Most caudal point on Lateral Epicondyle
forearm (generic)	SU	Most caudo-lateral point on ulnar styloid
	SR	Most caudo-dorsal point on radial styloid

Table 2: Definition of the axes of the local coordinate systems. For notation refer to Craig (1989). The vector prefix indicates the coordinate system in which the vector is defined, e.g. ${}^{G}\underline{y}_t$ defines the y-axis of the thorax with respect to the global coordinate system .

LCS	Axis	Definition
Thorax	${}^{G}\underline{y}_t$	$\{({}^{G}\underline{IJ} + {}^{G}\underline{C7})/2 - ({}^{G}\underline{PX} + {}^{G}\underline{T8})/2\} / \lVert {}^{G}\underline{IJ} + {}^{G}\underline{C7})/2 - ({}^{G}\underline{PX} + {}^{G}\underline{T8})/2\}/\} \rVert$ (vector from the midpoint between PX and T8 to the midpoint between IJ and C7, approximately vertical in the initial position)
	${}^{G}\underline{x}_t$	Perpendicular to the plane fitted to the points ${}^{G}\underline{IJ}$, ${}^{G}\underline{C7}$ and $({}^{G}\underline{PX} + {}^{G}\underline{T8})/2$, pointing to the right.
	${}^{G}\underline{z}_t$	Perpendicular to ${}^{G}\underline{x}_t$ and ${}^{G}\underline{y}_t$.
	Origin	${}^{G}\underline{IJ}$
Clavicle	${}^{G}\underline{x}_c$:	$({}^{G}\underline{AC} - {}^{G}\underline{SC}) / \lVert ({}^{G}\underline{AC} - {}^{G}\underline{SC}) \rVert$
	${}^{G}\underline{z}_c$	Perpendicular to ${}^{G}\underline{x}_c$ and ${}^{G}\underline{y}_t$ (Thoracic y-axis!!), pointing backward
	${}^{G}\underline{y}_c$	Perpendicular to ${}^{G}\underline{z}_c$ and ${}^{G}\underline{x}_c$
	Origin	${}^{G}\underline{SC}$
Scapula	${}^{G}\underline{x}_s$	$({}^{G}\underline{AA} - {}^{G}\underline{TS}) / \lVert ({}^{G}\underline{AA} - {}^{G}\underline{TS}) \rVert$.
	${}^{G}\underline{z}_s$	Perpendicular to $({}^{G}\underline{AI} - {}^{G}\underline{AA})$ and ${}^{G}\underline{x}_s$, pointing backward, i.e. perpendicular to the scapular plane.
	${}^{G}\underline{y}_s$	Perpendicular to ${}^{G}\underline{z}_s$ and ${}^{G}\underline{x}_s$.
	Origin	${}^{G}\underline{AC}$
Humerus (1st def.)	${}^{G}\underline{y}_h$	$({}^{G}\underline{GH} - {}^{G}\underline{E}) / \lVert ({}^{G}\underline{GH} - {}^{G}\underline{E}) \rVert$. ${}^{G}E = \left({}^{G}EL + {}^{G}EM\right)/2$
	${}^{G}\underline{z}_h$	Perpendicular to ${}^{G}\underline{y}_h$ and $({}^{G}\underline{EL} - {}^{G}\underline{EM})$, pointing backward.
	${}^{G}\underline{x}_h$	Perpendicular to ${}^{G}\underline{y}_h$ and ${}^{G}\underline{z}_h$.
	Origin	${}^{G}\underline{GH}$
Humerus (2nd def.)	${}^{G}\underline{y}_h$	$({}^{G}\underline{GH} - {}^{G}\underline{E}) / \lVert ({}^{G}\underline{GH} - {}^{G}\underline{E}) \rVert$. ${}^{G}E = \left({}^{G}EL + {}^{G}EM\right)/2$
	${}^{G}\underline{x}_h$	Perpendicular to the plane through the upper arm and forearm, defined by ${}^{G}\underline{y}_h$ and ${}^{G}\underline{y}_f$: ${}^{G}\underline{x}_h = {}^{G}\underline{y}_h \times {}^{G}\underline{y}_f$, pointing laterally.
	${}^{G}\underline{z}_h$	Perpendicular to ${}^{G}\underline{x}_h$ and ${}^{G}\underline{y}_h$.
	Origin	${}^{G}\underline{GH}$
Forearm (generic)	${}^{G}\underline{y}_f$	$({}^{G}E - {}^{G}\underline{F}) / \lVert ({}^{G}\underline{E} - {}^{G}F) \rVert$. ${}^{G}F = \left({}^{G}SR + {}^{G}SU\right)/2$
	Origin	**${}^{G}F$**

Table 3: Calculation of rotation matrices for joint rotations

	Joint	Rotation matrix
Clavicle relative to Thorax	Sternoclavicular joint	${}^{G}T.Rc_{i} = {}^{G}C \Rightarrow Rc_{i} = {}^{G}T^{T}.{}^{G}C$
Scapula relative to Clavicle	Acromioclavicular joint	${}^{G}C.Rs_{i} = {}^{G}S \Rightarrow Rs_{i} = {}^{G}C^{T}.{}^{G}S$
Humerus relative to Scapula	Glenohumeral joint	${}^{G}S.Rh_{i} = {}^{G}H \Rightarrow Rh_{i} = {}^{G}S^{T}.{}^{G}H$

Table 4: Calculation of rotation matrices for bone rotations

	Rotation matrix
Thorax relative to Global C.S.	$G.Rt_{i} = {}^{G}T \Rightarrow Rt_{i} = G^{T}.{}^{G}T$
Clavicle relative to Thorax	${}^{G}T.Rc_{i} = {}^{G}C \Rightarrow Rc_{i} = {}^{G}T^{T}.{}^{G}C$
Scapula relative to Thorax	${}^{G}T.Rs_{i} = {}^{G}S \Rightarrow Rs_{i} = {}^{G}T^{T}.{}^{G}S$
Humerus relative to Thorax	${}^{G}T.Rh_{i} = {}^{G}H \Rightarrow Rh_{i} = {}^{G}T^{T}.{}^{G}H$

Table 5: 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 the local coordinate systems.

	Rotation order	**Description**
Sternoclavicular joint	Y	Pro/retraction about the *thoracic* $^{G}\underline{y}_t$ axis
	Z’	elevation/depression about the local $\underline{z}_c$ axis
	X”	axial rotation about the local $\underline{x}_c$ (longitudinal axis)
Acromioclavicular joint	Y	Pro/retraction about the *clavicular* $^{G}\underline{y}_c$ axis
	Z’	lateral/medial rotation about the local $\underline{z}_s$ axis perpendicular to the scapular plane
	X”	anterior/posterior tilt about the local $\underline{x}_s$ axis through the scapular spine
Glenohumeral joint	Y	Plane of elevation with respect to the *scapular* $^{G}\underline{y}_s$ axis
	Z’	Elevation/depression about the local $\underline{z}_h$ axis
	Y”	axial rotation about the local $\underline{y}_h$ axis

Table 6: 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 coordinate systems.

	Rotation order	**Description**
Thorax	X	Forward/backward rotation about the *global* $\underline{Y}_G$ axis
	Z’	Lateral flexion about the local $^{G}\underline{z}_t$ axis
	Y”	Torsion about the local $^{G}\underline{y}_t$ axis
Clavicle	Y	Pro/retraction about the *thoracic* $^{G}\underline{y}_t$ 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 *thoracic* $^{G}\underline{y}_t$ axis
	Z’	lateral/medial rotation about the local $\underline{z}_s$ axis perpendicular to the scapular plane
	X”	anterior/posterior tilt about the local $\underline{x}_s$ axis through the scapular spine
Humerus	Y	Plane of elevation with respect to the *thoracic* $^{G}\underline{y}_s$ axis
	Z’	Elevation/depression about the local $\underline{z}_h$ axis
	Y”	axial rotation about the local $\underline{y}_h$ axis